2– Artificial Radioactive Reaction

Artificial radioactivity is radioactivity caused by human activities using a particle accelerator or a nuclear reactor. Artificial radioactivity has been present in the environment since the early 20th century. It includes all phenomena of transmutation of radioisotopes created artificially by bombarding stable elements (aluminum, beryllium, iodine, etc.) with various particle beams (neutron, proton, alpha particle, deuteron).

Historically, it was Frédéric Joliot-Curie and Irène Joliot-Curie who first discovered the phenomenon in **1934** by producing phosphorus 30 by bombarding aluminum 27 with an **alpha** particle usually from a source of radium.

$$^{27}_{13}Al + ^{4}_{2}He \longrightarrow ^{30}_{15}P^{*} + ^{1}_{0}n$$

Artificial radioisotopes are obtained by bombarding stable elements with various projectiles (neutron, proton, helium nuclei...).

$$A + \text{rayonnement} \longrightarrow B + \text{rayonnement}$$

Example:

The reaction that led to the discovery of artificial reactivity:

$$^{27}_{13}Al + ^{4}_{2}He \longrightarrow ^{30}_{15}P^{*} + ^{1}_{0}n$$

Note:

When an element has several isotopes, as is the case for phosphorus $^{31}_{15}P$ and the 2 radio-phosphors $^{30}_{15}P$ and $^{32}_{15}P$.

The radioisotope containing more neutrons than the stable isotope is radioactive β^-, while the one containing fewer neutrons is radioactive β^+.

$$^{32}_{15}P \ (Z = 15 ; N = 17) \longrightarrow \beta^-$$

$$^{30}_{15}P \ (Z = 15 ; N = 15) \longrightarrow \beta^+$$

$$^{32}_{15}P \longrightarrow ^{32}_{16}S + ^{0}_{-1}e \ (\beta^-)$$

$$^{30}_{15}P \longrightarrow ^{30}_{14}Si + ^{0}_{1}e \ (\beta^+)$$

- Three types of artificial reactions are distinguished:

1-Nuclear transmutation reaction:

2- Nuclear fission reaction:

3- Fusion reaction

1- Nuclear transmutation reaction:

The induced transmutation reactions produce nuclides with a mass number (A) equal to or very close to that of the nuclide used as a target.

Examples:

$^{14}_{7}N + ^{4}_{2}He \longrightarrow ^{17}_{8}O + ^{1}_{1}\boldsymbol{H}$ Rutherford

$^{6}_{3}Li + ^{2}_{1}H \longrightarrow ^{7}_{3}Li + ^{1}_{1}\boldsymbol{H}$

$^{27}_{13}Al + ^{4}_{2}He \longrightarrow ^{30}_{15}P^{*} + ^{1}_{0}\boldsymbol{n}$

$^{23}_{11}Na + ^{1}_{1}H \longrightarrow ^{23}_{12}Mg + ^{1}_{0}\boldsymbol{n}$

The abbreviated form of a nuclear reaction:

- $^{14}_{7}N + ^{4}_{2}He \longrightarrow ^{17}_{8}O + ^{1}_{1}\boldsymbol{H}$

1) ……. (…..,…..)…….

2) $^{14}_{7}N$ (…..,…..) $^{17}_{8}O$

3) $^{14}_{7}N$ ($^{4}_{2}He$,…..) $^{17}_{8}O$

4) $^{14}_{7}N$ ($^{4}_{2}He$, $^{1}_{1}H$) $^{17}_{8}O$

5) $^{14}_{7}N$ (α , p) $^{17}_{8}O$

Examples:

- $^{6}_{3}Li + ^{2}_{1}H \longrightarrow ^{7}_{3}Li + ^{1}_{1}\boldsymbol{H}$ $\boldsymbol{^{6}_{3}Li}$ (d , **p**)$\boldsymbol{^{7}_{3}Li}$
- $^{27}_{13}Al + ^{4}_{2}He \longrightarrow ^{30}_{15}P^{*} + ^{1}_{0}\boldsymbol{n}$ $\boldsymbol{^{27}_{13}Al}$ (α , **n**)$\boldsymbol{^{30}_{15}P^{*}}$
- $^{23}_{11}Na + ^{1}_{1}H \longrightarrow ^{23}_{12}Mg + ^{1}_{0}\boldsymbol{n}$ $\boldsymbol{^{23}_{11}Na}$ (**p** , **n**)$\boldsymbol{^{23}_{12}Mg}$

