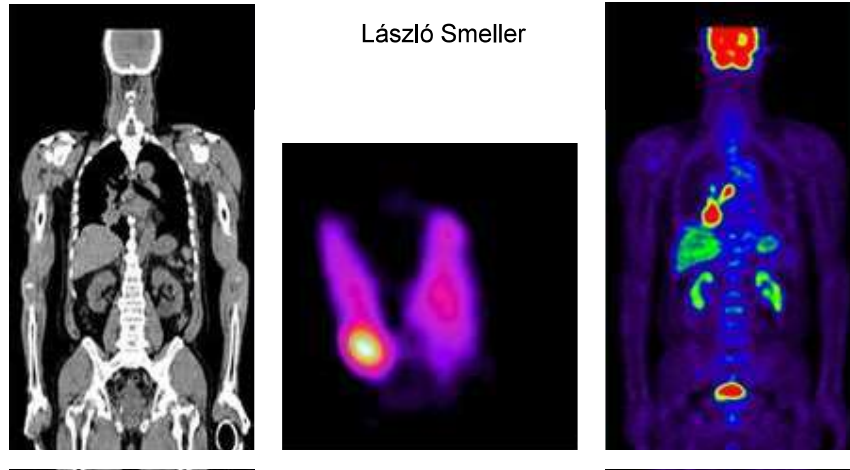
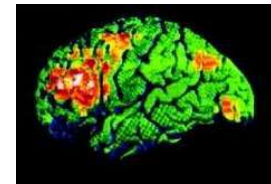


The atomic nucleus. Radioactivity. Nuclear radiations

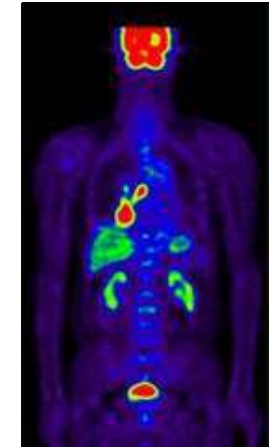
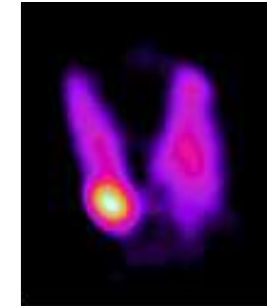


Why?

Medical/pharmaceutical applications of nuclear radiation:



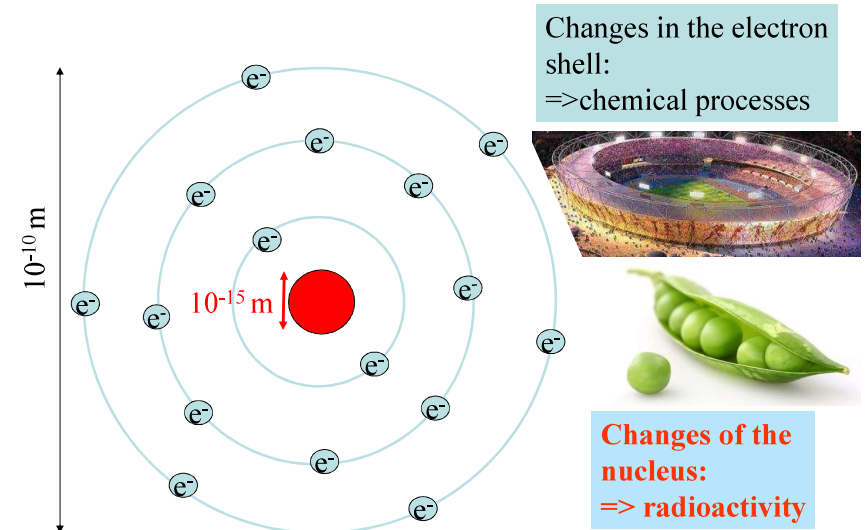
Nuclear imaging
Radiotherapy
Pharmacokinetics



