2.1. Introduction

The nuclei of certain atoms are prone to undergo transformations (changing from one element to another). These transformations can be either spontaneous (natural radioactivity) or induced (artificial radioactivity).

2.2. Conservation laws of Soddy and Fajans

Consider the following nuclear reaction : ${}^{A}_{Z}X \rightarrow {}^{A1}_{Z1}Y + {}^{A2}_{Z2}P$
Where : **X** is the **paren**t nucleus, **Y** is the **daughter** nucleus, and **P** is the ejected particle. During a natural or artificial nuclear reaction, the following conservation laws apply:

- **Conservation of nucleons (mass number):** $A = A_1 + A_2$
- **Conservation of charge (atomic number):** $Z = Z_1 + Z_2$

2.3. Natural radioactivity

Natural radioactivity is a physical phenomenon during which unstable nuclei spontaneously transform into more stable nuclei, releasing energy in the form of radiation: alpha (α), beta minus (β^-), and gamma (γ).

a) Emission (α)

It primarily concerns heavy nuclei with an atomic number Z>84, meaning the parent nucleus is very massive. Its instability is due to an excess of nucleons (an excess of protons and neutrons). The particle emitted is a helium nucleus (${}^{4}_{2}\mathbf{He}$**)**, as demonstrated by the following general reaction:

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

Example : ${}^{232}_{90}Th \rightarrow {}^{228}_{88}Ra + {}^{4}_{2}He$

Alpha radiation (α) is highly ionizing and therefore dangerous, very energetic, but has low penetration ability. Alpha particles are easily stopped by a few centimeters of air or by a sheet of paper.

b) Emission (β^-):

Beta minus (β^-) radioactivity occurs in nuclei that have an excess of neutrons (N > Z). It corresponds to the transformation of a neutron into a proton (${}^{1}_{0}n \rightarrow {}^{1}_{1}P + {}^{0}_{-1}e$). The emitted particle is an electron (${}^{0}_{-1}\mathbf{e}$**)**, as shown by the following reaction:

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

Example : ${}^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e$

Beta-minus radiation is highly ionizing and penetrating. It is stopped by an aluminum sheet a few millimeters thick.

c) Emission (γ)

During an alpha or beta-minus decay, the resulting daughter nucleus is in an excited state. The de-excitation of this nucleus releases a large amount of energy in the form of **electromagnetic radiation**, corresponding to the emission of high-frequency **photons**.

$^{A}_{Z}Y^{*} \rightarrow {}^{A}_{Z}Y + \gamma$

$^{A}_{Z}\mathbf{Y}^{*}$ is the daughter nucleus emitted in the excited state, while $^{A}_{Z}\mathbf{Y}$ is the de-excited daughter nucleus.

Example : $^{137}_{56}Ba^{*} \rightarrow {}^{137}_{56}Ba + \gamma$

Gamma radiation is less ionizing and highly penetrating; a substantial thickness of concrete or lead is required to shield against it.

2.4. Artificial radioactivity and nuclear reactions

Artificial radioactivity is created artificially by bombarding stable elements with various particles: neutrons, protons, or alpha particles. Nuclear reactions can be classified into: transmutation, fission, fusion, and beta-plus emission.

2.4.1. Transmutation reactions

Transmutation is the transformation of one nucleus into another in such a way that the values of A (mass number) and Z (atomic number) of the two nuclei are close to each other.

a) Transmutation by Helium

a.1. (α, p) reactions

$$^{A}_{Z}X + {}^{4}_{2}He \rightarrow {}^{A+3}_{Z+1}Y + {}^{1}_{1}H$$

Example :

$^{14}_{7}N + {}^{4}_{2}He \rightarrow {}^{17}_{8}O + {}^{1}_{1}H$ Or : $^{14}_{7}N(\alpha, p)\,{}^{17}_{8}O$ (Abbreviated writing)

a.2. (α, n) reactions

$$^{A}_{Z}X + {}^{4}_{2}He \rightarrow {}^{A+3}_{Z+2}Y + {}^{1}_{0}n$$

Examples :

$^{27}_{13}Al + {}^{4}_{2}He \rightarrow {}^{30}_{15}P + {}^{1}_{0}n$ Or : $^{27}_{13}Al\,(\alpha, n)\,{}^{30}_{15}P$

$^{9}_{4}Be + {}^{4}_{2}He \rightarrow {}^{12}_{6}C + {}^{1}_{0}n$ Or: $^{9}_{4}Be\,(\alpha, n)\,{}^{12}_{6}C$

b) Transmutation by Proton

b.1. (p, α) reactions

$$^{A}_{Z}X + {}^{1}_{1}H \rightarrow {}^{A-3}_{Z-1}Y + {}^{4}_{2}He$$

Example :

$^{19}_{9}F + {}^{1}_{1}H \rightarrow {}^{16}_{8}O + {}^{4}_{2}He$ Or : $^{19}_{9}F\,(p, \alpha)\,{}^{16}_{8}O$

b.2. (p, n) reactions :

$$^{A}_{Z}X + {}^{1}_{1}H \rightarrow {}^{A}_{Z+1}Y + {}^{1}_{0}n$$

Example :