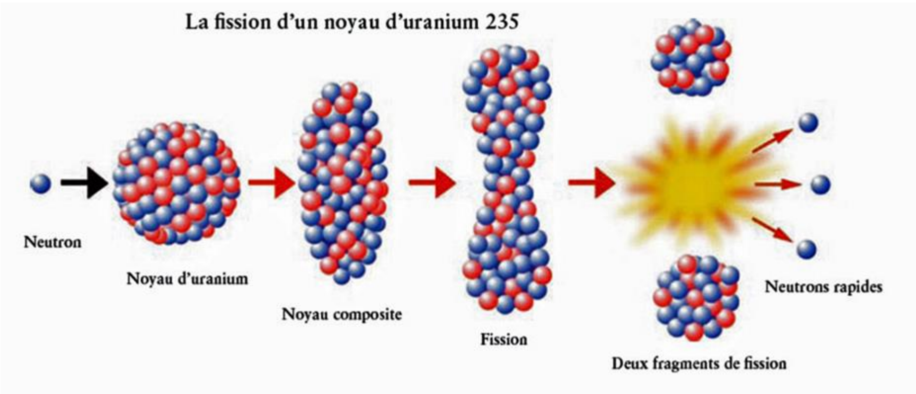
2- Nuclear fission reaction: الانشطار النووي

These reactions occur as a result of the bombardment of *a heavy nucleus* (**A>200**) by light particles to form lighter nuclei **(72<A<162).**

Examples:

Bombardment of the ^{235}U nucleus by a neutron

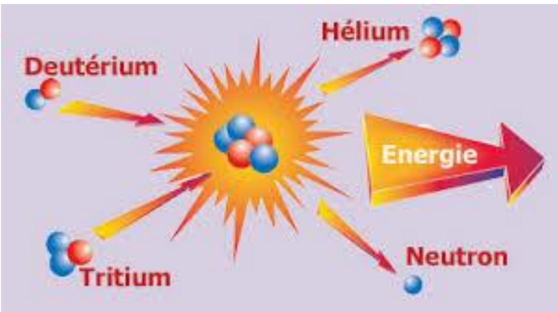
$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{143}_{56}Ba + ^{90}_{36}Kr + 3\ ^{1}_{0}n$$



- These reactions are accompanied by a strong release of energy.
- The energy released by 1 kg of Uranium is equivalent to that provided by the explosion of 12,000 tons of dynamite.
- This type of reaction is used in nuclear power plants to produce electricity.

3- Fusion reaction

This type of reaction is based on the fusion of light nuclides to form heavier nuclides (target nucleus, Z<4) .



Examples

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

2) ${}_{3}^{6}Li + {}_{1}^{2}H \longrightarrow 2\, {}_{2}^{4}He$

In the hydrogen bomb, reactions 1 and 2 occur.

- As the nuclei have a positive electrical charge, they repel each other, preventing them from merging. If these atoms are in a very hot environment, they will have sufficiently high velocities to be able to merge before being separated by electromagnetic repulsion. That's why we often talk about thermonuclear fusion.

  In the core of the Sun, the temperature is high enough for nuclear fusion reactions to occur: this is what makes the Sun shine, as these reactions release energy. Nuclear fusion is not yet used to produce energy because it is very difficult to create a reactor that operates at the necessary temperature of several million degrees! However, unfortunately, it is used in hydrogen bombs.

II.3 Radioactive decay law

Let the disintegration reaction of body A into stable body B be given as:

$A \longrightarrow B$ + rayonnement

à t=0 N_0 0 where N0 is the initial number of radioactive nuclei

à t N_t where Nt is the number of remaining radioactive nuclei at time t

The rate of disintegration of A is defined by the term Vd = -(dNt/dt)

(the negative sign (-) indicates the disappearance or rather the decrease in radioactive nuclei).

The study shows that the transformation of A into B over time follows a linear law:

$-\frac{dN_t}{dt} = \lambda . N_t = A$ (1) **(1)** **: N = N0-N**

$-\frac{dN_t}{dt}$: rate of disintegration

N_t: number of remaining radioactive nuclei at time t

λ: radioactive constant (s^{-1}) depends on the nature of the radioactive nucleus

A: absolute activity

dps: disintegrations per second

or **dpm**: disintegrations per minute

The former unit of A is the curie Ci (which corresponds to the disintegration of 1 g of Ra)

1Ci = 3.7×10^{10} dps;

1mCi = 10^{-3} Ci;

1µCi = 10^{-6} Ci

There is another unit: Rd = 10^{6} Bq (Rutherford), but the becquerel (Bq) is used more commonly.