Length scale of the nature

m		
10^0	meter	men
10^{-3}	millimeter	letters you can read
10^{-6}	micrometer	size of a cell (e.g. erythrocyte)
10^{-9}	nanometer	protein
10^{-10}	– angstrom	diameter of an atom, bond length H atom $\varnothing \approx 1$ angstrom (Å)
10^{-12}	picometer	wavelength of the X-ray
10^{-15}	femtometer	size of the nucleus

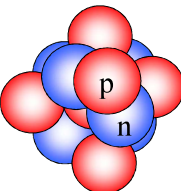
The electrons and the nucleus



Structure of the nucleus

Elementary charge = $1,6 \cdot 10^{-19} \text{ C}$

	charge	mass
proton	$+1 e$	1 atomic mass unit
neutron	0	1 atomic mass unit



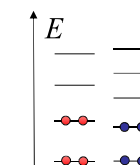
A (mass number) = number of protons + number of neutrons
 Z (atomic number) = number of protons

99 nucleon, 43 proton and 56 neutron

99 Tc 43

Stability of the nucleus

- Coulomb force: destabilization (electrostatic repulsion between the protons)
- Nuclear force: very strong attractive force acts only on short range ($\sim \text{fm}$) independent on the charge
- Quantized energy levels for the nucleus.
- Typical binding energy is in the MeV range $eV = 1,6 \cdot 10^{-19} \text{ J}$

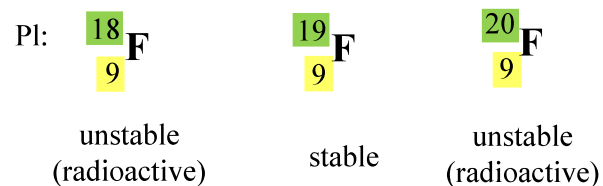


Isotopes

Number of protons is the same
Number of neutrons is different

Variants of the same element

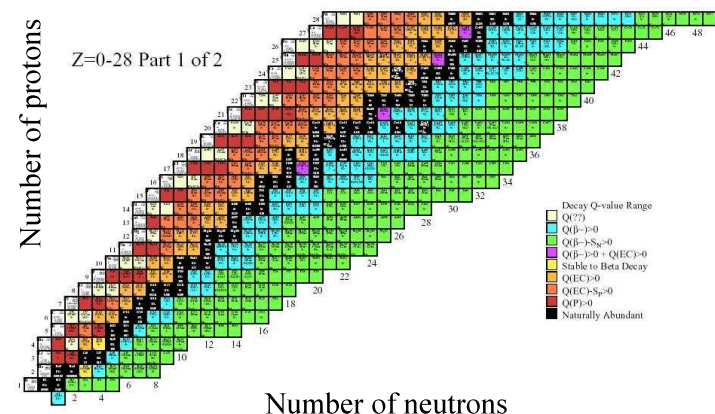
\Rightarrow the chemical properties are identical.

