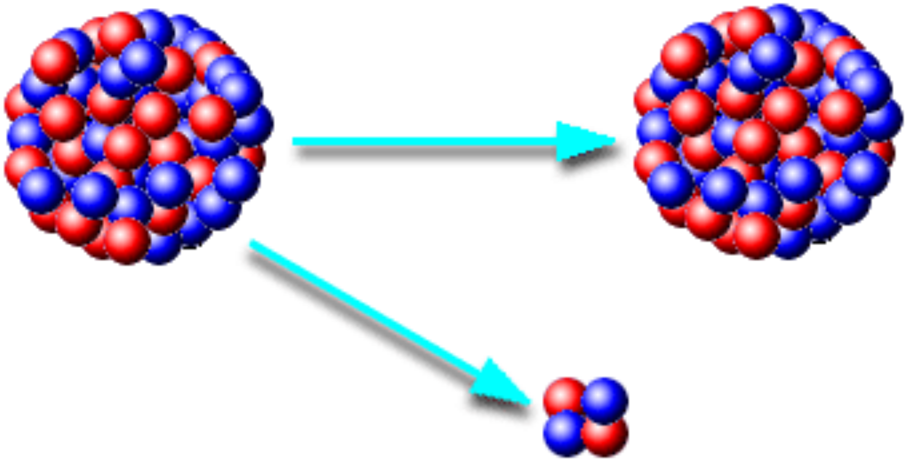
Chapter II
Basic Nuclear Properties



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1- Mass and binding energy

The usual practice in nuclear physics is not to always use SI units

- Energies are measured in units of eV:
  keV (10^3 eV)   MeV(10^6 eV)   GeV (10^9 eV)   TeV (10^{12} eV)
  Nuclear Physics   Particle physics
- Masses are expressed in units of MeV/c^2 or GeV/c^2 (i.e. using $m=E/c^2$)
  frequently the /c^2 is omitted

  m_e=9.1094 10^{-31} kg = 0.511 MeV/c^2="0.511 MeV" =0.00055 u
  m_p=1.6726 10^{-27} kg = 938.28 GeV/c^2=1836.1 m_e =1.00728 u
  m_n=1.6748 10^{-27} kg = 939.57 GeV/c^2=1838.7 m_e =1.00728 u
- Atomic/nuclear masses are often given in atomic mass unit (or unified mass unit)

$$1 \text{ unified mass unit (u)} = \frac{\text{Mass of an atom of } {}^{12}_{6}C}{12}$$

$$1u = 1g/\mathcal{N}_A = 1.6610^{-27}\,kg = 931.5\,MeV/c^2$$

this is a bit less than the mass of the proton or neutron because of the binding energy

1.1 Definitions

- The Binding Energy *B* is the energy required to split a nucleus into his constituents

$$m(^A_Z\mathrm{X})c^2 = Zm_pc^2 + Nm_nc^2 - B(A,Z)$$

- Convention : m stands for nucleus mass ≠ M stands for neutral atom mass
- Binding energy is very important. It gives information on
  - Forces between nucleons
  - Stability of nucleus
  - Energy released or required in nuclear decays or reactions
- If B(A,Z)>0 the nucleus is bound. It is a necessary condition for the stability but not sufficient (as we will see later)

- It is often more convenient to use the Masses of the neutral atoms : $M(^A_Z\mathrm{X})c^2 = m(^A_Z\mathrm{X})c^2 + Zm_e c^2 - B(Ze)$
  the binding energy of the electron is negligible with respect to the nuclear binding energy, so

$$\boxed{M(^A_Z\mathrm{X})c^2 = ZM(^1_1\mathrm{H})c^2 + (A-Z)m_n c^2 - B(A,Z)}$$

- Some numerical values :
  - $M(^4\mathrm{He}) = 3728.4\ \mathrm{MeV}/c^2 \rightarrow B = 28.30\ \mathrm{MeV}$
  - $M(^2\mathrm{H}) = 1876.12\ \mathrm{MeV}/c^2 \rightarrow B = 2.22\ \mathrm{MeV}$
  - $B(^{12}\mathrm{C}) = 6m_p + 6m_n + 6m_e - 12u = 92.16\ \mathrm{MeV} = 1.477\ 10^{-11}\mathrm{J}$
    small value, but one mole of $^{12}\mathrm{C}$ corresponds to $8.9\ 10^{12}\mathrm{J}$
    i.e. $2.5\ 10^6$ kWh ! i.e. 2 kt TNT
- Comparison of B/M for EM and strong nuclear force :
  - In the atom H : $B/M = B/(m_p+m_e) \approx 1.4\ 10^{-8}$
  - In the nucleus $^{12}\mathrm{C}$: $B/M = B/(6m_p+6m_n) \approx 8.2\ 10^{-3}$

1.2- Separation Energy

The separation energy S is the energy required to remove one nucleon (or an α particle) from a nucleus.

$$S/c^2 = \sum \text{(final masses) - (initial mass)}$$

$$S_n = B(A,Z) - B(A-1,Z)$$
$$S_p = B(A,Z) - B(A-1,Z-1)$$
$$S_\alpha = B(A,Z) - B(A-4,Z-2) - B(4,2)$$

- Separation energy = extraction energy (S>0 → energy cost)
- Even if a nucleus has B(A,Z)>0, it will not be stable if there is a negative S_i
- B's and M's are experimentally measured via mass spectroscopy (for the stable nuclei) or via the energetic balance of nuclear reactions and nuclear decays (for the instable nuclei)

1.3 Mass excess

Another convenient way to express the atomic mass is to subtract the mean contribution of A×1u.

The mass excess Δ is defined the following way :

$$\Delta(A,Z) = M(A,Z) - A \times (1u)$$

The mass defect is the opposite of the mass excess.

1.4- Nuclear reaction and Q-values

- Nuclear reaction : a+X→b+Y or X(a,b)Y
  a : projectile
  X : target
  b, Y : emergent particles
- Q-value :

$$Q = \sum_i M_i c^2 - \sum_f M_f c^2$$

  - Q>0 → Exothermic reaction
  - Q<0 → Endothermic reaction

2- Cross-section

The concept of cross section is the crucial key that opens the communication between the real world of experiment and the abstract, idealized world of theoretical models.

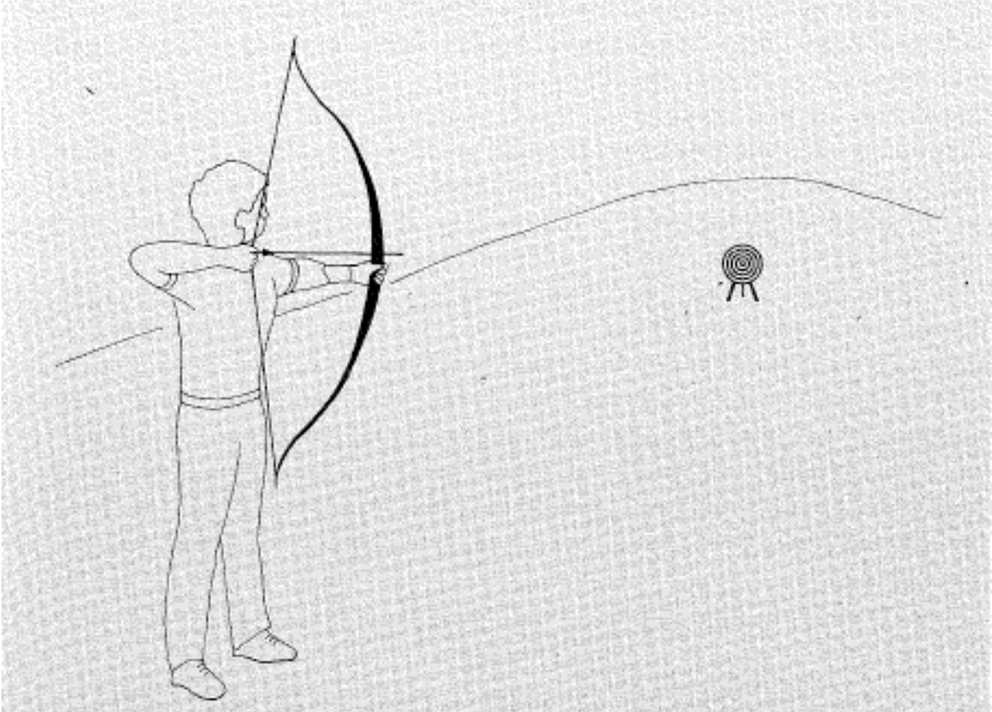


Fig. 2.8 Collisions in atomic and subatomic physics cannot be arranged in the same way as an archer tries to score a bull's-eye on the target. Instead the situation is more like that in Fig. 2.9.