$-\frac{dN_t}{dt} = \lambda . N_t = A$ (1) $\Rightarrow \frac{dN_t}{N_t} = -\lambda\, dt$: *1st order differential equation*

$\Rightarrow \int_{N_0}^{N_t} \frac{dN_t}{N_t} = - \int_0^t \lambda\, dt \quad \Rightarrow \quad \mathbf{Ln} \frac{N_t}{N_0} = -\lambda t \Rightarrow N_t = N_0 \cdot e^{-\lambda t}$ **(2)**

(2) is called the law of radioactive decay or law of radioactive disintegration..

Another form of the law:

we have $n = \frac{m}{M} = \frac{Nt}{N_A} \Rightarrow Nt = \frac{m}{M} \cdot N_A$ (3)

$n_0 = \frac{m_0}{M} = \frac{N_0}{N_A} \Rightarrow N_0 = \frac{m_0}{M} \cdot N_A$ (4)

By replacing (3) and (4) into (2) $\Rightarrow$ $m_t = m_0 \cdot e^{-\lambda t}$

By multiplying (2) by "λ" : $\lambda N_t = \lambda N_0 \cdot e^{-\lambda t} \Rightarrow A_t = A_0 \cdot e^{-\lambda t}$

$N_t = N_0 \cdot e^{-\lambda t}$ **(2)** ***Nt exponentially decreases with time.***

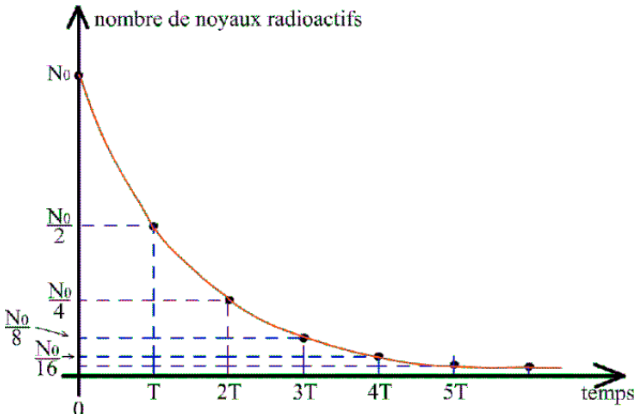
Half-life time $t_{1/2}$: period T

- The radioactive period is the time after which half of the initial nuclei have undergone decay. When $t = t_{1/2}$

- $t = t_{1/2} = T \Rightarrow N_t = \frac{N_0}{2}$

(2) $\Rightarrow \frac{N_0}{2} = N_0 \cdot e^{-\lambda . t_{1/2}} \Rightarrow$

$t_{1/2} = T = \frac{Ln2}{\lambda}$



$t = T = t_{1/2} \Rightarrow N_t = \frac{N_0}{2}$

$t = 2.T \Rightarrow N_t = \frac{N_0}{4} = \frac{N_0}{2^2}$

$t = 3.T \Rightarrow N_t = \frac{N_0}{8} = \frac{N_0}{2^3}$

$t = n.T \Rightarrow N_t = \frac{N_0}{2^n}$ Number of remaining nuclei

Exemple :

- ${}^{187}_{75}Re$: T = 3 x 10^{12} ans
- ${}^{213}_{84}Po$ T = 4,2 x 10^{-6} s
- **N' : number of disintegrated nuclei**

$$N' = N_0 - N_t = N_0 - \frac{N_0}{2^n} = N_0 \left(1 - \frac{1}{2^n}\right)$$

N' number of disintegrated nuclei

Examples :

$^{187}_{75}Re$: T = 3 x 10^{12} years ; $^{213}_{84}Po$ T = 4,2 x 10^{-6} s ; $^{209}_{84}Po$ T = 103 years

$^{210}_{84}Po$ T = 138,376 days ; $^{203}_{84}Po$ T = 36,7 min

The units of measurement for radioactivity

- There are three units of measurement for radioactivity:

The Becquerel (Bq): it measures radioactivity itself, which is the number of atoms that decay and emit radiation per unit of time. The higher the measured activity, the more radiation and energy are emitted.