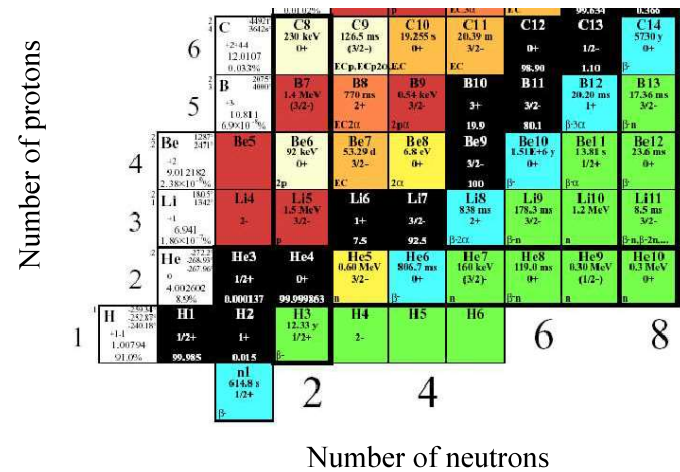
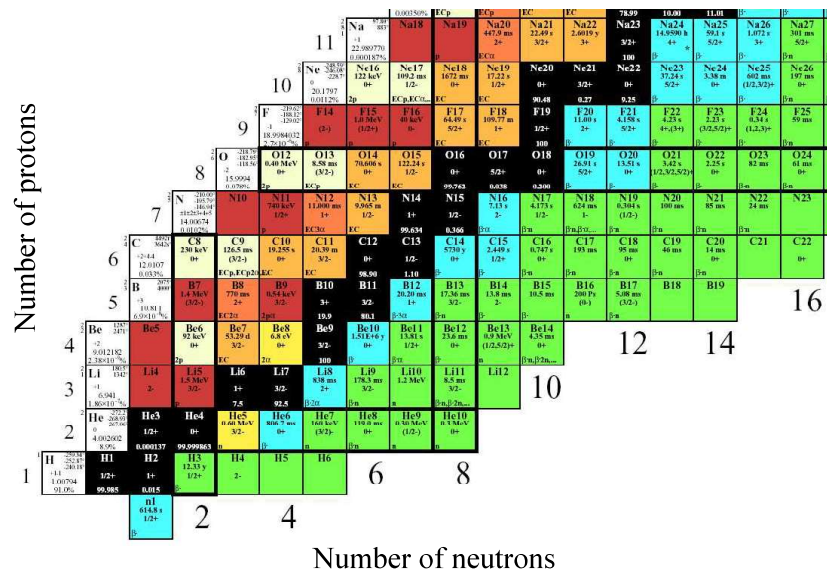


isotope \leftrightarrow radioactive isotope



Table of isotopes





Radioactive decays and particles

α - decay

α - particle = ${}^4_2\text{He}$ nucleus

β - decay : β^-
 β^+

β^- particle = electron

β^+ particle = positron

Isomeric transition

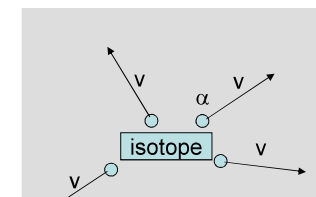
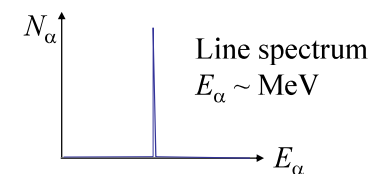
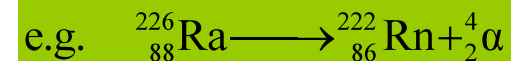
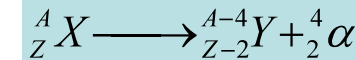
γ -ray

K-electron capture

characteristic x-ray photon

α - decay

α - decay: an α particle (${}^4\text{He}$ nucleus) will be emitted
typical for the heavy atoms



neutron surplus

β^- - decay

e.g.: $^{20}_9F$, $^{32}_{15}P$, $^{59}_{26}Fe$, $^{131}_{53}I$

$$^A_ZX \longrightarrow ^A_{Z+1}Y + ^0_{-1}\beta + \bar{\nu}$$

$$^1_0n \longrightarrow ^1_1p + ^0_{-1}\beta + \bar{\nu}$$

remains in the nucleus leave the nucleus

e.g.: $^{32}_{15}P \longrightarrow ^{32}_{16}S + ^0_{-1}\beta + \bar{\nu}$

β^- -ray: e^- , $\bar{\nu}$

$\beta^- = ^0_{-1}\beta = e^-$

continuous energy spectrum

proton surplus

β^+ - decay

e.g.: $^{11}_6C$, $^{15}_8O$, $^{18}_9F$, $^{52}_{26}Fe$

$$^A_ZX \longrightarrow ^A_{Z-1}Y + ^0_{+1}\beta + \nu$$

$$^1_1p \longrightarrow ^1_0n + ^0_{+1}\beta + \nu$$

remains in the nucleus leave the nucleus

e.g.: $^{30}_{15}P \longrightarrow ^{30}_{14}Si + ^0_{+1}\beta + \nu$

β^+ -ray: e^+ , ν

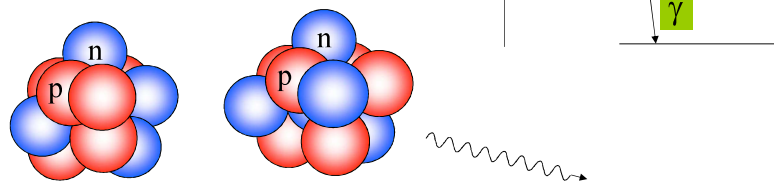
continuous energy spectrum

These isotopes must be produced artificially (e.g. in cyclotron)

Prompt γ -radiation

The daughter nucleus has an **energetically unfavoured** arrangement of nucleons.