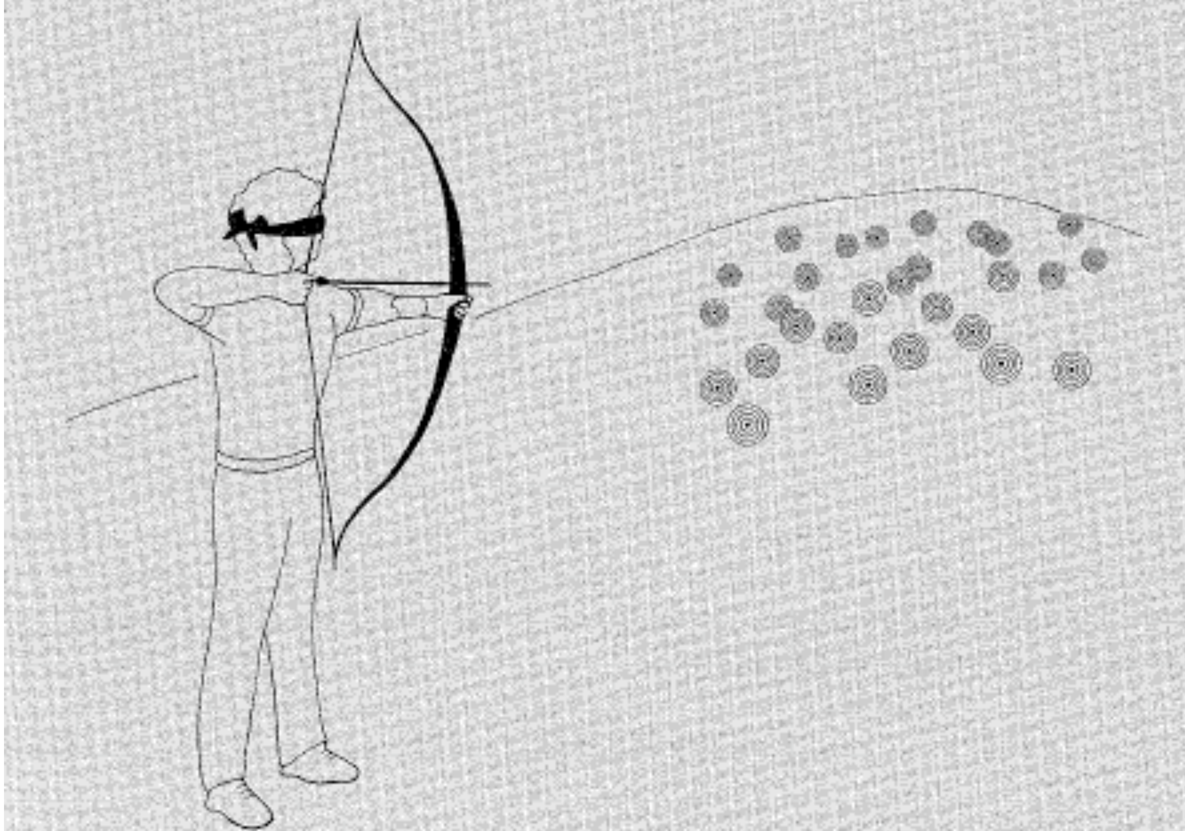


Fig. 2.9 Clearly the chance that the blindfolded archer hits any target is proportional to the density of targets and to the area (cross-section) presented by each, and to the number of arrows that he fires if he has more than one attempt, provided, of course, that he is firing into the region of the assembly of targets. When an arrow does strike the target the archer will score depending on which ring of the target is struck. The probability of a given single score for the blind archer will be proportional to that partial area of the whole target which yields that score. In atomic and nuclear collisions the total cross-section gives the probability that a collision will occur and a partial cross-section gives the probability that the collision has a given outcome.

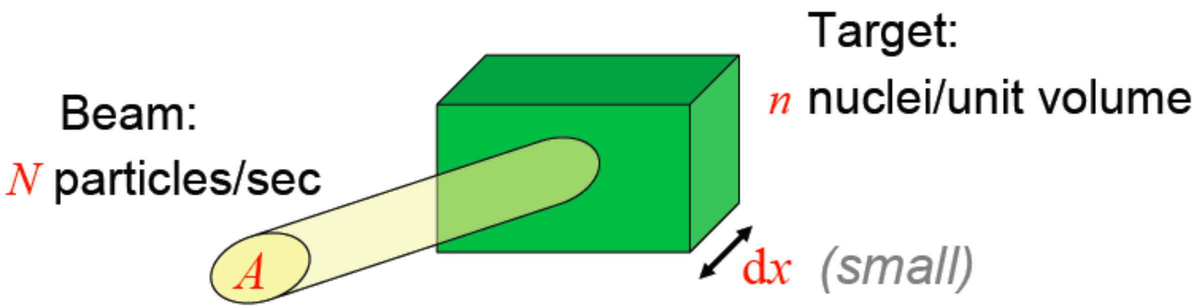
2.1 Definition

- The strength of a particular reaction between two particles is specified by the interaction cross-section σ
- A cross-section is an effective target area presented to the incoming particle for it to cause the reaction. The area is a quantitative measure of the probability of collision between two particles.
- Units : [σ]= barn 1 barn=10^{-28} m^2 (area)
- The cross section is defined for a single target particle as the reaction rate per target particle, Γ, per unit incident flux, Φ, i.e.

$$\sigma = \Gamma / \Phi$$

  For a single target particle, where the flux Φ is the number of beam particles passing through unit area per second
- Γ is given by Fermi's Golden Rule

Consider a beam of particles incident upon a target:



- Number of target particles in area A : $N_T = nA\mathrm{d}x$
- Incident Flux : $\Phi = N/A$
- Number of particles scattered per unit-time $N_s = \Gamma N_T$

$$\sigma = \frac{\Gamma}{\Phi} = \frac{\text{Number of scattered particles/sec}}{N_T \Phi} = \frac{N_s}{N_T \Phi}$$

$$N_s = \Phi N_T \sigma$$

"Experimental" point of view

Beam attenuation in a target of thickness L :

The variation of N is driven by N_s=-dN can be written : $$\frac{\mathrm{d}N}{N} = -n\sigma \mathrm{d}x$$

- In general we have

$$\int_{N_0}^{N} -\frac{\mathrm{d}N}{N} = \int_0^L n\sigma \mathrm{d}x$$

$$N = N_0\, e^{-\sigma n L}$$

- Thin target (i.e. $\sigma n L \ll 1,\ \ e^{-\sigma n L} \approx 1 - \sigma n L$)

$$N = N_0(1 - \sigma n L)$$

number scattered = $N_0 - N = N_0 \sigma n L$

2.3 Different kind of cross-sections

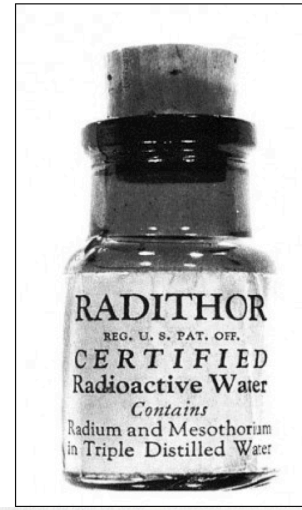
Some additional definitions :

- Total cross section: The cross section for a collision to occur with any possible outcome
- Geometric cross-section: geometric cross section of the nuclei of the target
- Partial cross section: The cross section for a collision to occur with a particular outcome.
  Examples :
  - Elastic scattering by the target
  - Inelastic scattering
  - Absorption by the target (capture)
  - Creation of a new nucleus
- Differential cross-section: When a kinematic variable for one of the products of a collision can be continuous, the partial cross section per unit range of that variable at a specified value of the variable is called a differential cross section. (see next chapter)
  Examples:
  - Differential x-section for scattering at an Angle θ : $d\sigma/d\theta$
  - Differential x-section for scattering at a particular energy E : $d\sigma/dE$
  - Doubly differential x-section : $d^2\sigma/dEd\theta$

3- The laws of radioactivity

- At the beginning of the century Radithor was a well known patent medicine. It consisted of triple distillated water containing a minimum of 1 microcurie each of the Radium 226 and 228 as well as 1 microcurie of isothioranium. Raditor was manufactured from 1918 to 1928.

- Advertisement for the cosmetic cream Tho-Radia :
  “La science a créé ThoRadia pour embellir les femmes. A elles d’en profiter.
  Reste laide qui veut !”