The Gray (Gy): it measures the absorbed dose, which is the energy transferred by ionizing radiation to matter per unit of mass (1 Gy = 1 joule per kilogram). For the same absorbed dose, the effects vary depending on the nature of the radiation (1 gray of alpha radiation is considerably more dangerous than 1 gray of beta radiation).

The Sievert (Sv): it is the equivalent dose, which measures the biological effects of radiation on living matter. For the same amount of deposited energy, different types of radiation have different effects on tissues. The equivalent dose allows for the evaluation of biological effects of radiation in radiation protection (i.e., at low doses).

Application of radioactivity

The applications of radioactivity are numerous, and we can mention:

- ✓ Dating of ancient samples, rocks, and sediments,
- ✓ Energy production: nuclear power plants,
- ✓ Military applications.

1- Dating in archaeology

The age of animal or plant matter can be determined using radioactive elements.

Radioactive carbon-14 (^{14}C) is continuously produced in the atmosphere through the interaction of cosmic ray neutrons with atmospheric nitrogen-14 (^{14}N) according to the reaction:

$$^{14}_{7}N + ^{1}_{0}n \longrightarrow ^{14}_{6}C^{*} + ^{1}_{1}p$$

Carbon-14 $^{14}_{6}C^{*}$ oxidizes to form $^{14}CO_2$ and participates in the cycle of living matter, maintaining a constant concentration.

Dating using ${}^{14}_{6}C^{*}$ is based on the presence of a minute amount of radiocarbon in every organism

$r_o = \frac{N({}^{14}_{6}C^{*})}{N(C_{total})} \approx 10^{-12}$ (C_{total} : ${}^{12}C$, ${}^{13}C$ et ${}^{14}C$)

After the organism's death, ${}^{14}_{6}C^{*}$ is no longer absorbed, and its proportion decreases because this isotope is radioactive (β-), with a half-life (T) of 5730 years.

$${}^{14}_{6}C^{*} \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}e \ (\beta^{-}),$$

Measuring the activity of a sample allows the evaluation of the ratio r and, therefore, the date of its death. In fact, $\mathbf{r = r_o . e^{-\lambda t}}$

Example:

Measuring this ratio r on an ancient object allows dating of the object.

Example:

Measuring the activity of a mummy in a sarcophagus yields a ratio $A = 6.\,10^{-13}$. The half-life of ${}^{14}_{6}C^{*}$ is $T = t_{1/2} = 5730$ years.

Solution:

$$r = r_0 . e^{-\lambda t} \Rightarrow \frac{r}{r_0} = e^{-\lambda t} \Rightarrow \text{Ln}\frac{r}{r_0} = -\lambda t \Rightarrow \text{Ln}\frac{r_0}{r} = \lambda t \Rightarrow$$

$$\Rightarrow t = \frac{1}{\lambda} . \text{Ln}\frac{r_0}{r} \quad \text{avec} \quad T = \frac{\text{Ln } 2}{\lambda} \Rightarrow \frac{1}{\lambda} = \frac{T}{\text{Ln}2} \Rightarrow \boldsymbol{t = \frac{T}{\text{Ln } 2} \text{Ln}\frac{r_0}{r}}$$

AN:

$$t = \frac{5730}{\text{Ln } 2} \text{Ln}\frac{1.\,10^{-12}}{6.\,10^{-13}} \Rightarrow t = 4222{,}8 \text{ ans} \approx 4223 \text{ ans},$$

The mummy has been in the sarcophagus for 4223 years,

Exemple

La période de ${}^{14}C$ est de T = 5568 ans et qu'un échantillon de charbon de bois fraichement préparé donne une activité de $A_0 = 15{,}3 \frac{dpm}{gr}$. Quel est l'âge d'un échantillon de bois trouvé dans une grotte préhistorique dont un échantillon de même masse que le précédent donne une activité $A_t = 9{,}6\ dpm/gr$.