The surplus energy will be immediately (ns) emitted in form of the γ radiation



Atomic number, mass number are unchanged.

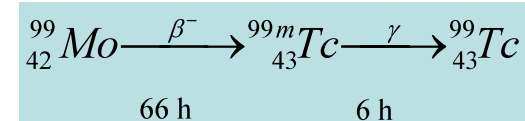
Isomeric transition

If the excited state of the daughter nucleus is metastable, the γ -radiation will be emitted later.

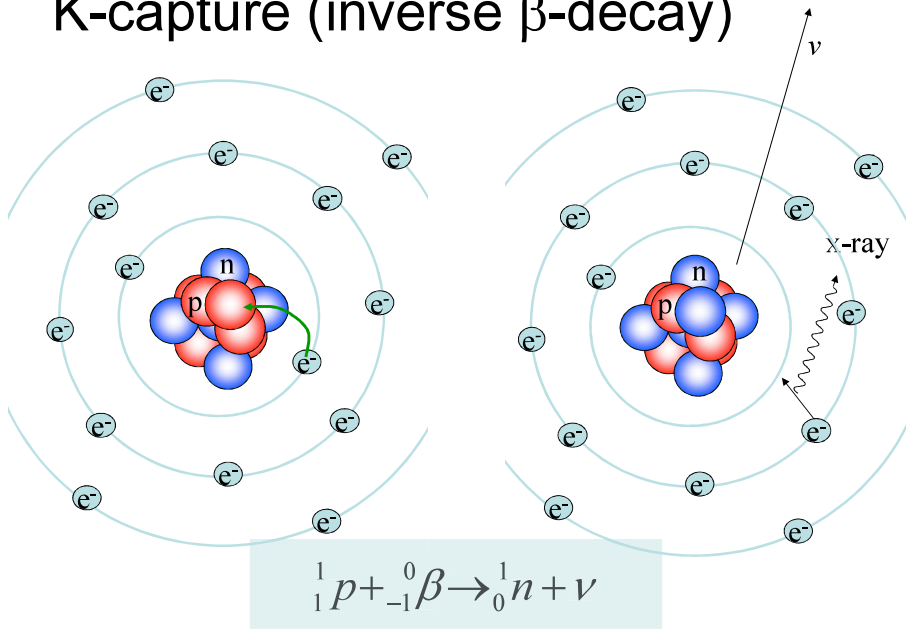
The parent and daughter atoms can be separated: the daughter atom emits **only γ -radiation!**

=> Isotope diagnostics (nuclear imaging)