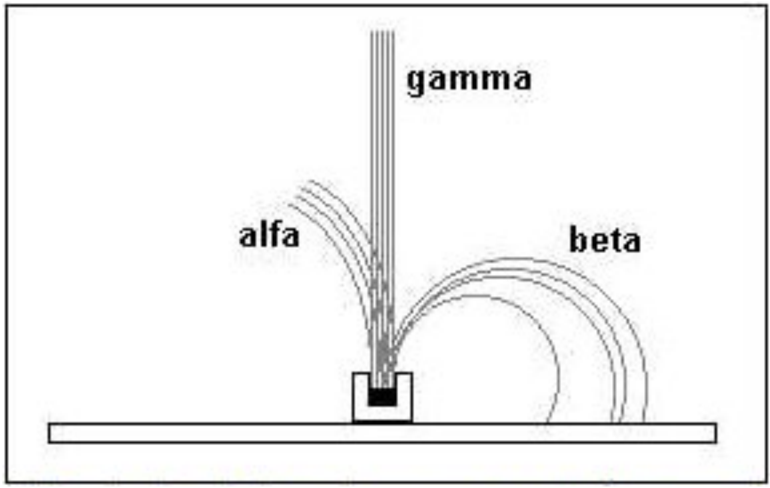
3. Les produits de beauté et élixir de jouvence au thorium et au radium étaient commercialisés dans les années 1920.

3.1- What is radioactivity ?

Definition : Radioactivity is the random spontaneous transformation of an atomic nucleus by the emission of a radiation in the form of particle or electromagnetic waves.

Why ? The final state is less energetic than the initial state (Q-value>0)

The most common decay modes are:
α decay, $\beta^{\pm}$ decay , γ decay
and fission.

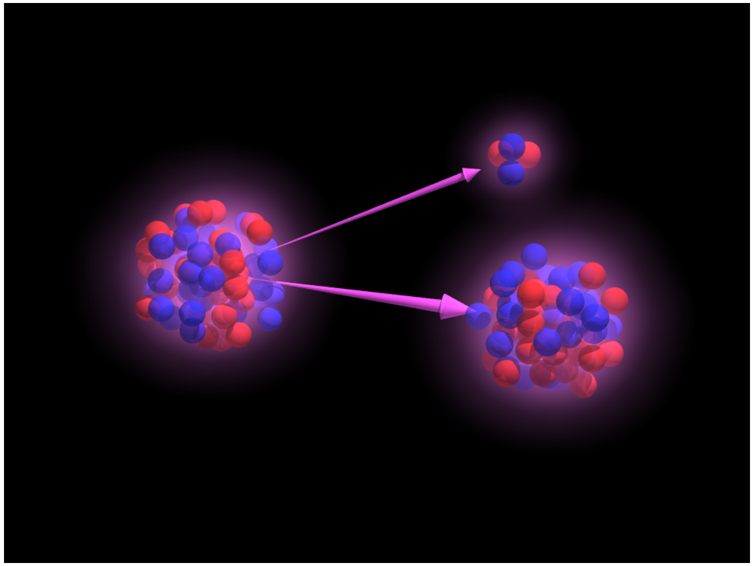


Common decay modes

- **α decay**

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

$$ Q_\alpha = M(X) - M(Y) - M({}^{4}He) $$



- **γ decay** $ {}^{A}_{Z}\mathrm{X}^* \longrightarrow {}^{A}_{Z}\mathrm{X} + \gamma $

$$ Q_\gamma = M(X^*) - M(X) $$

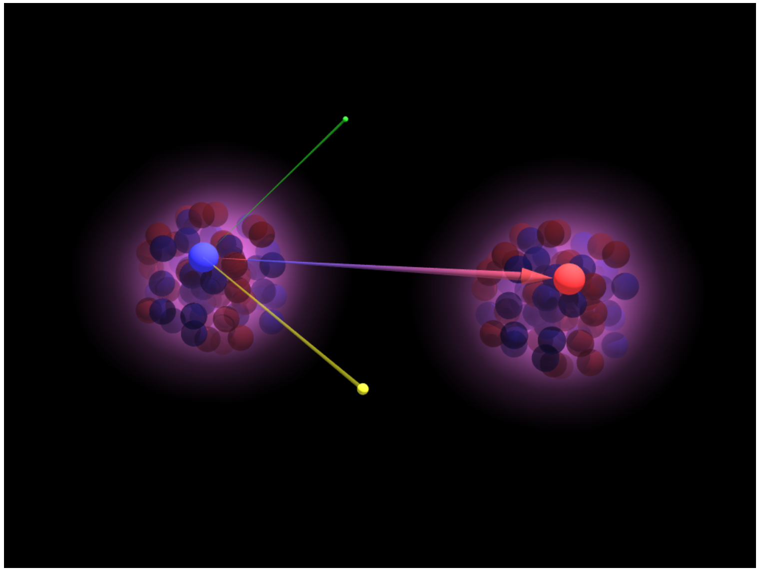
- **β⁻ decay**

$$ {}^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z+1}\mathrm{Y} + e^- + \bar{\nu}_e $$

At the nucleon level:

$$ n \longrightarrow p + e^- + \bar{\nu}_e $$

$$ Q_{\beta^-} = M(X) - M(Y) $$



Common decay modes

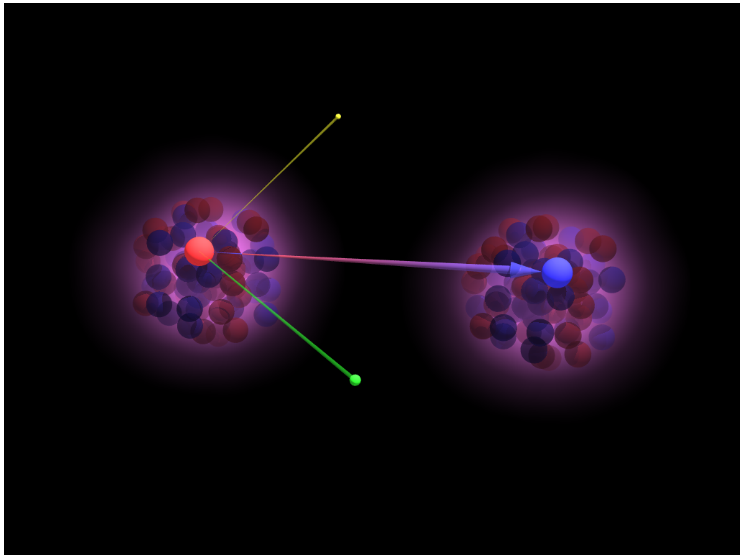
- **β⁺ decay**

$$ {}^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z-1}\mathrm{Y} + e^{+} + \nu_e $$

At the nucleon level:

$$ p \longrightarrow n + e^{+} + \nu_e $$

$$ Q_{\beta^+} = M(X) - M(Y) - 2m_e $$

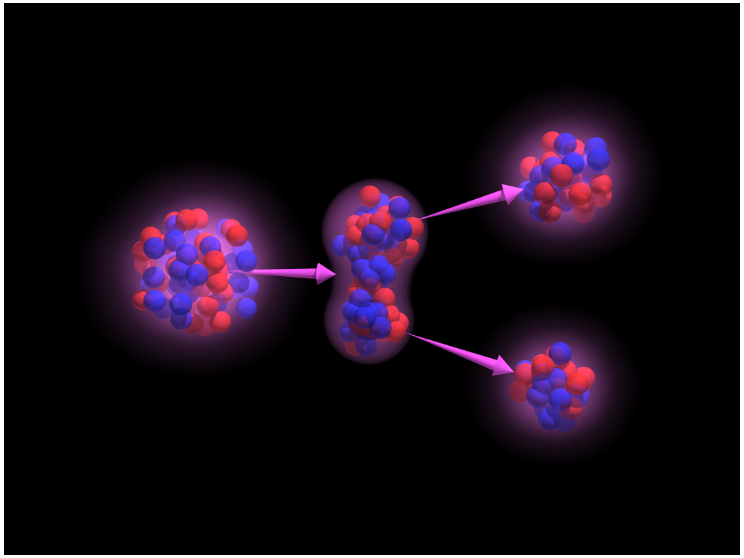


- **Fission**

$$ {}^{A}_{Z}\mathrm{X} \longrightarrow {}^{A-a}_{Z-z}\mathrm{Y} + {}^{a}_{z}\mathrm{W} $$

Fission can be more complicated

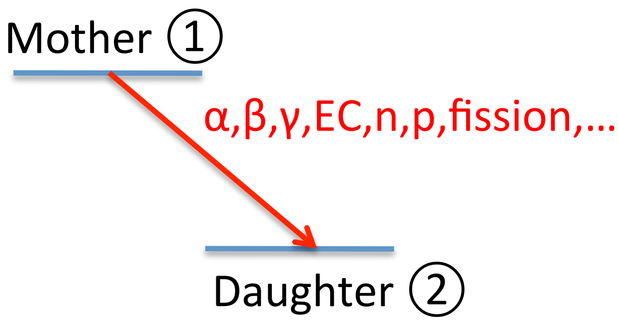
$$ Q_f = M(X) - M(Y) - M(W) $$



3.2 The radioactive decay law

- A decay is the transition from one quantum state (initial state or mother) to another (final state or daughter).

