Chapter 3

Radioactivity

I. Natural radioactivity

II. Artificial radioactivity and nuclear reactions: nuclear fission, nuclear fusion, transmutation

III. Radioactive decay kinetics: radioactive decay law: activity of a radioactive nucleus, radioactive half-life or half-life time

Natural radioactivity was first discovered by French physicist Antoine Henri BECQUEREL (1886) by chance. He noticed that uranium and potassium sulfate emitted invisible radiation capable of penetrating a light-tight cover and printing a photographic plate. This radiation is unaffected by any external intervention (temperature, pressure, ...), which distinguishes it from a chemical reaction. It is a spontaneous nuclear reaction. Ernest RUTHERFORD discovers the nature of radiation: the radiation emitted is different in nature, with two types (α and β) influenced by magnetic and electric fields and a third (γ) insensitive to the previous fields.

The α et β emission is accompanied by a highly energetic photon emission that constitutes the γ -ray.

Radioactivity is the natural property of certain atomic nuclei to emit radiation spontaneously (the transformation of atomic nuclei during which radiation is emitted is called radioactivity). This corresponds to a spontaneous search for nuclear stability. This emission of radiation accompanies the phenomenon of radioactive decay, which transforms the nucleus of the "father" element (X) into a son nucleus (Y). In this way, the nucleus of a radioactive isotope will spontaneously transform into the nucleus of a more stable isotope of the same element, or into the nucleus of an isotope of another chemical element.

- **Core stability**

Let be the kernel of the following element ${}^{A}_{Z}X$ and A=Z+N:

- ✓ If the ratio $\frac{A-Z}{Z} = 1,$ the element's nucleus is said to be stable. A stable nucleus is one that retains the same composition indefinitely.

- ✓ If the ratio $\frac{A-Z}{Z} \geq 1.5$, the nucleus is said to be unstable. An unstable, or radioactive, nucleus is one that disintegrates by spontaneously emitting α, β and γ particles.

- **Soddy and Fajans conservation law**

Consider the following reaction:

$$^{A}_{Z}X \rightarrow ^{A1}_{Z1}Y + ^{A2}_{Z2}P$$

Where X is the parent nucleus, Y is the child nucleus and P is an ejected (emitted) particle. During a natural or artificial nuclear transformation, there are:

- ✓ Conservation of the total number of nucleons or mass number: A = A1 + A2
- ✓ Conservation of charge number: Z = Z1 + Z2
- ✓ Conservation of momentum and total energy.

I. Natural radioactivity

Natural radioactivity refers to the property of certain nuclei to disintegrate spontaneously by emitting various types of radiation: an α particle, an electron (or negaton) $^{0}_{-1}e$ (β^-) or a positron $^{0}_{+1}e$ (β^+); and sometimes a highly energetic electromagnetic radiation called γ radiation. The nucleus that decays is called the father nucleus, and the nucleus that appears is called the son nucleus.

a) Alpha α radioactivity: this mainly concerns heavy elements with atomic numbers Z > 83, i.e. the parent nucleus is very massive, and its instability is due to an excess of nucleons: an excess of protons or neutrons. The particle emitted in this case is the helium nucleus $^{4}_{2}He$ (the α particle), as shown by the following general reaction:

$$^{A}_{Z}X \rightarrow ^{A-4}_{Z-2}Y + ^{4}_{2}He$$

Example:

- Uranium 238 is a radioactive α nucleus: $^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$ (Th : **son core**)
- Radon 222 is a radioactive α nucleus: $^{222}_{86}Rn \rightarrow {}^{218}_{84}Po + {}^{4}_{2}He$ (Po : **son core**)

Alpha particles are easily stopped by a few centimetres of air or sheet of paper, and have little penetrating power. α radiation is the most ionizing, and there are no medical applications for α radioactivity.

B) Beta β radioactivity:

β radioactivity results from too great an imbalance between neutrons and protons in the nucleus. These are transformations with no change in the mass number A (this type of radioactivity concerns unstable light nuclei). A distinction is made between :

- ✓ **β^- radioactivity :** β^- radioactivity affects nuclides with an excess of N > Z neutrons. During this decay, an electron is emitted $^{0}_{-1}e$ and an antineutrino $\bar{\upsilon}$ (a particle with no charge and no mass, necessary to ensure the principle of conservation of energy).