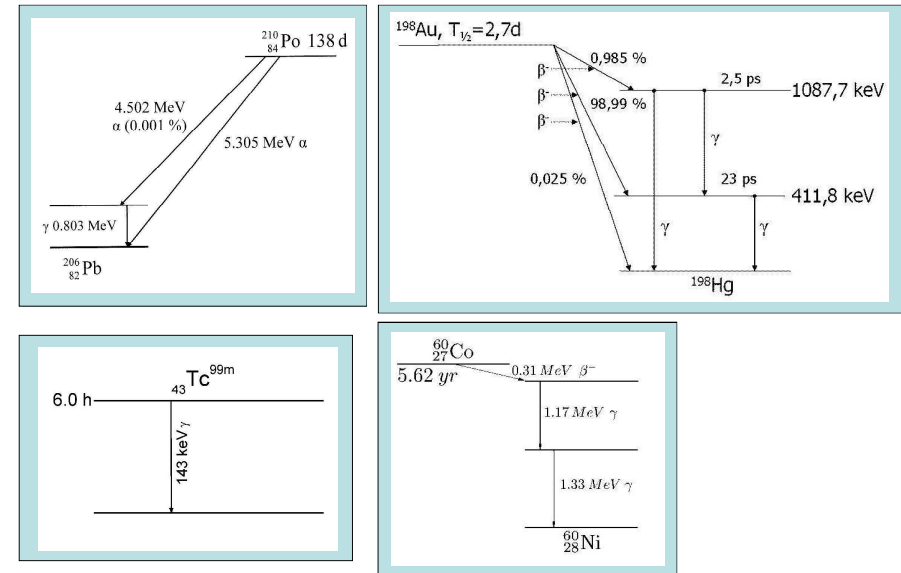
E.g.: $^{99m}_{42}Tc$



K-capture (inverse β -decay)



Some examples of the decay paths



How to produce radioactive isotopes?

β^- decaying:

n surplus \rightarrow irradiate by neutrons
(in a nuclear reactor)

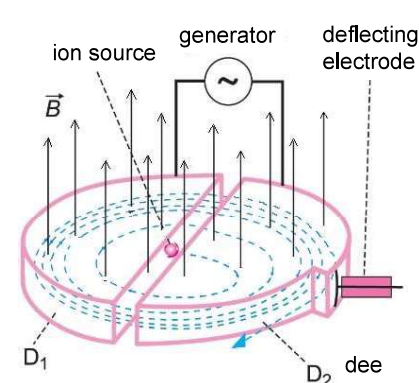
β^+ decaying:

p surplus \rightarrow irradiate by protons
Coulomb repulsion \rightarrow you need accelerated protons!
 \rightarrow cyclotron

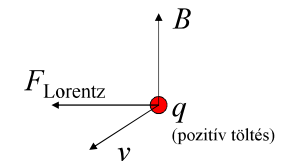
Ciklotron

Protons or alpha particles are accelerated on a spiral path.

Typical energy: few 10 MeV (max 50 MeV)



$$\vec{F}_{\text{Lorentz}} = q\vec{v} \times \vec{B}$$



$$qBv = F_{\text{Lorentz}} = F_{\text{cp}} = mv^2/R$$

Characteristics of radioactive decays in general

activity	characterizes the source
half life time	characterizes the speed of the decay (depends on the type of the isotope)
particle energy	characterizes the radiation (depends on the type of the isotope)

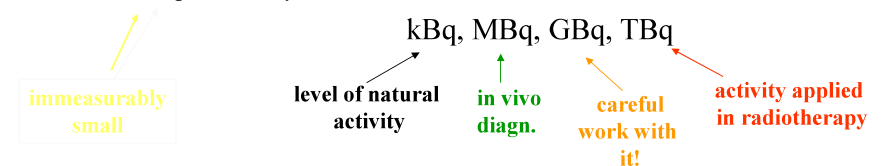
Activity (Λ)

$$\Lambda = \left| \frac{dN}{dt} \right| \quad \left(= \left| \frac{\Delta N}{\Delta t} \right| \right)$$

N = Number of undecayed atoms
 t = time
 ΔN = Number of decays during Δt time

Activity = number of decays in a unit time

unit: becquerel Bq
 1 Bq = 1 decay/sec



Law of radioactive decay

$$\Delta N = -\lambda N \Delta t$$

N : Number of undecayed nuclei

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

λ : decay constant (probability of the decay [1/s])
 $1/\lambda = \tau$ average lifetime

Differential equation

solution:

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

Exponential decrease

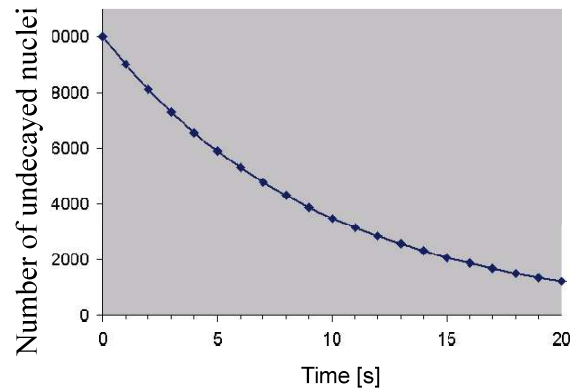
number of undecayed atoms at $t=0$

An example

- $N_0 = 10000$ $\lambda = 0.1 \text{ 1/s}$
- After 1 sec : 9000 ($10000 \times 0.1 = 1000$ decayed)
- After 2 sec : 8100 ($9000 \times 0.1 = 900$ decayed)
- After 3 sec : 7290 ($8100 \times 0.1 = 810$ decayed)
- After 4 sec : 6561 ($7290 \times 0.1 = 729$ decayed)
-

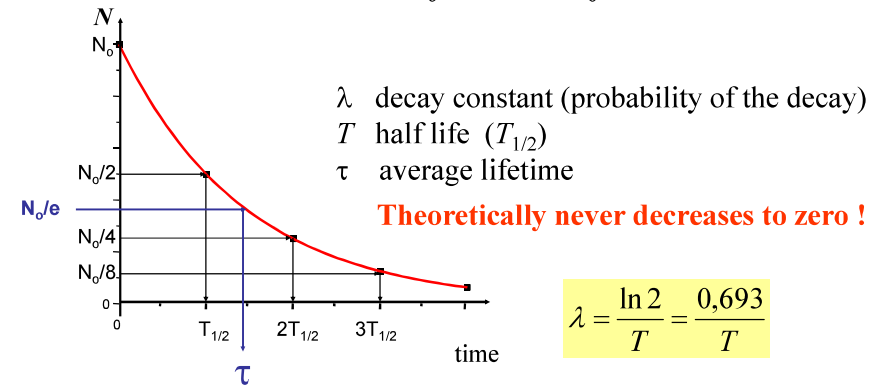
An example

- $N_0 = 10000$ $\lambda = 0,1 \text{ } 1/\text{s}$
- 1 sec 9000
- 2 sec 8100
- 3 sec 7290
- 4 sec 6561
-