The transition rate is given by
$\Gamma(1 \rightarrow 2) = \lambda$
where λ is the number of transitions per unit time.
$[\lambda]=T^{-1}$



$\lambda \mathrm{d}t$ is the (constant) probability a nucleus will decay in time dt

λ depends only on the structure of the initial and final state. It can be calculated via Fermi's Golden Rule :

$$\Gamma_{if} = \lambda = 2\pi |M_{fi}|^2 \rho(E_f)$$

Single nucleus decay (it's the same thing for particles)

Let $p(t)$ be the probability that a nucleus will still exist at time t, if it was known to exist at t=0 (i.e. $p(0) = 1$)

prob(nucleus decays in the next time interval dt) = $p(t)\lambda \mathrm{d}t$
prob(nucleus survives in the next time interval dt) = $p(t)(1 - \lambda \mathrm{d}t)$

$$p(t)(1-\lambda \mathrm{d}t) = p(t+\mathrm{d}t) = p(t) + \tfrac{\mathrm{d}p}{\mathrm{d}t}\mathrm{d}t$$

$$\tfrac{\mathrm{d}p}{\mathrm{d}t} = -p(t)\lambda$$

$$\textstyle\int_1^p \frac{\mathrm{d}p}{p} = -\int_0^t \lambda \mathrm{d}t$$

$$\Longrightarrow \boxed{p(t) = e^{-\lambda t}}$$

Exponential decay law

The probability that a nucleus lives until time t and decays in time dt is

$$p(t)\lambda \mathrm{d}t = \lambda e^{-\lambda t}\mathrm{d}t$$

The average lifetime of the particle is

$$\tau = \langle t \rangle = \int_0^\infty t\lambda e^{-\lambda t}\mathrm{d}t = \left[-te^{-\lambda t}\right]_0^\infty + \int_0^\infty e^{-\lambda t}\mathrm{d}t = \left[-\frac{1}{\lambda}e^{-\lambda t}\right]_0^\infty = \frac{1}{\lambda}$$

$\tau = 1/\lambda$ and $p(t) = e^{-t/\tau}$

- Multiple nuclei (e.g. material containing N nuclei)
  - Number of nuclei remaining at time t :

$$N(t) = N(0)\,p(t) = N(0)\,e^{-\lambda t}$$

  where *N(0)* is the number of nuclei at time *t*=0

  - Number of nuclei remaining after the lifetime τ:

$$\frac{N(\tau)}{N(0)} = e^{-\tau/\tau} = e^{-1} \simeq 36.8\%$$

  - Half-life $T_{1/2}$ (or period): time over which 50% of the nuclei decay

$$\frac{N(T_{1/2})}{N(0)} = \frac{1}{2} = e^{-\lambda T_{1/2}} \Longrightarrow T_{1/2} = \frac{\ln 2}{\lambda} = 0.693\tau$$

  the radioactive periods have a wide range :

^{238}U	**$T_{1/2}$=4.5 10^9 years**
^{226}Ra	$T_{1/2}$=1617 years

^{222}Rn	**$T_{1/2}$=3.8 days**
^{214}Po	$T_{1/2}$=1.6 10^{-4} s

- Rate of decays:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = -\lambda N(0)e^{-\lambda t} = -\lambda N(t)$$

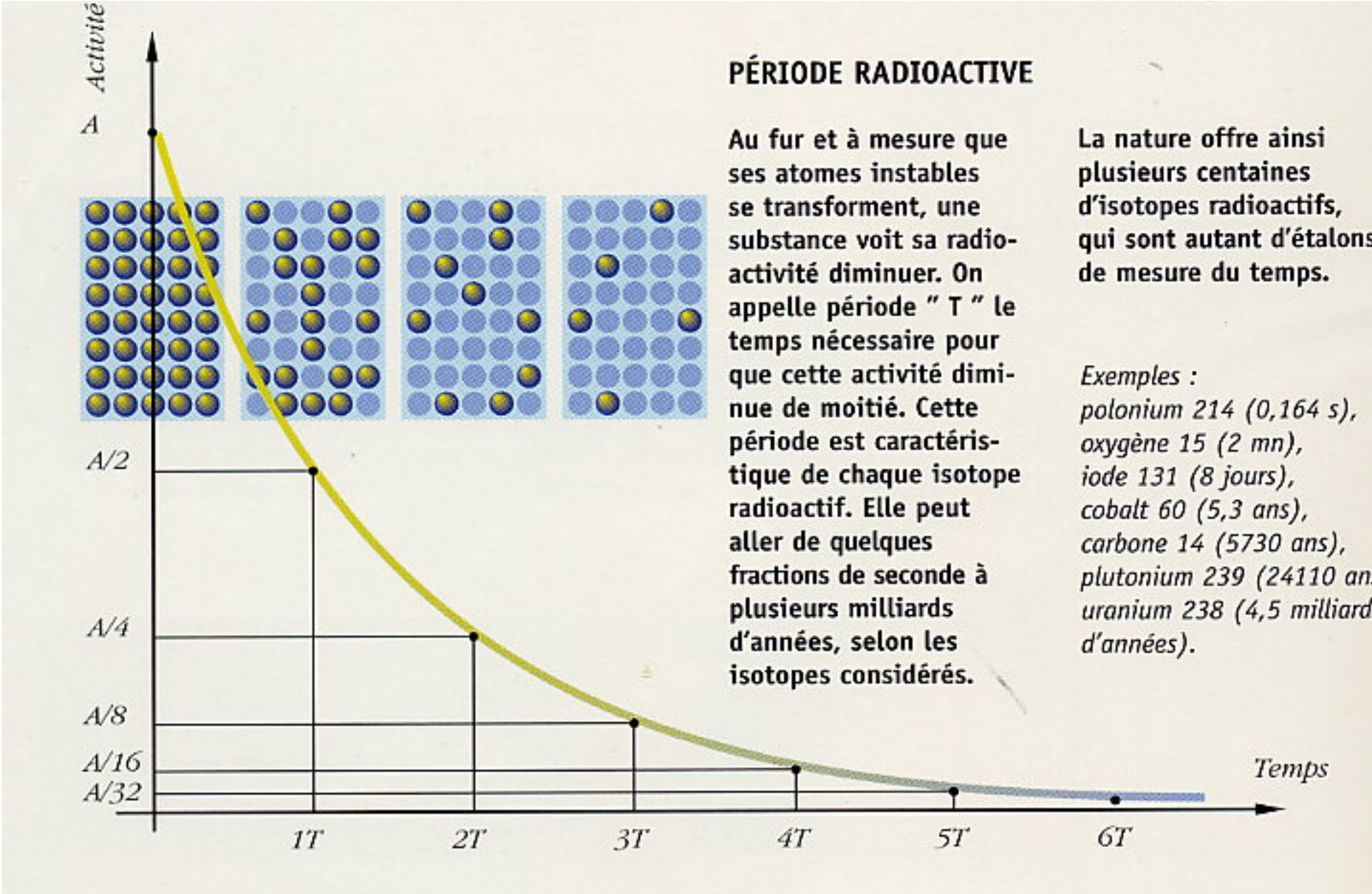
- Activity: number of decays per unit time at time t. This is the instantaneous decay speed.

$$A(t) = \left|\frac{\mathrm{d}N}{\mathrm{d}t}\right| = \lambda N(0)e^{-\lambda t} = \lambda N(t) = N(t)/\tau$$

$$A(t) = \lambda N(0)e^{-\lambda t} = A(0)e^{-\lambda t}$$

- Units of radioactivity: defined as the number of decays per unit time = activity

  Becquerel (Bq) = 1 decay per second
  Curie (Ci) = 3.7 10^{10} decays per second (originally the activity of 1 gram of radium)



PÉRIODE RADIOACTIVE

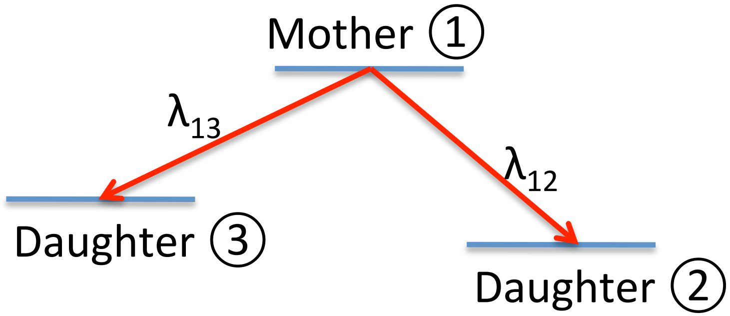
Au fur et à mesure que ses atomes instables se transforment, une substance voit sa radio-activité diminuer. On appelle période " T " le temps nécessaire pour que cette activité dimi-nue de moitié. Cette période est caractéris-tique de chaque isotope radioactif. Elle peut aller de quelques fractions de seconde à plusieurs milliards d'années, selon les isotopes considérés.