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e + {}^{0}_{0}\bar{\upsilon}$$

It concerns unstable isotopes with an excess of neutrons. During this emission, a neutron is transformed into a proton according to the reaction below:

$$^{1}_{0}n \dashrightarrow {}^{1}_{1}P + {}^{0}_{-1}e$$

Example :

- The transformation of carbon 14 into nitrogen 14 is followed by the emission of a β^- particle: $^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e + {}^{0}_{0}\bar{\upsilon}$
- Cobalt 60 is a radioactive nucleus β^- : $^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + {}^{0}_{-1}e + {}^{0}_{0}\bar{\upsilon}$ (Ni : **son core**)

The β^- radiation is moderately penetrating, and is stopped by an aluminum foil a few millimeters thick. Its ionization power is moderate, and it has a number of medical applications, especially for the detection of metastases (example: thyroid cancer).

- ✓ **β^+ radioactivity:** β^+ radioactivity affects nuclides with an excess of Z > N protons. During this decay, a positron is emitted ${}^{0}_{+1}e$ (antiparticle associated with the electron), and a neutrino υ. $${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e + {}^{0}_{0}\upsilon$$

  It concerns unstable isotopes with an excess of protons. Such elements will seek to stabilize by increasing N and decreasing Z. For such nuclides, a proton is transformed into a neutron. Simultaneously, a positron is ejected from the nucleus. The positron is the antiparticle of the electron, with the same mass but the opposite charge.

$$ {}^{1}_{1}P \longrightarrow {}^{1}_{0}n + {}^{0}_{1}e $$

Example :

- Phosphorus 30 is a radioactive nucleus β^+ : $${}^{30}_{15}P \rightarrow {}^{30}_{14}Si + {}^{0}_{+1}e + {}^{0}_{0}\upsilon$$

β^+-radiation is a very short-lived particle, moderately penetrating as in the case of β^--radiation, and only concerns artificial nuclei (the positron has a very short life time, and cannot exist in the nucleus, so it is emitted during a nuclear reaction).

- ✓ **γ radioactivity (or de-excitation):** the Y son nucleus is generally obtained in an excited state (high energy level), and is referred to as Y* (excited son nucleus). This state is unstable, and the nucleus de-excites by evacuating this excess energy by emitting γ electromagnetic radiation (very energetic particles called photos, possessing neither mass nor charge but an energy $E=h\upsilon$).

Thus, the transformation from the father nucleus to the stable son nucleus is generally accompanied by the emission of electromagnetic radiation γ:

$$\left.\begin{array}{l} {}^{A}_{Z}X \rightarrow {}^{A_1}_{Z_1}Y^{*} + {}^{A_2}_{Z_2}P \\ {}^{A_1}_{Z_1}Y^{*} \rightarrow {}^{A_1}_{Z_1}Y + {}^{0}_{0}\gamma \end{array}\right\} \Rightarrow \boxed{{}^{A}_{Z}X \rightarrow {}^{A_1}_{Z_1}Y + {}^{A_2}_{Z_2}P + {}^{0}_{0}\gamma}$$

Example : Dysprosium reaction: ${}^{152}_{66}Dy^{*} \rightarrow {}^{152}_{66}Dy + \gamma$

γ radiation is pure electromagnetic radiation, i.e. it has no mass or charge but is highly energetic, with a penetrating power greater than that of α *et* β particles (a thick layer of concrete or lead is needed to protect against it.) with a lower ionizing power.

γ radiation is widely used in the medical field (scintigraphy) to explore the human body. The isotopes used are iodine ^{131}I for functional exploration of the thyroid and, above all, technetium ^{99}Tc, whose advantage lies in its short half-life (T = 6.02 h), which minimizes the dose equivalents administered.

II. Artificial radioactivity and nuclear reactions

In 1934, **Frédéric Joliot-Curie** and **Irène Joliot-Curie** were the first to discover the phenomenon. They bombarded aluminum 27 with α particles to produce phosphorus 30.

Artificial radioactivity is created artificially by bombarding stable elements with various particle beams: neutron, proton, α particle, electron.

There are three types of nuclear reaction: nuclear transmutation, nuclear fission and nuclear fusion.

II.1. Nuclear transmutation

The nuclide formed by this reaction (son nucleus) has a mass number equal to or very close to that of the target (father nucleus).