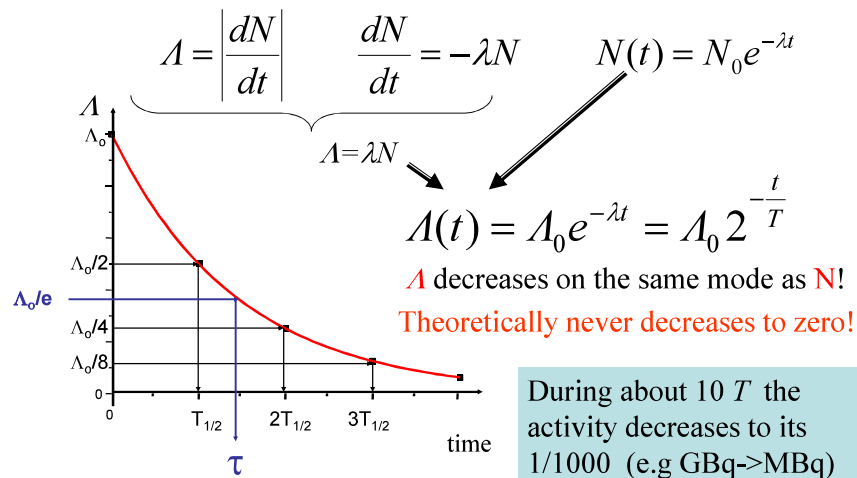


Law of radioactive decay

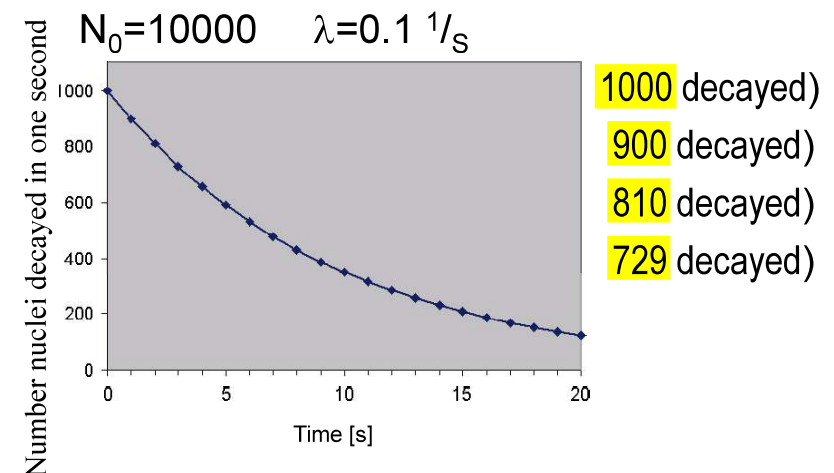
$$N(t) = N_0 e^{-\lambda t} = N_0 2^{-\frac{t}{T}}$$



Decrease of the activity as a function of time



Example



Few examples for half life

^{232}Th	$1,4 \cdot 10^{10} \text{ y}$	^{60}Co	5,3 y
^{238}U	$4,5 \cdot 10^9 \text{ y}$	^{59}Fe	1,5 m
^{40}K	$1,3 \cdot 10^9 \text{ y}$	^{56}Cr	1 m (28 d)
^{14}C	5736 y	^{131}I	8 d
^{137}Cs	30 y	$^{99\text{m}}\text{Tc}$	6 h
^3H	12,3 y	^{18}F	110 min
		^{11}C	20 min
		^{15}O	2 min
		^{222}Th	2,8 ms

Don't learn these numbers!

Typical energy levels in the microworld

Excitation of the outer electrons

eV (aJ)

light



Electron transition between inner electrons

keV (fJ)

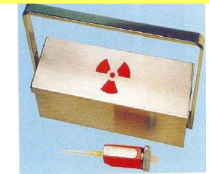
X-ray



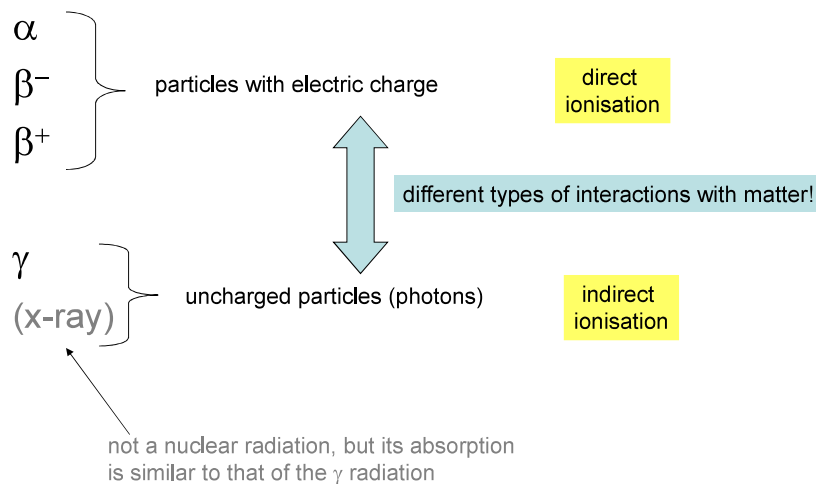
Transformation of the nucleus (decay)

MeV (pJ)

