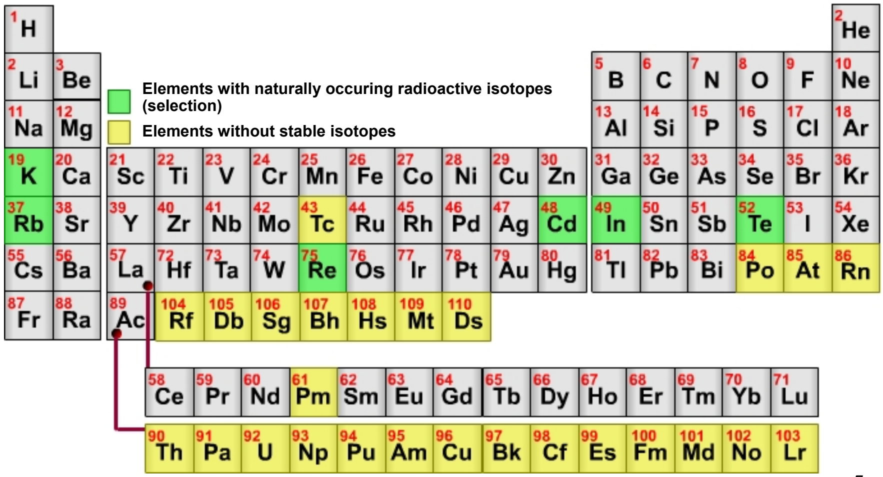
2) Nuclear Stability and nuclear radiation (2)

Periodic Table of the Elements vs. Nuclide Chart

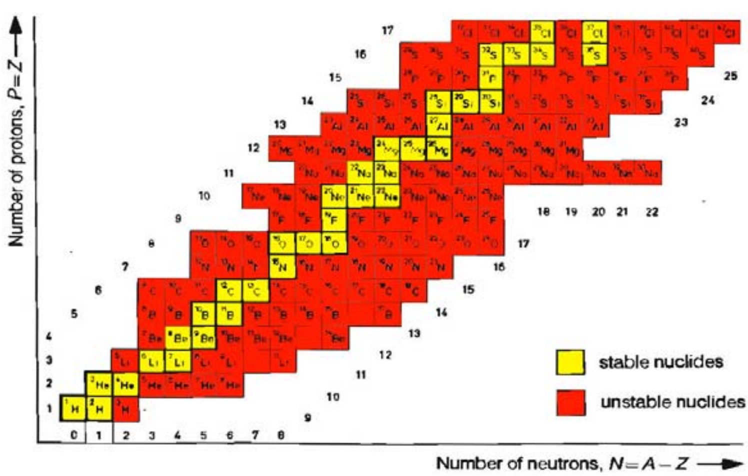
Approx. 115 different chemical elements ⇒ Periodic Table of Elements



2) Nuclear Stability and nuclear radiation (3)

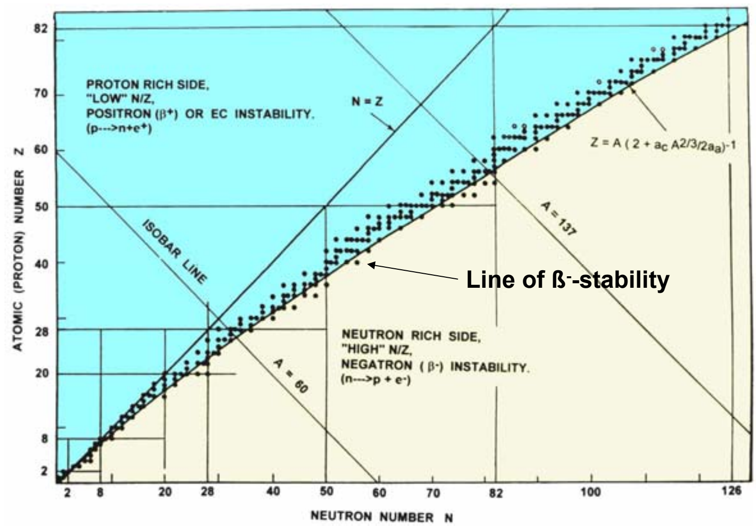
Periodic Table of the Elements vs. Nuclide Chart

Approx. 2800 different nuclides ⇒ Chart of nuclides



2) Nuclear Stability and nuclear radiation (4)