Example:

- The first artificial transmutation was carried out by Rutherford in 1919, when he discovered the east proton:

$^{14}_{7}N + {}^{4}_{2}He \longrightarrow {}^{1}_{1}H + {}^{17}_{8}O$; $^{14}_{7}N\,(\alpha,p)\,{}^{17}_{8}O$ **(Simplified or abbreviated writing)**

- $^{32}_{16}S + {}^{1}_{0}n \longrightarrow {}^{1}_{1}P + {}^{32}_{15}P$; $^{32}_{16}S\,(n,p)\,{}^{32}_{15}P$

II.2. Nuclear fission

Heavy elements disintegrate to produce lighter atoms and neutrons which in turn bombard other neighboring nuclei, causing them to fission - a nuclear chain reaction.

Example :

$$^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{132}_{51}Sb + {}^{101}_{41}Nb + 3\,{}^{1}_{0}n$$

$$^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{139}_{56}Ba + {}^{94}_{36}Kr + 3\,{}^{1}_{0}n$$

$$^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{95}_{38}Sr + {}^{139}_{54}Xe + 2\,{}^{1}_{0}n$$

$$^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{135}_{53}I + {}^{97}_{39}Y + 4\,{}^{1}_{0}n$$

Uncontrolled nuclear fission ⟶ Atomic bomb (tested at Hiroshima).

Controlled nuclear fission ⟶ Nuclear power plant

The energy released by this type of reaction is of the order of 200 MeV/atom.

The energy released by the fission of a nucleus is: E liberated = E reactants – E products > 0.

The fission reaction is therefore an endothermic reaction, i.e. one that is accompanied by an adsorption of energy (E > 0).

II.3. Nuclear fusion

Is a reaction in which two light nuclei unite to form a heavier element, with the emission of a particle (proton or neutron).

Example: The fusion of two deuterium nuclei $^{2}_{1}$H into helium $^{3}_{2}$He or tritium $^{3}_{1}$H :

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + ^{1}_{0}n + 3{,}8MeV$$

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{1}H + ^{1}_{0}p + 4MeV$$

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n + 17{,}6MeV$$

Nuclear fusion is the principle behind thermonuclear bombs (H-bombs or hydrogen bombs).

To trigger such a fusion reaction, the positively-charged nuclei must be forced together, overcoming their mutual repulsion (like two magnets repelling each other): This is only possible at very high temperatures (the temperature corresponds to the intensity of the shocks between the particles).

The fusion reaction is accompanied by the release of energy (E < 0), making it an exothermic reaction.

III. Radioactive decay kinetics

III.1. Energy aspect

Consider the general case of a nuclear reaction:

$$\underbrace{^{A_1}_{Z_1}X_1 + ^{A_2}_{Z_2}X_2}_{\textbf{Reactants}} \rightarrow \underbrace{^{A_3}_{Z_3}X_3 + ^{A_4}_{Z_4}X_4}_{\textbf{Products}}$$

During the nuclear reaction, the total number of nucleons and the overall charge are conserved, but accompanied by a loss of mass (Δm) corresponding to the release of energy given by Einstein's relation:

$$E = \Delta m . C^2$$

$$\textbf{With} : \Delta m = \sum m\,(\,\textbf{Products}\,) - \sum m\ \textbf{(Reactants)}$$

C : Celerity of light = $2{,}98.10^{8}$ m.s^{-1} ≈ 3.10^{8} m.s^{-1}

The unit of energy is the Joule (J). In nuclear energy, however, the most appropriate unit is the electron volt (eV). This corresponds to the energy of an electron subjected to a potential difference of 1 volt:

$$\boxed{1\ eV = 1{,}602.10^{-19}(Coulomb) \times 1(Volt) = 1{,}602.10^{-19}\,J}$$

$$\boxed{1\ MeV = 10^{6}\ eV = 1{,}602.10^{-13}\,J}$$

Energy of an amu (1amu) : $\mathbf{1\,a\,m\,u = 933\ MeV}$

III.2. Kinetics aspect (radioactive decay)

Consider the disintegration of body A into body B, which is non-radioactive (stable):

$$A \longrightarrow B \quad \textbf{(B is not radioactive)}$$

A $t = 0$	N_0	
A t	N	$N_0 - N$

Experience shows that the number of atoms (dN/dt) that decay between t and t+dt is proportional to the number of atoms N present at time t:

$$-\frac{dN}{dt} = \lambda N$$

dN: represents the variation in the number of radioactive nuclei A over time dt.

The (-) sign comes from the fact that N decreases over time

N: designates the number of A nuclei (radioactive) remaining at time t

N_0 represents the number of initial A cores at t = 0.