La nature offre ainsi plusieurs centaines d'isotopes radioactifs, qui sont autant d'étalons de mesure du temps.

Exemples :
polonium 214 (0,164 s),
oxygène 15 (2 mn),
iode 131 (8 jours),
cobalt 60 (5,3 ans),
carbone 14 (5730 ans),
plutonium 239 (24110 ans),
uranium 238 (4,5 milliards d'années).

3.3 Multiple decay

More than one decay mode :



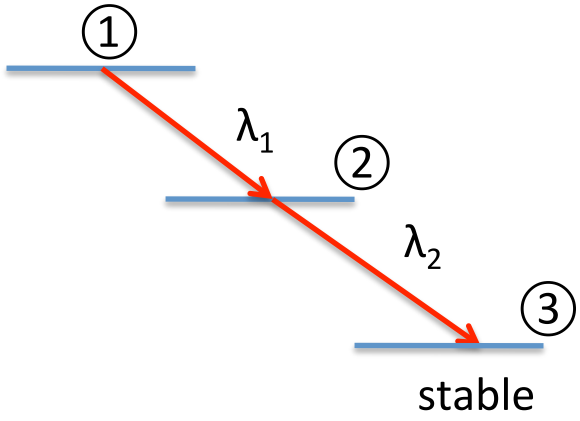
$$\frac{\mathrm{d}N_1}{\mathrm{d}t} = -\lambda_{12}N_1 - \lambda_{13}N_1 = -(\lambda_{12}+\lambda_{13})N_1$$
$$\lambda = \lambda_{tot} = \lambda_{12} + \lambda_{13}$$
Evolution of the population: $N_1(t) = N_1(0)e^{-\lambda_{tot}t}$

Generalization :assuming n decay modes, i=1..n

- λ_i are the partial decay constants, and $\lambda_{tot} = \sum_{i=1}^{n} \lambda_i$ (sum of proba)
- $A_i(t) = \lambda_i N(t)$ are the partial activities
- $\tau_i = 1/\lambda_i$ are the partial lifetimes, and $\tau_{tot} = \frac{1}{\sum \frac{1}{\tau_i}}$
- $BR(i) = \lambda_i/\lambda_{tot}$ are the branching ratios with $\sum_i BR(i) = 1$

3.4 Decay chains

- Chain with 3 elements : populations $N_1(t)$, $N_2(t)$, $N_3(t)$



$$\begin{cases} \frac{\mathrm{d}N_1}{\mathrm{d}t} = -\lambda_1 N_1(t) \\ \frac{\mathrm{d}N_2}{\mathrm{d}t} = +\lambda_1 N_1(t) - \lambda_2 N_2(t) \\ \frac{\mathrm{d}N_3}{\mathrm{d}t} = +\lambda_2 N_2(t) \end{cases}$$

the solution of this system of differential equations is :

$$\begin{cases} N_1(t) = N_1(0) e^{-\lambda_1 t} \\ N_2(t) = \frac{\lambda_1 N_1(0)}{\lambda_2 - \lambda_1}(e^{-\lambda_1 t} - e^{-\lambda_2 t}) + N_2(0) e^{-\lambda_2 t} \\ N_3(t) = N_1(0)\left(1 + \frac{1}{\lambda_2 - \lambda_1}(\lambda_1 e^{-\lambda_2 t} - \lambda_2 e^{-\lambda_1 t})\right) + N_2(0)(1 - e^{-\lambda_2 t}) + N_3(0) \end{cases}$$

If at t=0, only nuclei of type ① exist, the solutions become simpler:

$$\begin{cases} N_1(t) = N_1(0)e^{-\lambda_1 t} \\ \\ N_2(t) = \frac{\lambda_1 N_1(0)}{\lambda_2 - \lambda_1}(e^{-\lambda_1 t} - e^{-\lambda_2 t}) \\ \\ N_3(t) = N_1(0)\left(1 + \frac{1}{\lambda_2 - \lambda_1}(\lambda_1 e^{-\lambda_2 t} - \lambda_2 e^{-\lambda_1 t})\right) \end{cases}$$

And the activities are :

$$\begin{cases} A_1(t) = \lambda_1 N_1(0)\, e^{-\lambda_1 t} \\ \\ A_2(t) = \frac{\lambda_1 \lambda_2 N_1(0)}{\lambda_2 - \lambda_1}\left(e^{-\lambda_1 t} - e^{-\lambda_2 t}\right) \end{cases}$$

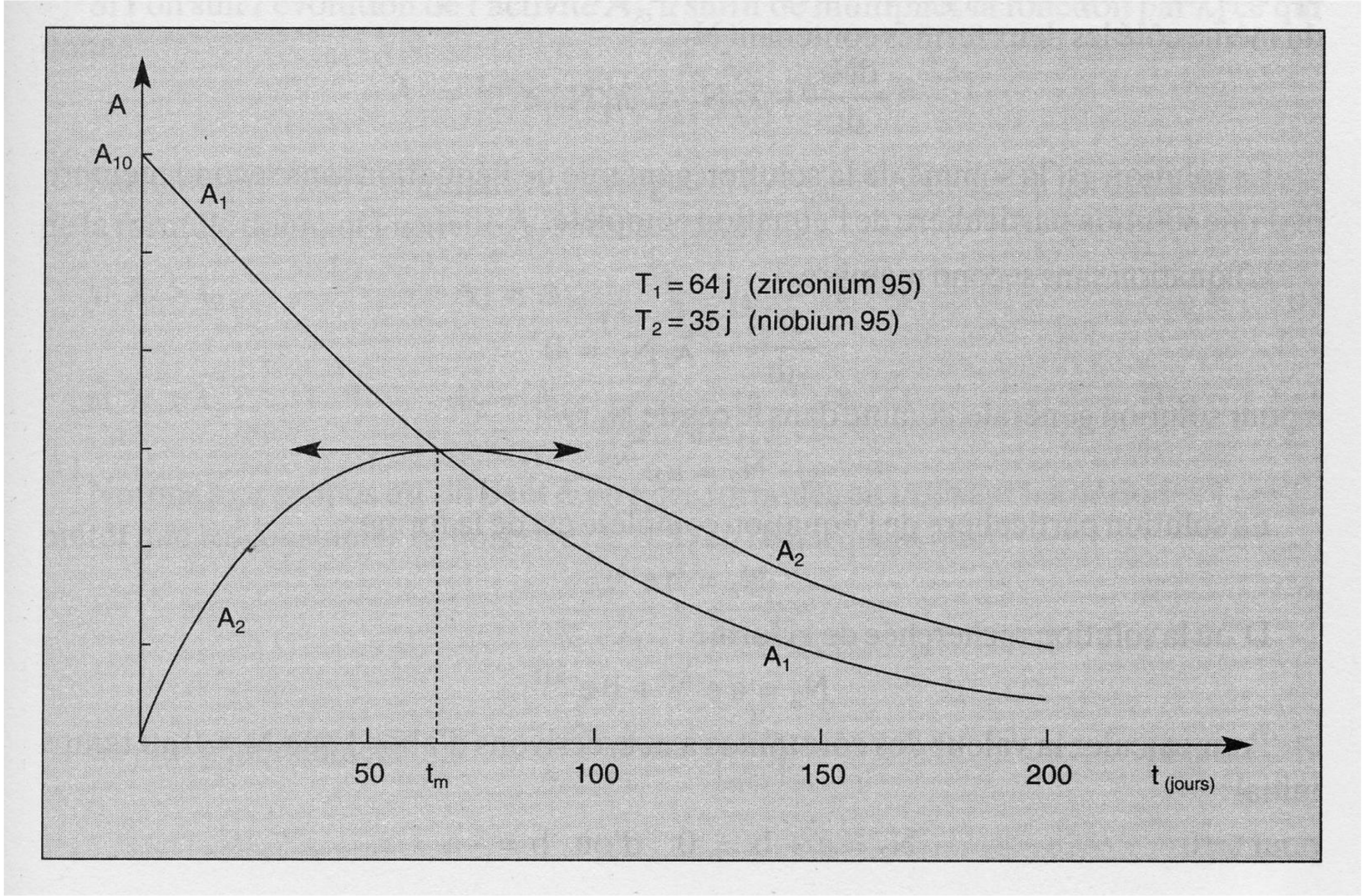
Where A_2 has a maximum at $t_M = \frac{1}{\lambda_2 - \lambda_1} \ln \frac{\lambda_2}{\lambda_1}$