Dependence of the nuclear stability on the composition of the nuclei



2) Nuclear Stability and nuclear radiation (5)

Proton/neutron number

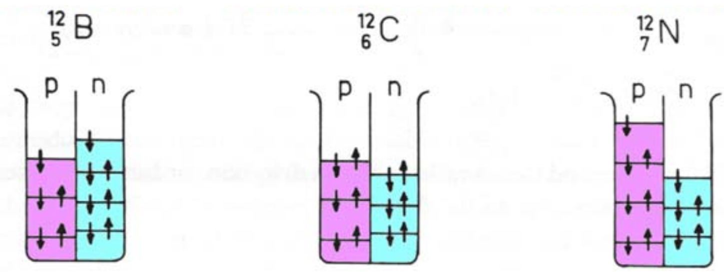
Statistical Resu□Ǘ checking all stable nuclides

Number of protons	Number of Neutrons	Probability
Even	Even	Very common, 158 nuclei
Even	Odd	Common, 53 nuclei
Odd	Even	Common, 50 nuclei
Odd	Odd	Rare , only 6 nuclei

2) Nuclear Stability and nuclear radiation (6)

The theory of proton/neutron orbitals

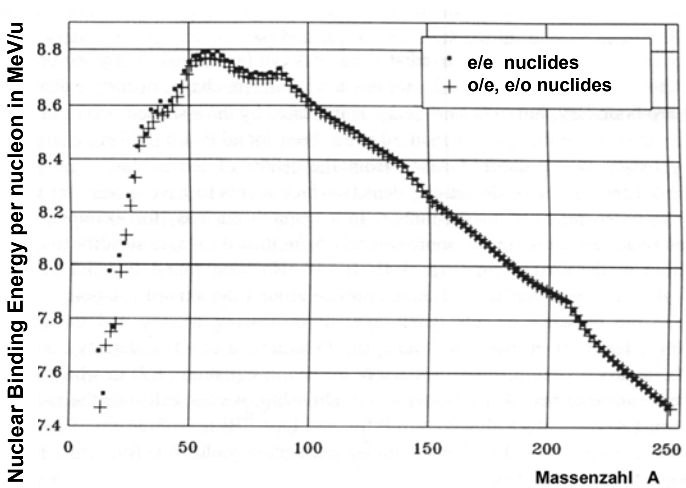
Isobaric nuclides ^{12}X and assumed nucleone orbitals



Instable	**Stable**	**Instable**
$^{12}_{5}B \longrightarrow ^{12}_{6}C + e^-$		$^{12}_{7}N \longrightarrow ^{12}_{6}C + e^+$
$(n \longrightarrow p + e^-)$		$(p \longrightarrow n + e^+)$
ß⁻ decay		**ß⁺ decay**

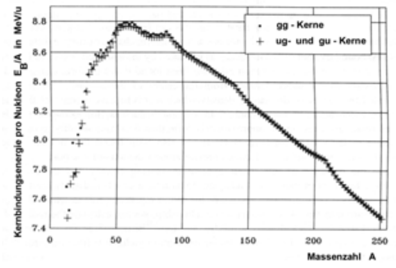
2) Nuclear Stability and nuclear radiation (7)

The Nuclear Binding energy and nuclide masses



2) Nuclear Stability and nuclear radiation (8)

The Nuclear Binding energy and nuclide masses



Remember!

mass of a proton: 1.67252×10^{-27} kg
mass of a neutron: 1.67482×10^{-27} kg

The mass of an atomic nucleus is always less than that of the sum of its components.

Mass of a nuclide: $M = Z\,M_{proton} + N\,M_{neutron} - \delta_M$ **where δ_M is the mass defect**

$$E = m c^2$$

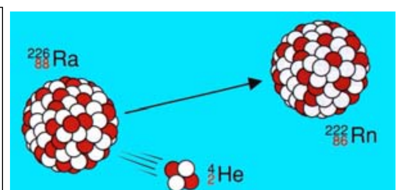
2) Nuclear Stability and nuclear radiation (9)

α - Radiation

Emission of a helium nucleus

- atomic number decreases by two units
- mass number decreases by 4 units

- typical for heavy nuclides
- α-particle carries almost all energy of the decay (low mass of He compared to the recoil nucleus