$^{63}_{29}Cu + {}^{1}_{1}H \rightarrow {}^{63}_{30}Zn + {}^{1}_{0}n$ Or : $^{63}_{29}Cu\,(p, n)\,{}^{63}_{30}Zn$

b.3. (p, d) reactions :

$\mathbf{{}^{A}_{Z}X + {}^{1}_{1}H \rightarrow {}^{A-1}_{Z}Y + {}^{2}_{1}H}$

Example :

${}^{9}_{4}Be + {}^{1}_{1}H \rightarrow {}^{8}_{4}Be + {}^{2}_{1}H$ Or : ${}^{9}_{4}Be\ (p, d)\ {}^{8}_{4}Be$

c) Transmutation by neutron :

c.1. (n, p) reactions :

$\mathbf{{}^{A}_{Z}X + {}^{1}_{0}n \rightarrow {}^{A}_{Z-1}Y + {}^{1}_{1}H}$

Example :

${}^{32}_{16}S + {}^{1}_{0}n \rightarrow {}^{32}_{15}P + {}^{1}_{1}H$ Or : ${}^{32}_{16}S\ (n, p)\ {}^{32}_{15}P$

2.4.2. Fission reaction:

A heavy nucleus (mass number $A > 200$) splits into two lighter nuclei ($72 < A < 162$) than the target nucleus and neutrons according to the following process:

$\mathbf{{}^{A}_{Z}X + {}^{1}_{0}n \rightarrow {}^{A1}_{Z1}Y + {}^{A2}_{Z2}W + y\ {}^{1}_{0}n}$

Example :

${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{91}_{36}Kr + {}^{142}_{56}Ba + 3\ {}^{1}_{0}n$

The released neutrons can trigger new fission reactions. If the process doesn't stop, it leads to a chain reaction that becomes explosive: this is the principle of the atomic bomb.

2.4.3. Fusion reaction:

It is the union of two light nuclei to form a heavier nucleus. This reaction is initiated by high temperatures (10^7 K) and releases a considerable amount of energy. It occurs as follows:

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

Examples :

${}^{3}_{1}H + {}^{1}_{1}H \rightarrow {}^{4}_{2}He$

${}^{6}_{3}Li + {}^{2}_{1}H \rightarrow 2\ {}^{4}_{2}He$

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

Nuclear fusion is the principle of the hydrogen bomb.

2.4.4. β^+ Emission:

β^+ emission involves nuclei with an excess of protons ($Z > N$). It corresponds to the transformation of a ***proton*** into a ***neutron*** (${}^{1}_{1}H \rightarrow {}^{1}_{0}n + {}^{0}_{1}e$). The emitted particle is a positron ($\mathbf{{}^{0}_{+1}e}$) according to the reaction:

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

Example :

${}^{30}_{15}P \rightarrow {}^{30}_{14}Si + {}^{0}_{+1}e$

β^+ radiation is moderately penetrating and only involves artificial nuclei.

2.5. Quantitative aspects of radioactive decays:

a) Energetic aspect:

Nuclear reactions are always accompanied by a loss of mass (Δm), which corresponds to the release of energy given by Einstein's equation: $\mathbf{\Delta E = \Delta m.C^2}$

Δm : mass loss $(\mathbf{\Delta m = \sum m_{reactants} - \sum m_{products}})$.

C : Speed of light in the vacuum ($C = 3.10^8$ m/s)

Example : ${}^{230}_{90}Th \rightarrow {}^{226}_{88}Ra + {}^{4}_{2}He$

$m_{Th} = 230{,}1047$ amu, $m_{Ra} = 226{,}0957$ amu, $m_{He} = 4{,}0039$ amu

$\mathbf{\Delta m = \sum m_{reactant} - \sum m_{products}} = (m_{Th}) - (m_{Ra} + m_{He})$

$= (230{,}1047) - (226{,}0957 + 4{,}0039) = \mathbf{0{,}0051\ amu = 0{,}85.10^{-29}\ Kg}$

$\mathbf{\Delta E = \Delta m.C^2} = 0{,}85.10^{-29} * (3.10^8)^2 = \mathbf{7{,}65.10^{-13}\ J = 4{,}78\ MeV}$

b) Kinetic aspect:

b.1. Law of radioactive decay:

Consider the following nuclear reaction:

A → B **A :** unstable nucleus (radioactive)

B : stable nucleus (non-radioactive)

The experiment shows that the number of stable nuclei that decay is proportional to the number of unstable nuclei (N) present at a given time (t).