Nuclear radiation
 α , β , γ



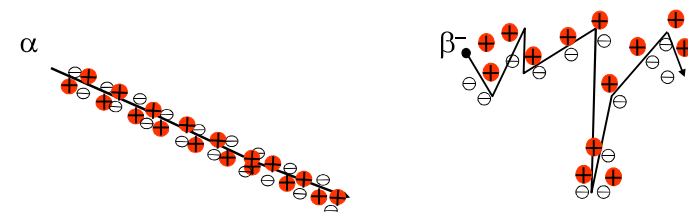
Absorption of the nuclear radiation



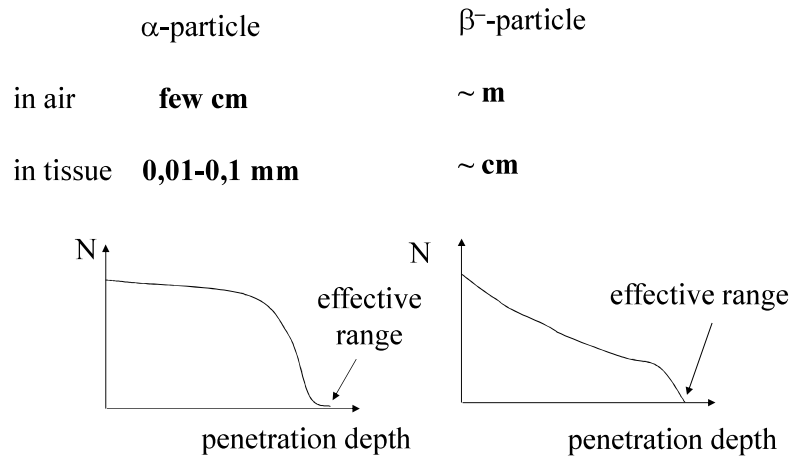
Absorption of the charged particles

Ionizing during the path => continuous decrease of the particle energy
The energy after a given path length decreases to the thermal value

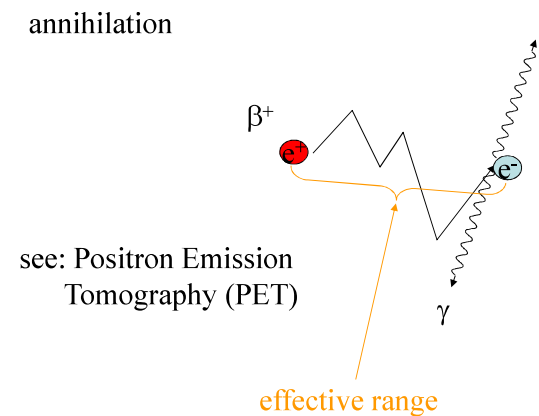
effective range



Effective range

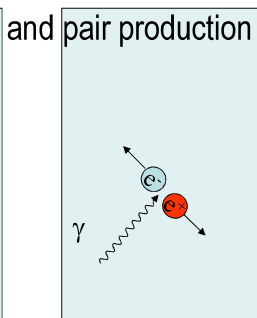
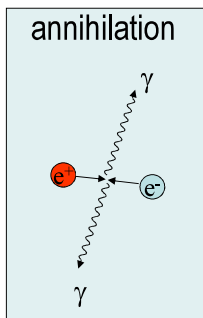


β^+ -radiation



Electron and positron

- particle - antiparticle
- same mass,
- charge: same value, but different

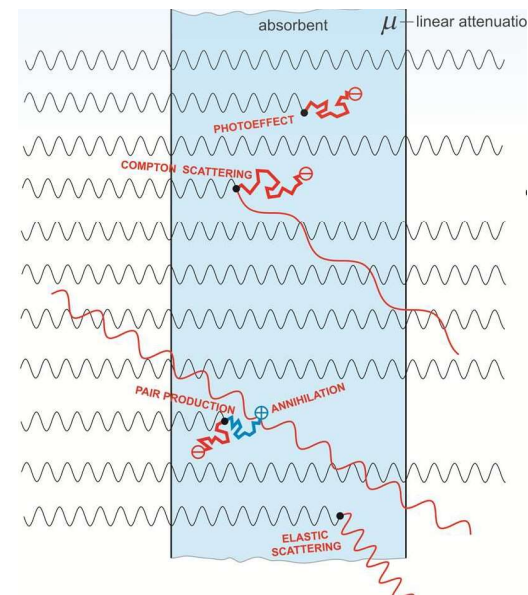


Einstein:
mass-energy
equivalence

$$E=mc^2$$

$$m_e c^2 = 511 \text{ keV} \approx 0,5 \text{ MeV}$$

Absorption of the γ -radiation (and x-ray)



Absorption processes
happen accidentally :

Photoeffect,
Compton-effect,
Pair production,
(elastic scattering)