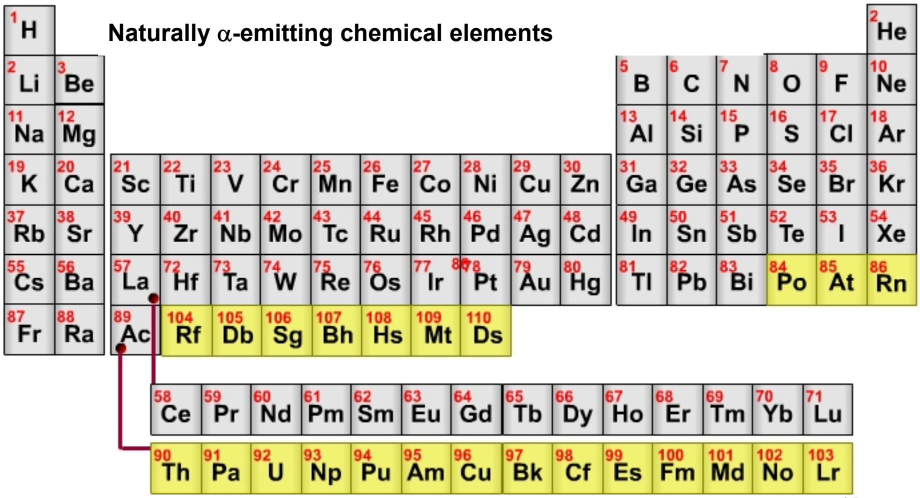


According to $\Delta E = (M_{mother} - M_{daughter} - M_{\alpha})\,c^2$, nuclides with A > 140 should be α--instable

- high nuclear binding energy of the He-nucleus
- however, the decay is kinetically hindered (high energy barrier to be surmounted by the α-particle

2) Nuclear Stability and nuclear radiation (10)

α - Radiation



2) Nuclear Stability and nuclear radiation (11)

α - Radiation

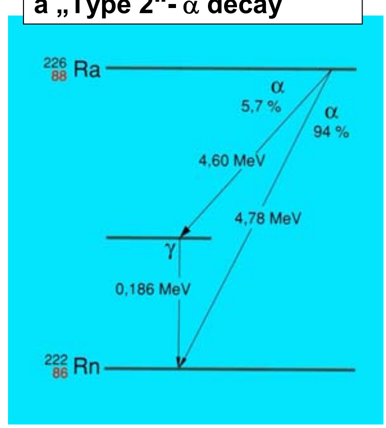
α-Spectra

Type 1
- all α-particles originating from a certain decay are monoenergetic
- one α-line is observed in the spectrum

Type 2
- two or more lines
- the α-decay leads to excited stated beside the ground state of the daughter

Type 3
- one main line and more (less intense) line(s) at higher energies
- excited states of the mother are involved

Transitions according to a „Type 2“- α decay



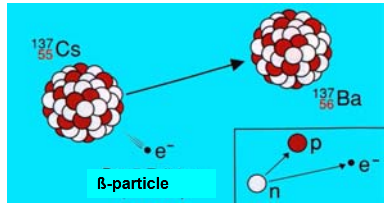
2) Nuclear Stability and nuclear radiation (12)

$ß^-$ - Radiation

Emission of a $ß^-$-particle (nuclear electron)

- atomic number increases by one unit
- mass number remains unchanged

- typical for nuclides with excess of neutrons
- internal conversion of a neutron into a proton (+ $ß^-$-particle + antineutrino)



$ß^-$ Decay: $${}^{1}_{0}n(nucleus) \rightarrow {}^{1}_{1}p(nucleus) + {}^{0}_{-1}e^- + {}^{0}_{0}\overline{\nu}$$

- formation of an anti-neutrino is required from the **Laws of the conservation of the spin and the energy**
- main energy distribution between the $ß^-$-particle and the anti-neutrino
- often accompanied by γ-radiation

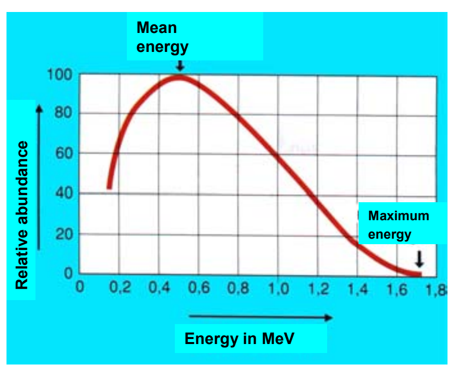
2) Nuclear Stability and nuclear radiation (13)