The decay rate is expressed as: $-dN/dt = \lambda . N$

After integration: $Ln (N/N_0) = -\lambda . t \rightarrow N/N_0 = e^{-\lambda t}$

The decay law is expressed as follows: $\mathbf{N = N_0\, e^{-\lambda t}}$

Where:

- N: number of unstable nuclei remaining at time t.
- N_0: number of unstable nuclei at the initial time t=0.
- λ: decay constant or radioactive constant (s^{-1}, min^{-1}, h^{-1}, $year^{-1}$, etc.).

b.2. Radioactive period or half-life (T or $t_{1/2}$)

The period T (also denoted as $t_{1/2}$) is the time required for the number of unstable nuclei at the initial time (N_0) to decrease by half.

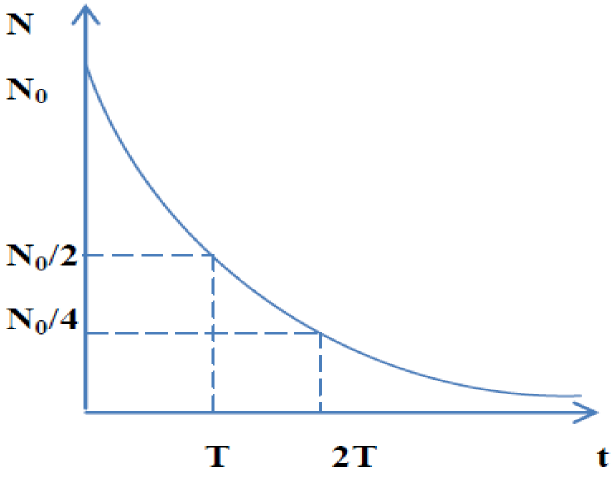
We have : $N = N_0\, e^{-\lambda t}$

When : $t = T$; then ; $N = N_0 / 2$

So : $(N_0 / 2) = N_0\, e^{-\lambda T} \rightarrow e^{-\lambda T} = (1/2) \rightarrow Ln (e^{-\lambda T}) = Ln(1/2)$

$-\lambda T = Ln(1/2)$; or ; $Ln(1/2) = -Ln2$; whence ; $-\lambda T = -Ln2$

So : $\mathbf{T = Ln2/\lambda}$



b. 3. Radioactive activity (A)

The radioactive activity A of a radioactive sample is the number of decays that occur per second at a given moment:

$A = - dN/dt = \lambda N \rightarrow \mathbf{A = \lambda.N}$

Units

- ***Disintegrations per second (dps).***
- ***Disintegrations per minute (dpm).***
- ***Disintegrations per hour (dph).***
- ***Becquerel (Bq)***: **1 Bq = 1 dps**
- ***Curie (Ci)***: **1Ci = $3{,}7.10^{10}$ dps = $3{,}7.10^{10}$ Bq**

*Relationship between disintegration and activity

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

$N = N_0 e^{-\lambda t} \rightarrow \lambda. N = \lambda. N_0 e^{-\lambda t} \rightarrow \mathbf{A = A_0 e^{-\lambda t}}$

Where:

- A: Activity at time t≠0.
- A_0: Initial activity at time t=0.

*Relationship between disintegration and mass

The law of radioactive decay can be written in another form based on the mass of the radioactive element studied since:

In 1 mole of the element, there is Avogadro's number (N_A).

$$1 \text{ mol} \longrightarrow N_A$$

$$\text{n moles of the element } (m/M) \longrightarrow N$$

So : $\mathbf{N = m. N_A / M}$; and ; $\mathbf{N_0 = m_0 . N_A /M}$

We replace N and N_0 by their formulas; it results that:

$(m. N_A/M) = (m_0. N_A/M). e^{-\lambda t}$ so ; $\mathbf{m = m_0 e^{-\lambda t}}$ or $\mathbf{n = n_0 . e^{-\lambda t}}$

With:

- n: number of moles of the unstable nucleus at time $t \neq 0$
- n_0: number of moles of the unstable nucleus at time $t=0$
- m: mass of the unstable nucleus at time $t \neq 0$
- m_0: mass of the unstable nucleus at time $t=0$

Number of decayed nuclei

$N' = N_0 - N = N_0 - N_0 e^{-\lambda t} = N_0 (1 - e^{-\lambda t}) \rightarrow \mathbf{N' = N_0 (1 - e^{-\lambda t})}$

Where:

- N′: number of decayed nuclei

Mass of decayed nuclei

$m' = m_0 - m = m_0 - m_0 e^{-\lambda t} = m_0 (1 - e^{-\lambda t}) \rightarrow \mathbf{m' = m_0 (1 - e^{-\lambda t})}$

Where:

- m′: mass of decayed nuclei

2.6. Applications of radioactivity

- **Defense Sector:** nuclear missiles, atomic bombs, hydrogen bombs, etc.
- **Energy Source:** electricity production
- **Medicine:** radioactive iodine is used in thyroid scans, tumor irradiation, etc.
- **Radioactive tracers:** for monitoring various industrial manufacturing processes.
- **Carbon-14:** for dating ancient objects (up to about 40,000 years).

2.7. Dangers of radioactivity:

Nuclear radiation destroys organic molecules: cells and tissues. These effects include:

- **Pathological effects:** lesions, production of cancers and leukemias.
- **Genetic effects:** modification of genes.