Solution :

$A_0 = \lambda . N_0 \quad et \quad A_t = \lambda . N_t$

$$N_t = N_0 e^{-\lambda . t} \Rightarrow \ln\frac{N_t}{N_0} = \ln e^{-\lambda . t} \Rightarrow ln\frac{A_t/\lambda}{A_0/\lambda} = -\lambda . t$$

$$ln\frac{A_0}{A_t} = \frac{ln2}{T} . t \Rightarrow t = \frac{T}{\ln 2} . ln\frac{A_0}{A_t}$$

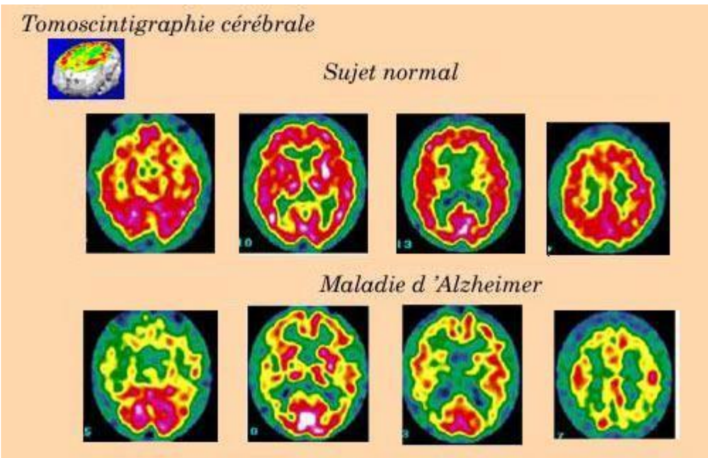
$$AN: \ \boldsymbol{t = 3695\ années}$$

Applications to energy

- Radioactivity is, along with neutron emission, the essential form of energy released by nuclear fission reactions.
- Electricity production by nuclear power plants
- In these plants, primary energy is produced by a reactor loaded with uranium enriched in unstable isotope 235. This mixture is unstable because the absorption of a slow neutron by uranium 235 transforms it into uranium 236, which undergoes fission, releasing two to three neutrons. Thus, there is a possibility of a chain reaction. Radioactivity and the kinetic energy of fission products are converted into heat in the material surrounding the reactor core. To produce electricity, this heat is converted into steam that drives a turbine.
- In February 2020, more than 440 slow neutron nuclear reactors were "operational" worldwide according to the International Atomic Energy Agency (IAEA). France, which historically relies on nuclear power, produced 70.6% of its electricity in 2019 through its 19 nuclear power plants totaling 58 reactors.
- A new generation of fast neutron reactors, operating at high temperatures, could achieve much higher efficiencies than current slow neutron reactors. It would allow for the direct and more efficient use of fertile fuel, which currently constitutes the majority of waste from first-generation plants. These "breeder" reactors are the subject of studies and developments in most major nuclear-powered countries, particularly in China, India, and the United States.

Radioactivity is also applied in medicine.

- When we talk about radioactivity in medicine, we mean "nuclear medicine." Nuclear medicine refers to all medical procedures that require the administration of a radioactive substance.
- Radioactivity is used notably in medical imaging services with scintigraphy. This involves injecting a radioactive substance into an organ or tissue of the patient, which, thanks to the radiation emitted by the substance circulating and binding to certain areas, is captured by a specific camera, creating a visual mapping of the area to be explored.
- It is also used in laboratory analysis in radioimmunology. Radioimmunology allows for the detection of antibodies in a person's serum or the search for a specific antigen using antibodies.
- Radioactive sources target cells to destroy them. Radioactivity is part of the field of oncology, which deals with the study, diagnosis, and treatment of cancers, which are the result of abnormal cell growth.



Comparison of a brain tomoscintigraphy of a normal patient and a patient with Alzheimer's

- Tomoscintigraphy is a medical imaging technique used to detect gamma radiation emitted by a radioactive substance introduced into the body (scintigraphy), which allows obtaining cross-sectional images (tomographies) of different organs. It can be observed from these sections that the brain of the patient with the disease has less brain activity.
- In biology, radioactivity can be used in agri-food and agronomy.
- In the agricultural and agri-food sectors, radioactivity is used, for example, for crop protection against insects or food preservation. Gamma irradiation is used industrially in food hygiene.
- In industry, it is used for various tasks (welding inspection, leak or fire detection, etc.).

Danger of radioactivity

The consequences of exposure to radioactive radiation are of types:

- Somatic effects (الآثار الجسدية)that affect the individual, especially the blood-forming organs (red blood cells) or the mucous membranes of the skin or intestine. ((الأغشية المخاطية للجلد أو الأمعاء).
- Genetic effects(الآثار الجينية) that affect the species, such as modifications of the genetic heritage (التراث الجيني).