$ß^-$ - Radiation

ß-Spectra

- ß-particles have no distinct energy
- energy distribution between ß-particle and anti-neutrino
- typical parameters are E_{max} and E_{mean}
- E_{mean} is only about 1/3 of E_{max}

Typical ß-spectrum



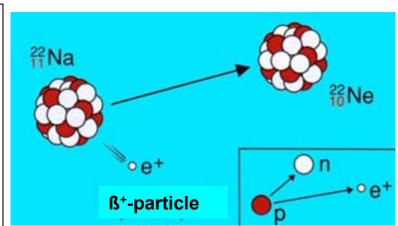
2) Nuclear Stability and nuclear radiation (14)

ß⁺- Radiation

Emission of a positron (ß⁺-particle)

- atomic number decreases by one unit
- mass number remains unchanged

- typical for nuclides with excess of protons
- internal conversion of a proton into a neutron (+ positron + neutrino)



ß⁺ Decay: $${}^{1}_{1}p(nucleus) \rightarrow {}^{1}_{0}n(nucleus) + {}^{0}_{1}e^{+} + {}^{0}_{0}\nu$$

- formation of a neutrino is required from the **Laws of the conservation of the spin and energy**
- similar process like the ß⁻-decay
- emission of a neutrino

2) Nuclear Stability and nuclear radiation (15)

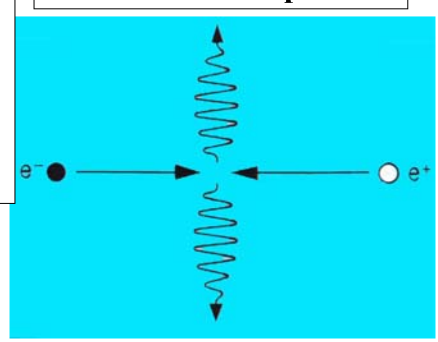
ß⁺- Radiation

Emission of a positron (ß⁺-particle)

- a positron is not stable and reacts immediately with an electron to form two γ-quants
- transformation of **matter** into **energy**

- no ß⁺-spectra are measured
- instead of this, **two** γ-quants with distinct energy can be detected ($E = m c^2$)

Annihilation of a positron



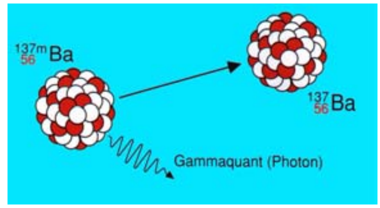
2) Nuclear Stability and nuclear radiation (16)

γ- Radiation

Emission of electromagnetic radiation during a nuclear reaction

- no changes in atomic number nor mass number

- relaxation of an excited state into the ground state



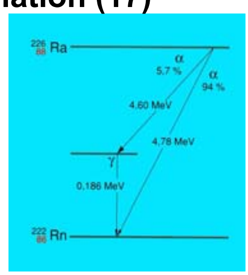
- γ-radiation often accompanies α- and ß-processes

- pure γ-emitter are rare (metastable isomers of nuclides)

- highly penetrating electromagnetic radiation

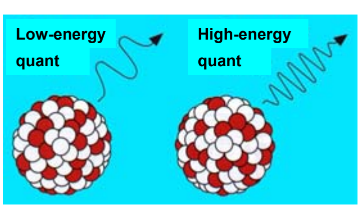
2) Nuclear Stability and nuclear radiation (17)

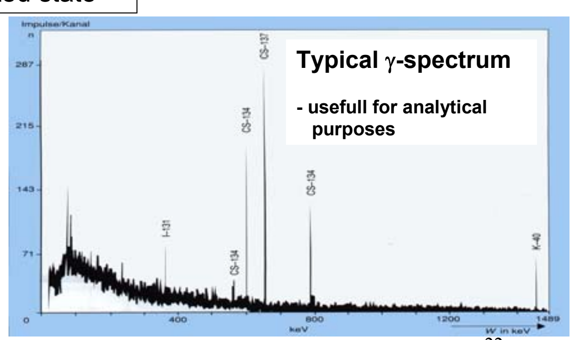
γ- Radiation



γ- Spectra

- discrete line spectra representing the γ-transition of a nuclear decay
- γ-lines are representative for a distinct nuclide relaxation of an excited state