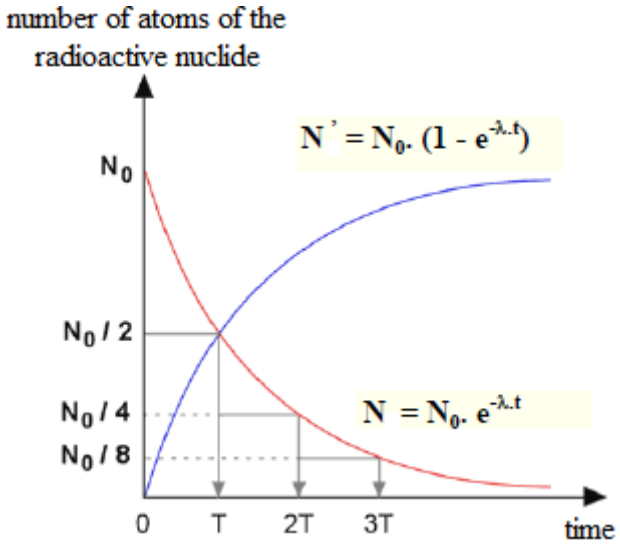
λ: radioactive or decay constant (s^{-1}, h^{-1}, $année^{-1}$ …)

Integrating the equation from time t = 0 to a given time t :

$$\int_{N0}^{N} \frac{dN}{N} = \int_{0}^{t} -\lambda t \qquad \Rightarrow \ln\frac{N}{N_0} = -\lambda.t \Rightarrow N = N_0 e^{-\lambda.t}$$

This is the law of radioactive decay.

N'=N_0-N (designates the number of B nuclei formed at time t)



As we can express this law of radionuclide decay as a function of mass:

Knowing that :

$$m = \frac{N \times M}{N_A}$$

M : **molar mass of the radionuclide**
m : **mass of the radionuclide at t**
N : **number of radionuclide remaining at t**
N_A : **Avogadro number**

The result is: $m = m_0 \ e^{-\lambda.t}$

III.3. Activity of a radioactive nucleus

By definition, the activity "A" of a radionuclide is equal to the number of disintegrations that occur per unit of time (usually time in seconds). Activity can be perceived as a decay rate.

$$A = -\frac{dN}{dt} = \lambda N$$

The unit in which activity A is expressed is:

Unit: the **Becquerel**: 1 Bq = 1 dps (disintegration per second)

Le **Curie**: 1Ci = $3{,}7.10^{10}$ dps = $3{,}7.10^{10}$ Bq

We also have the law of activity, expressed by the following relationship:

$$A = A_0.e^{-\lambda t}$$

The concept of the activity of a source can be used to date an object (age of archaeological finds).

i. Dating

$$A = A_0 \,.\, e^{-\lambda t} \Rightarrow \frac{A}{A_0} = e^{-\lambda t} \Rightarrow \ln\left(\frac{A}{A_0}\right) = -\lambda.t$$

$$\boxed{t = \frac{\ln A/A_0}{\lambda}}$$

Knowing a radioelement contained in the object, we determine its constant λ.

If we can measure A, if we know the activity A_0 of the sample, then we can know the date of origin "t" of the object.

Note:

1. Cas : $A \longrightarrow B$ (B is not radioactive)

At the moment of equilibrium, as many atoms of B are formed per unit time as disappear from A. hence: $A_A = A_B \Rightarrow \lambda_A \,.\, N_A = \lambda_B.N_B$

2. Cas : $A \longrightarrow B^* \longrightarrow C$ (C is stable); (B is radioactive)

For *A*: $N_A = N_{A0}.e^{-\lambda_A.t}$

For B : $\frac{dN_B}{dt}$ is written : $\frac{dN_B}{dt} = \lambda_A.N_A - \lambda_B.N_B$

Or : $\frac{dN_B}{dt} + \lambda_B.N_B = \lambda_A.N_{A0}e^{-\lambda_A.t}$

It is a differential of first order with a second member that leads to the number of nuclei of (B) present at time (t): $N_B = N_{A0}.\frac{\lambda_A}{\lambda_B - \lambda_A}.\left(e^{\lambda_A.t} - e^{\lambda_B.t}\right)$

III.4. Activity of a radioactive nucleus

By definition, the period ($t_{1/2}$ or T) is the time required for half the initial nuclei (N_0) to decay.

Thus: $t = T \longrightarrow N = N_0/2$ Replacing in the decay law we obtain:

$$T = \frac{\ln 2}{\lambda}$$