Special cases:

If $T_1 >> T_2$ (i.e. $\lambda_1 << \lambda_2$), then after a time $t >> T_2$, A1(t)~A2(t) → **Equilibrium**

If $T_1 << T_2$ (i.e. $\lambda_1 >> \lambda_2$), then after a time $t >> T_1$, A1(t)~0 and ② decays with its own period

Example : A=95 isobaric chain, ${}_{40}Zi \rightarrow {}_{41}Nb \rightarrow {}_{42}Mo$



3.4.1 Bateman equations

Generalization : Bateman (1910)

$N_1 \rightarrow N_2 \rightarrow \ldots \rightarrow N_n$ with only material 1 at t=0

$$\begin{cases} \frac{\mathrm{d}N_1}{\mathrm{d}t} = -\lambda_1 N_1(t) \\ \frac{\mathrm{d}N_2}{\mathrm{d}t} = +\lambda_1 N_1(t) - \lambda_2 N_2(t) \\ \vdots \\ \frac{\mathrm{d}N_n}{\mathrm{d}t} = +\lambda_{n-1} N_{n-1}(t) \end{cases}$$

$$N_p = \sum_{i \leq p} C_i e^{-\lambda_i t} \quad \text{with } C_i = N_1(0) \prod_{\alpha=1}^{\alpha=p-1} \lambda_\alpha \left[\prod_{j \neq i}^{p} (\lambda_j - \lambda_i) \right]^{-1}$$

Non examinable

3.4.2 Natural radioactivity

- There are 2 sources of natural radioactivity:
  - Radioelement created with the Earth: Telluric radioactivity
  - Cosmic rays: both the cosmic rays (p,light nucleus, energetic γ) and the radioelements they produce (^{14}C,^{3}H,…) are sources of radioactivity.
- In the case of the telluric radioactivity, the first element of the decay chain has a period far greater than all his daughters, then the Bateman equations can be simplified :
  If for each i, $T_1 >> T_i$ and after a time $t >> T_i$, then the activities are identical in the decay : $A_1(t) \sim A_2(t) \sim \ldots \sim A_{n-1}(t)$
  This is the "secular equilibrium"
- There are 4 natural radioactive chains on earth.
  - Origin : creation of the earth
  - secular equilibrium state
  - Mix of α and β^- decay

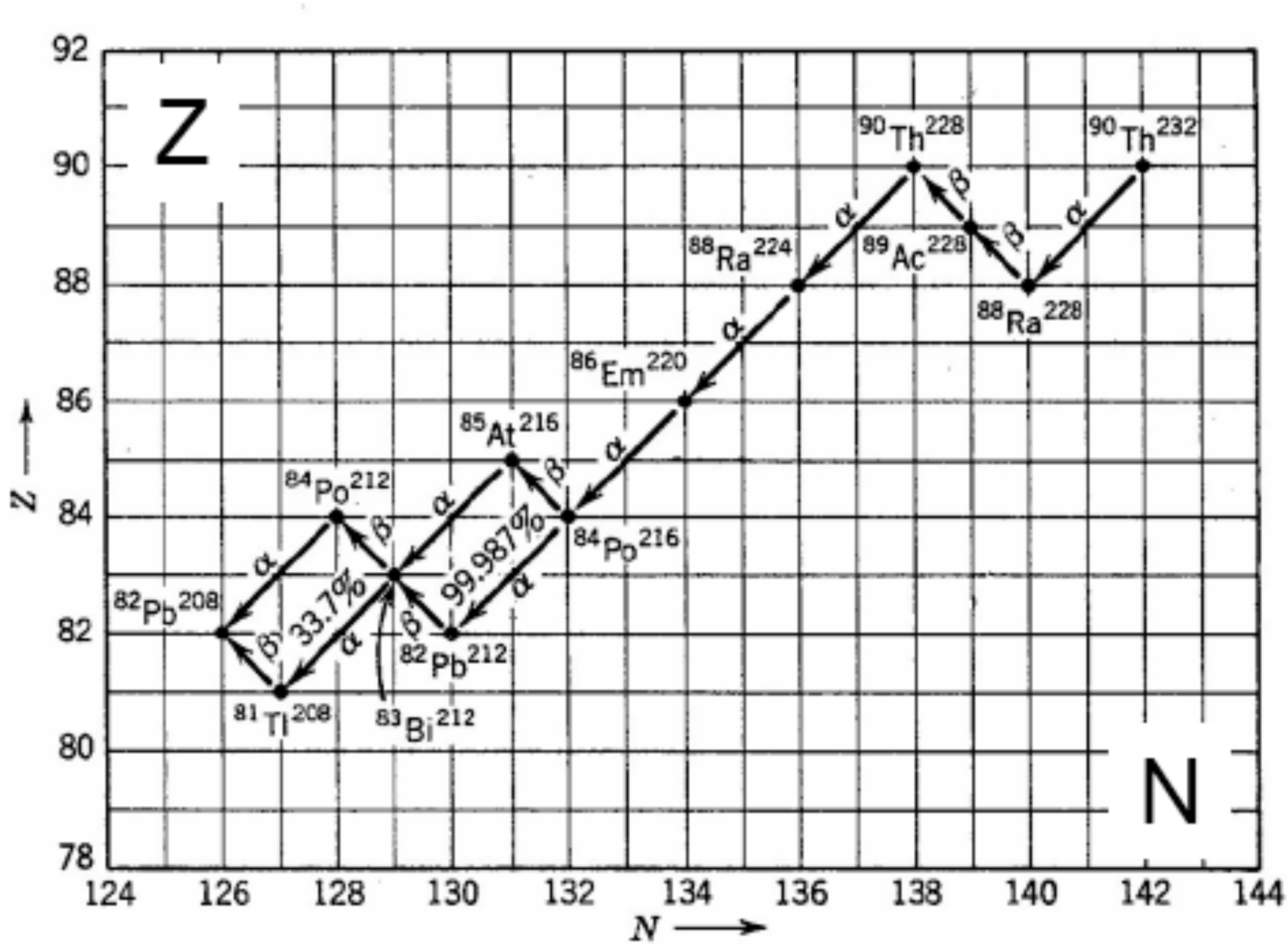
Series Name	Type	Final nucleus (stable)	Longest Lived Nucleus →	$T_{1/2}$ (years)
Thorium	4n	^{208}Pb	^{232}Th	$1.41\ 10^{10}$
Neptunium (Extinct)	4n+1	^{209}Bi	^{237}Np	$2.14\ 10^{6}$
Uranium	4n+2	^{206}Pb	^{238}U	$4.47\ 10^{9}$
Actinium	4n+3	^{207}Pb	^{235}U	$7.04\ 10^{8}$

4n+2 series

	Désintégration	$T_{1/2}$		Désintégration	$T_{1/2}$
1	$^{238}U \to {}^{234}Th + \alpha$	4.468×10^9 ans	8	$^{218}Po \to {}^{214}Pb + \alpha$	3.05 minutes
2	$^{234}Th \to {}^{234}Pa + \beta^-$	24.10 jours	9	$^{214}Pb \to {}^{214}Bi + \beta^-$	26.8 minutes
3	$^{234}Pa \to {}^{234}U + \beta^-$	6.75 heures	10	$^{214}Bi \to {}^{214}Po + \beta^-$	19.7 minutes
4	$^{234}U \to {}^{230}Th + \alpha$	2.45×10^5 ans	11	$^{214}Po \to {}^{210}Pb + \alpha$	164 μs
5	$^{230}Th \to {}^{226}Ra + \alpha$	8.0×10^4 ans	12	$^{210}Pb \to {}^{210}Bi + \beta^-$	22.3 jours
6	$^{226}Ra \to {}^{222}Rn + \alpha$	1.60×10^3 ans	13	$^{210}Bi \to {}^{210}Po + \beta^-$	5.01 jours
7	$^{222}Rn \to {}^{218}Po + \alpha$	3.824 jours	14	$^{210}Po \to {}^{206}Pb + \alpha$	138.4 jours

In this natural radioactive chain, ^{222}Rn is a gas and can cause health problems 7000 ^{222}Rn /m^2/s are escaping the ground. It accounts for 1/3 of the average radioactivity exposure for the French population.