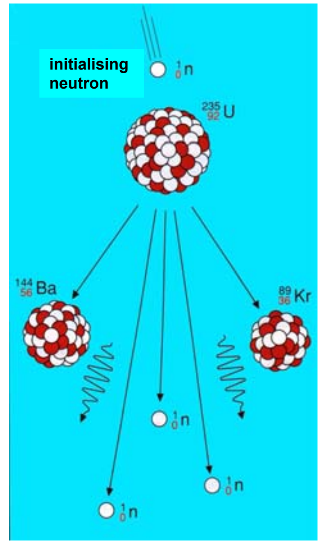




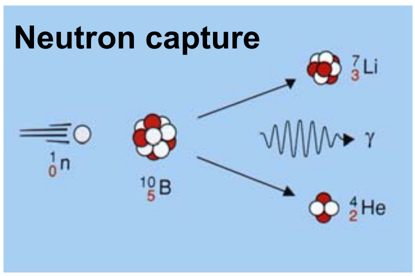
2) Nuclear Stability and nuclear radiation (18)

Neutron-Radiation

- e.g. during processes of nuclear fission
- neutrons have no charge
- no direct interactions with electron shells
- risk due to neutrons is often under-estimated

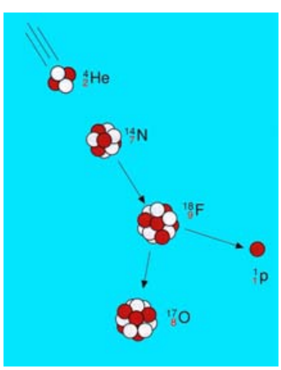


Typical reaction of neutrons



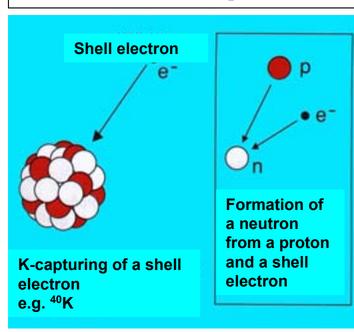
2) Nuclear Stability and nuclear radiation (19)

Proton-Radiation



- rare type of radioactive decay
- explored in 1982
- works with proton-rich nuclides left from the line of ß-stability
- competing with the favoured ß+-decay

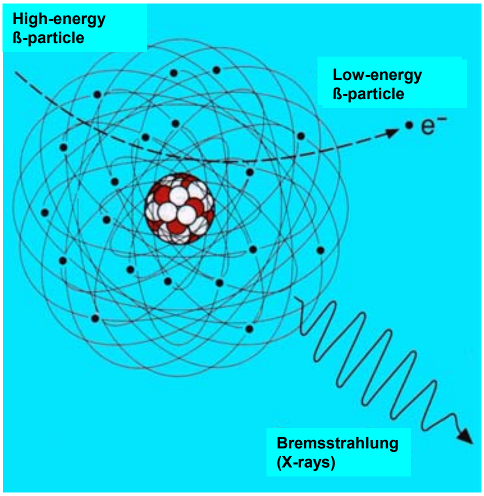
Electron Capture



- a K-shell electron is captured by the proton-rich nucleus
- transmutation of a proton into a neutron
- comparable with positron decay
- decrease of the atomic number by one

2) Nuclear Stability and nuclear radiation (20)

Bremsstrahlung

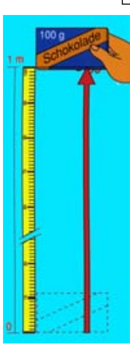


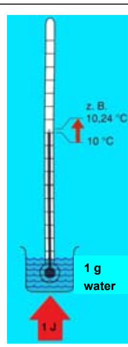
- **no direct nuclear radiation**
- secondary radiation that occurs when ß-particles cross the electron shells of atoms
- ß-particles lose a part of their energy
- this energy is released by the atom as secondary X-rays (bremsstrahlung)
- the higher the atomic number of the absorber the higher the amount of bremsstrahlung

(Consequences for shielding!)

2) Nuclear Stability and nuclear radiation (21)

Energy range of nuclear radiation





Typical energy scale is 1 eV

1 eV = 1,602 x 10^{-19} J
1 J = 6,242 x 10^{18} eV

Please Note! This is a **single particle energy**, not the molare scale

Typical energies for α-particles

Isotope	Typical energies (MeV)
^{210}Po	5,30438 .....
^{222}Rn	5,48952 .....
^{226}Ra	4,78438; 4,6017 ....
^{238}U	4,197 ...
^{239}Po	5,157, 5,144 ...

Typical energies for ß-particles

Isotope	Energy (MeV)
^{60}Co	0,3 ; 1,5 .....
^{285}Kr	0,7.....
^{131}I	0,6....

Typical energies for γ-radiation

Isotope	Energy (MeV)
^{137m}Ba	0,602
^{99m}Tc	0,140

Energy range of nuclear radiation

The range of nuclear radiation is dependent on the radiation type
(Remember! α-Radiation consists of huge particles
ß-radiation consists of small particles
γ-radiation consists of photons (electromagnetic waves)

The range of nuclear radiation is energy dependent

Range of α-particles

Energy in MeV	Range in Air	Muscle Tissue	Aluminium
1	0.32 cm	4 µm	2 µm
4	2.5 cm	31 µm	16 µm
6	4.6 cm	56 µm	30 µm
8	7.4 cm	91 µm	48 µm
10	10.6 cm	130 µm	67 µm

Energy range of nuclear radiation

Range of ß-particles

Energy in MeV	Range in Air	Muscle Tissue	Aluminium
0.01	3 mm	2.5 µm	9 µm
0.5	1.2 m	1.87 mm	0.6 mm
1	3.06 m	4.75 mm	1.5 mm
10	39 m	60 mm	19 mm

Range of γ-radiation
(Note! Half-thickness, not range)

Energy in MeV	Half-thickness in Water	Concrete	Lead
0.01	4.15 cm	1.75 cm	0.1 mm
0.5	7.2 cm	3.4 cm	0.4 cm
1	9.8 cm	4.6 cm	0.9 cm
10	31 cm	12.9 cm	1.2 cm

2) Nuclear Stability and nuclear radiation (24)

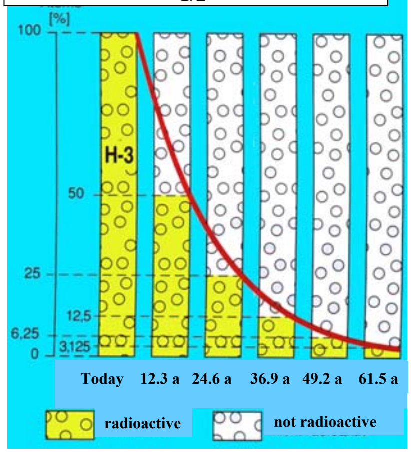
Half-life of radioactive nuclides

- Disintegration of radioactice nucei is a statistical process
- follows a first-order kinetics

  $A \rightarrow B + X + \Delta E$
- Half lifes are characteristic for the individual nuclides

Isotope	Symbol	Half-life	Decayt
Uranium-238	${}^{238}_{92}U$	$4{,}468 \times 10^{9}$ a	α
Potassium-40	${}^{40}_{19}K$	$1{,}28 \times 10^{9}$ a	β^-, K
Plutonium-239	${}^{239}_{94}Pu$	$2{,}411 \times 10^{4}$ a	α
Cäsium-137	${}^{137}_{55}Cs$	30,17 a	β^-
Iodine-131	${}^{131}_{53}I$	8,02 d	β^-
Thorium-231	${}^{231}_{90}Th$	25,5 h	β^-
Radon-220	${}^{220}_{86}Rn$	55,6 s	α
Polonium-214	${}^{214}_{84}Po$	$1{,}64 \times 10^{-4}$ s	α

Example: Decay of tritium
$T_{1/2}$ = 12.3 a



2) Nuclear Stability and nuclear radiation (25)

The Law of the Radioactive Decay

- Disintegration of radioactive nucei is a statistical process
- follows a first-order kinetics

$$A \rightarrow B + X + \Delta E$$

$$N = N_0 \cdot e^{-\lambda \cdot t}$$

N_0 = number of radioactive nuclei at t = 0
N = number of radioactive nuclei at $t = t_t$
λ = decay constant (s^{-1})

- relationship with half-life:

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0{,}693}{\lambda}, \qquad \ln 2 = \lambda\, T_{1/2} \quad \text{or} \quad 0{,}5 = e^{-\lambda t}$$