4n series


Z
N
92
90
88
86
84
82
80
78
124
126
128
130
132
134
136
138
140
142
144
Z →
N →
90Th232
90Th228
88Ra228
89Ac228
88Ra224
86Em220
84Po216
85At216
84Po212
83Bi212
82Pb212
81Tl208
82Pb208
99.987%
33.7%
α
β

3.5 Irradiation and formation of the radioelements

- On earth, ~340 natural nuclear species, but ~ 3000 have be created and studied
- Example of neutron capture :

Irradiation Radioelement

$$^{23}_{11}\mathrm{Na} + n \longrightarrow ^{24}_{11}\mathrm{Na} \longrightarrow ^{24}_{12}\mathrm{Mg} + e^- + \bar{\nu}_e$$

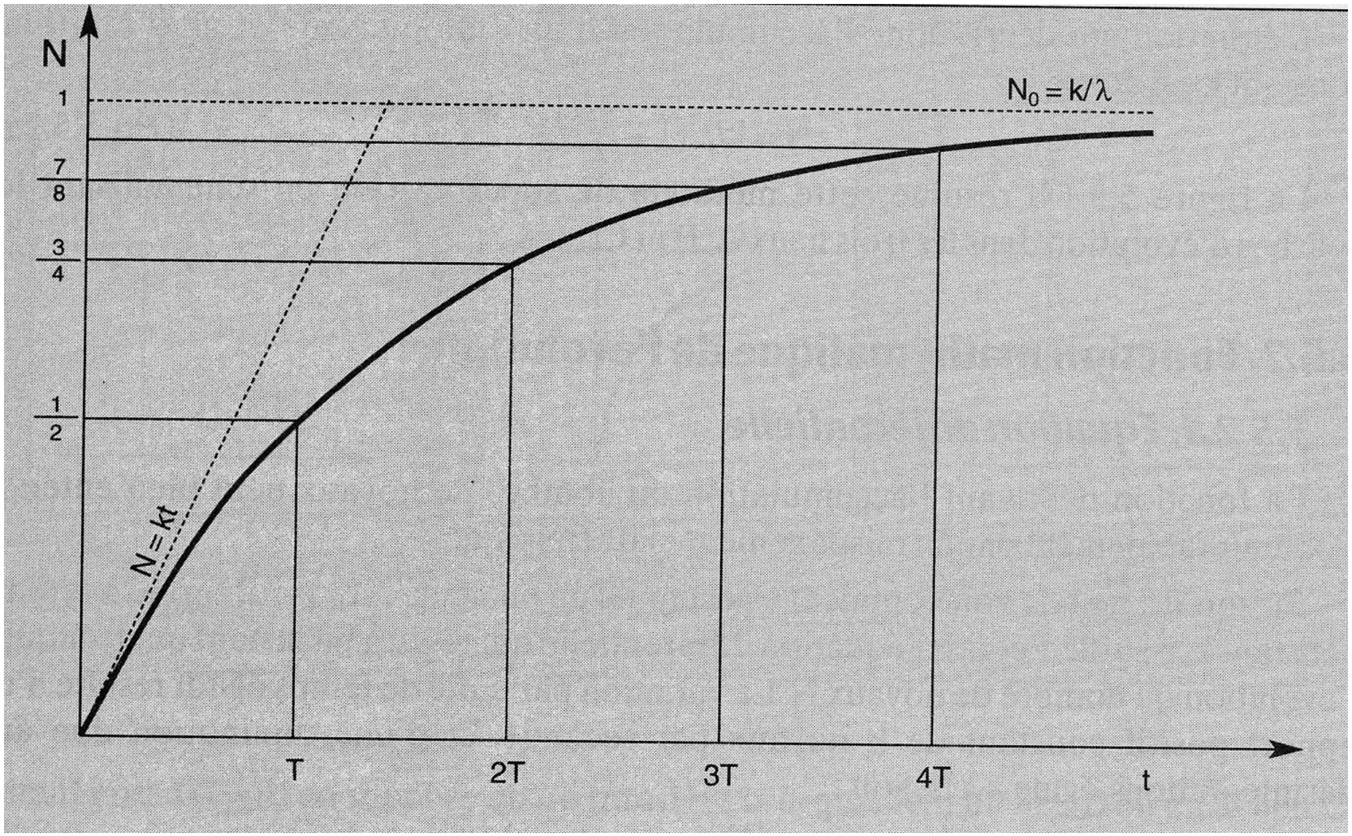
① ② ③

- Q is the creation rate, $Q = \Phi N_T \sigma$ where:
  - Φ is the number of incident neutrons per time unit.
  - N_T the number of target per surface unit.
  - σ the cross-section of neutron capture.

  OR
  - Φ is the number of incident neutrons per time unit and per surface unit.
  - N_T the total number of targets.
  - σ the cross-section of neutron capture.

The balance population gives : $\frac{\mathrm{d}N_2}{\mathrm{d}t} = Q - \lambda_2 N_2$ with $N_2=0$ at t=0.

$$\Longrightarrow N_2(t) = \frac{Q}{\lambda_2}(1 - e^{-\lambda_2 t})$$



3.6 Dosimetry

- Mean free path of radiations :

	In a solid	In the air
α (5MeV)	~20 μm	~5 cm
β	~mm	~cm
γ	~cm	~m

- neutrons : ~cm in water, parafine
- Energy loss is greater for charged particles

- Dose :the radioactive dose is the energy deposited per mass unit in a medium by ionizing radiation per unit mass
  Unity : 1 gray = 1 Gy = 1 J/kg (note : 1Gy=100Rad)
- Effective dose (measure the effect on living body):
  the Dose is not a good indicator of the likely biological effect. 1 Gy of α radiation would be much more biologically damaging then 1 Gy of γ radiation for example. weighting factors can be applied reflecting the different relative biological effects to find the equivalent dose :
  $D_{eq}=D.F_Q$
  Where F_Q is a quality factor taking into account the noxiousness of the for human body.
  Unity : 1 Sievert = 1Sv (note : 1Sv = 100 rem)

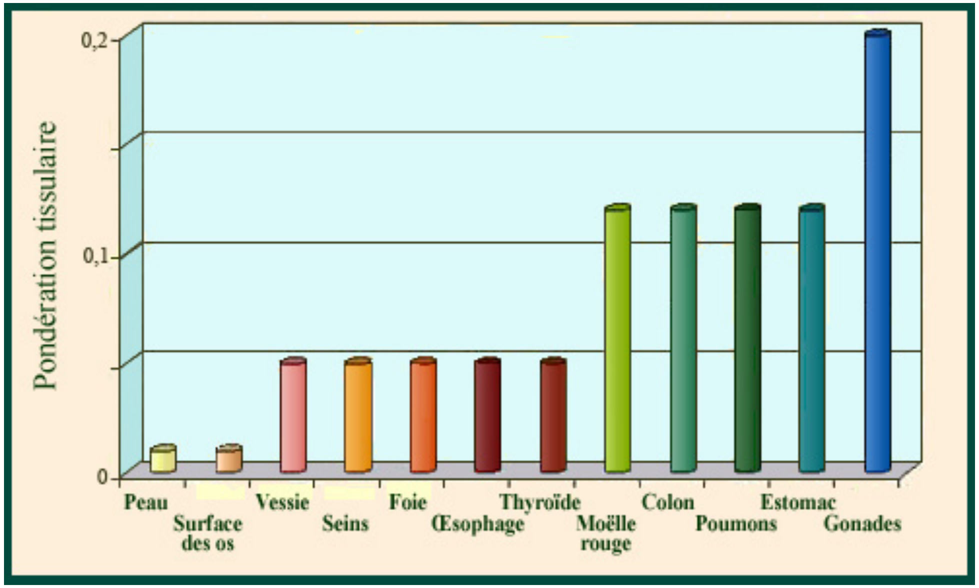
Radioactivity	F_Q
X,γ,β	1
Proton	10
α, heavy fragment (fission)	20

neutrons

Energy	F_Q
<10 keV	1
10keV – 100 keV	10
100keV – 2 MeV	20
2MeV – 20 MeV	10
> 20 MeV	5

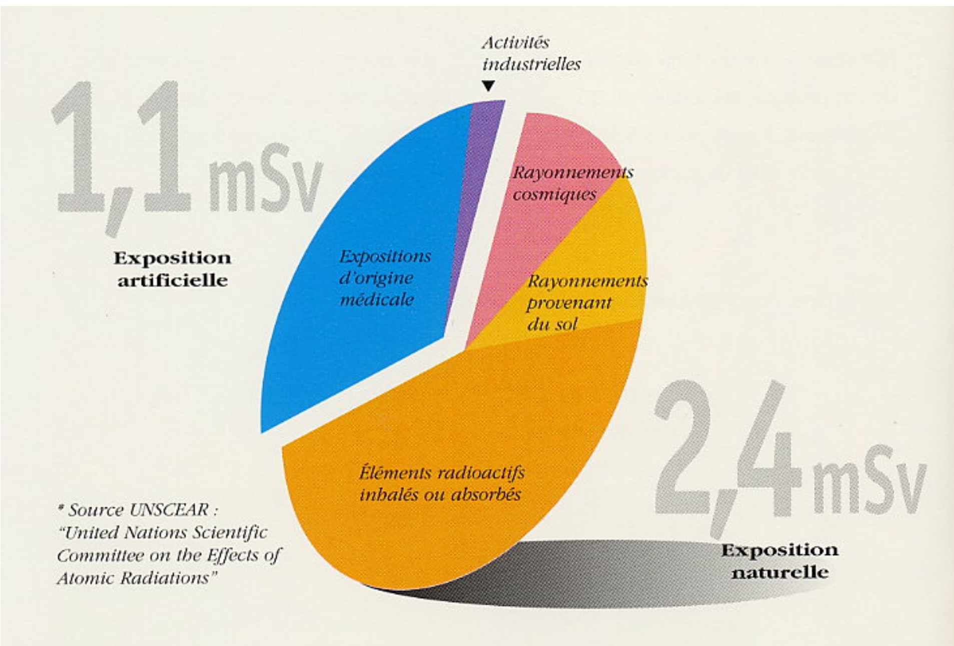
✓ An additional quality factor F_S is sometime added to the definition in order to take into account the sensitivity of the irradiated biological tissue :

- smallest F_S : muscle, skin
- biggest F_S : nervous system, gonads, marrow (moelle in french)

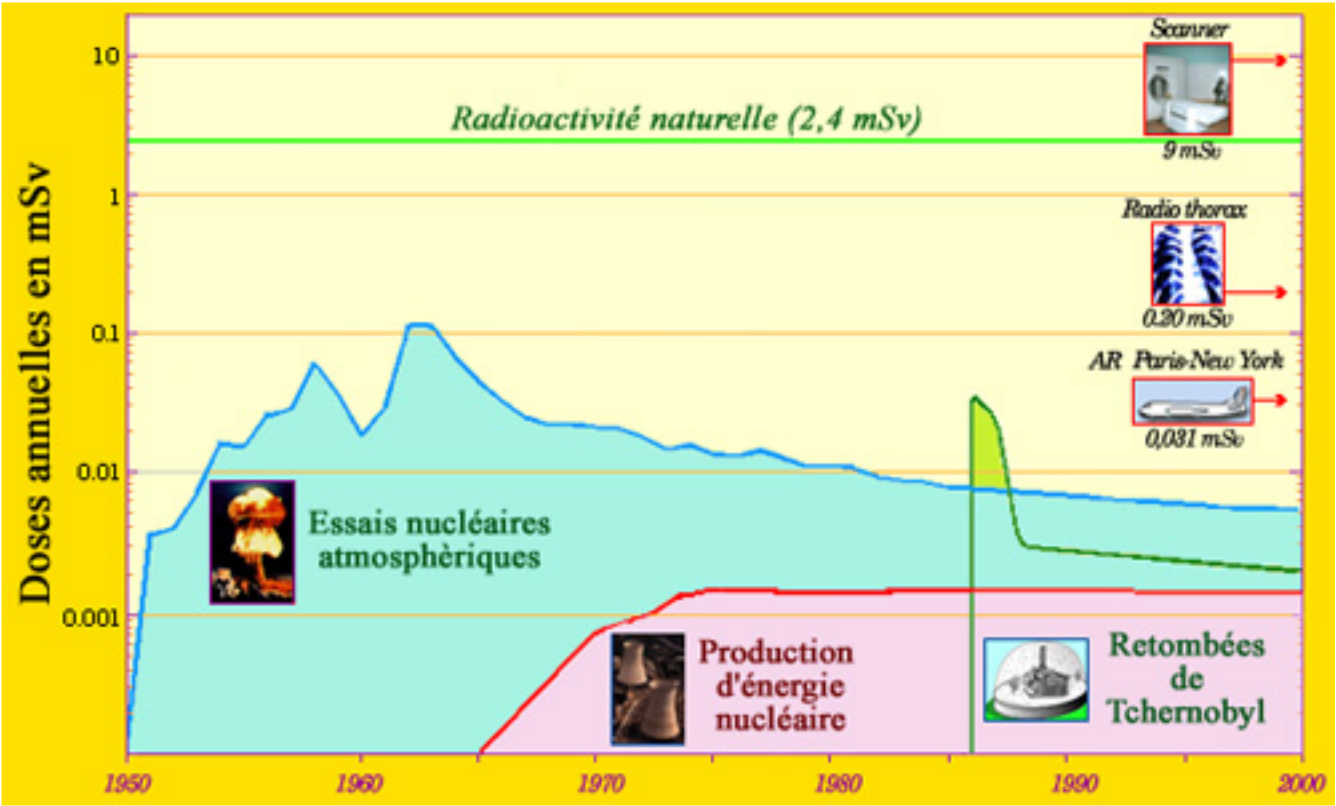


✓ biological period : timescale for the evacuation of the radioactivity by the body

Equivalent dose	Comment
0.03 mSv	Paris-NewYork Flight
1 mSv	Average medical irradiation
20 mSv	Maximum / year (for a controlled worker)
~1 Sv	Expected 2.5 year round-trip to mars
3-5 Sv	death in 2 months @ 50%
10 Sv	Fast death



Natural radioactivity of the human body:
- 0.25 mSv / year
-4000 Bq of ^{40}K and 4000 Bq of ^{14}C



Source : http://www.laradioactivite.com/

EFFETS DES DOSES* REÇUES PAR IRRADIATION HOMOGÈNE DU CORPS ENTIER

→ Entre 0 et 250 mGy : aucun effet biologique ou médical immédiat ou à long terme n'a été observé chez l'enfant ou l'adulte. C'est le domaine des faibles doses.

→ Entre 250 et 1 000 mGy : quelques nausées peuvent apparaître et une légère diminution du nombre de globules blancs.

→ Entre 1 000 et 2 500 mGy : vomissements, modification de la formule sanguine, mais évolution satisfaisante ou guérison complète assurée,

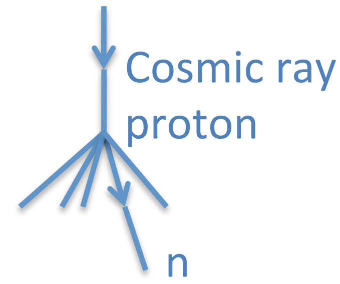
→ Entre 2 500 et 5 000 mGy : les conséquences pour la santé deviennent graves ; l'hospitalisation est obligatoire ; la dose de 5 000 mGy reçue en une fois est mortelle pour une personne sur deux.

→ Au delà de 5 000 mGy : le décès est presque certain.

Des effets tardifs (risques de cancers..., qui augmentent avec la dose) ont aussi été observés au-dessus de 250 mGy.

**Ce tableau se réfère à des doses absorbées en une seule fois, par irradiation homogène du corps entier. Dans ce cas le gray est équivalent au sievert pour les rayonnements X, γ et β, et à 25 Sv pour les rayonnements a. Des doses cumulées très supérieures à 5 Gy sont utilisées sur une portion de l'organisme en radiothérapie (60 à 80 Gy), elles sont déposées localement par séances de 2 à 3 Gy à raison de cinq à six séances par semaine.*

3.7 Radioactive dating



Radio-carbon dating (Scope: recent organic matter)

- ✓ ^{14}C is continuously formed in Earth's upper atmosphere

  $${}^{14}_{7}\mathrm{N} + n \longrightarrow {}^{14}_{6}\,\mathrm{C} + p$$

  Production rate of ^{14}C is approx constant.
  Checked with dating from tree rings (Dendrochronology)
  ⚠ Complications for future generations will results from burning of fossil fuels (increase ^{12}C in atmosphere), nuclear bomb tests (quantity of ^{14}C almost double in the 1950's and 1960's)

- ✓ The carbon in living organisms is continuously exchanged with atmospheric carbon.
  Equilibrium: ~1 atom of ^{14}C for 10^{12} atoms of other carbon isotopes (98.89% of ^{12}C and 1.11% of ^{13}C)

- ✓ ^{14}C decays in dead organisms: ${}^{14}_{6}\mathrm{C} \longrightarrow {}^{14}_{7}\,\mathrm{N} + e^{-} + \bar{\nu}_e$, $T_{1/2}$=5730 years
  No more ^{14}C absorbed from atmosphere
  In fresh organic material observe ~15 decays/minute/gram of carbon

- ✓ Measure the specific activity to obtain age (i.e. number of decays per second per unit mass)

3.8 Applications of radioactivity

- Radioactive dating
- Medicine (radiology, tracers and radiotherapy)
- Energy
- Sterilization of medical instruments and food
- Radiation is used as a non nondestructive method to inspect materials and make measurements.