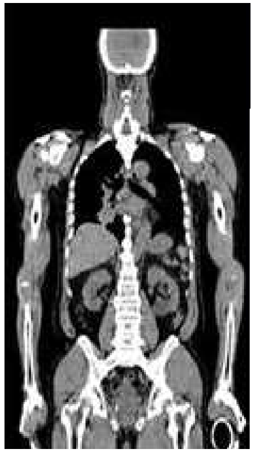
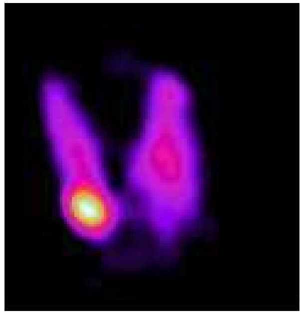
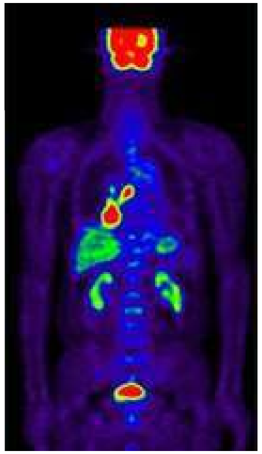
The atomic nucleus. Radioactivity. Nuclear radiations

László Smeller

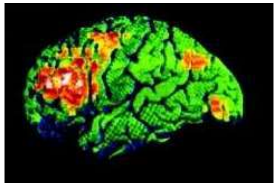




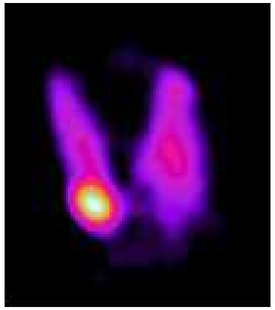


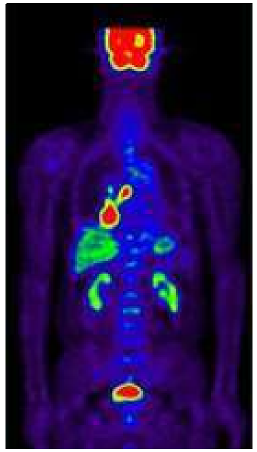
Why?

Medical/pharmaceutical applications of nuclear radiation:

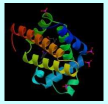
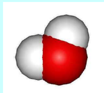
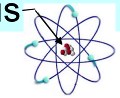


- Nuclear imaging
- Radiotherapy
- Pharmacokinetics

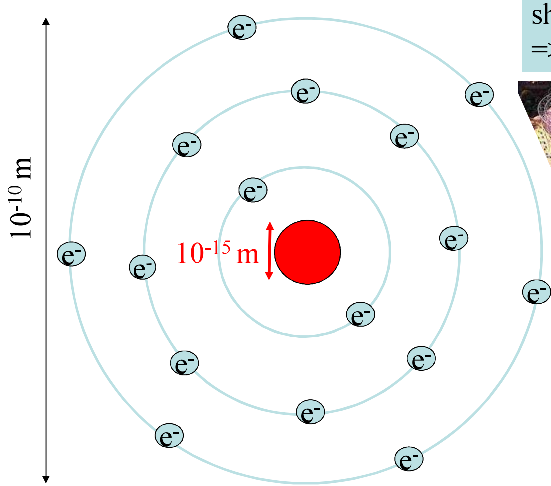




Length scale of the nature

m		
10^{0}	meter	men 
10^{-3}	millimeter	letters you can read
10^{-6}	micrometer	size of a cell (e.g. erytrocyte)  ∅ 7μm
10^{-9}	nanometer	protein 
10^{-10}	– angstrom	diameter of an atom, bond length H atom ∅ ≈ 1 angstrom (Å) 
10^{-12}	picometer	wavelength of the X-ray
10^{-15}	femtometer	size of the nucleus 

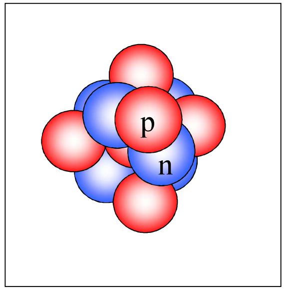
The electrons and the nucleus



Changes in the electron shell:
=>chemical processes

Changes of the nucleus:
=> radioactivity

Structure of the nucleus



Elementary charge=1,6·10^{-19} 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

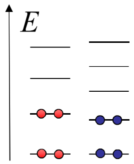
$^{99}_{43}$Tc

99 nucleon, 43 proton and 56 neutron

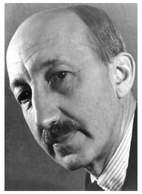
Stability of the nucleus

- Coulomb force: destabilization
  (electrostatic repulsion between the protons)
- Nuclear force: very strong
  attractive force
  acts only on short range (~fm)
  independent on the charge

- Quantized energy levels for the nucleus.
- Typical binding energy is in the MeV range
  eV=1,6·10^{-19} J



Isotopes



Number of protons is the same

Number of neutrons is different

Variants of the same element

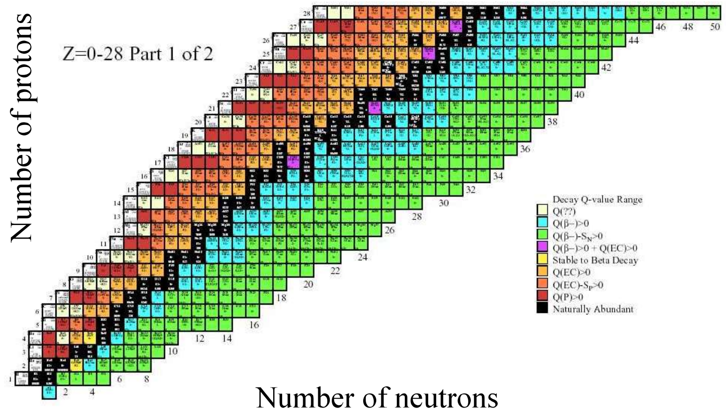
⇒ the chemical properties are identical.

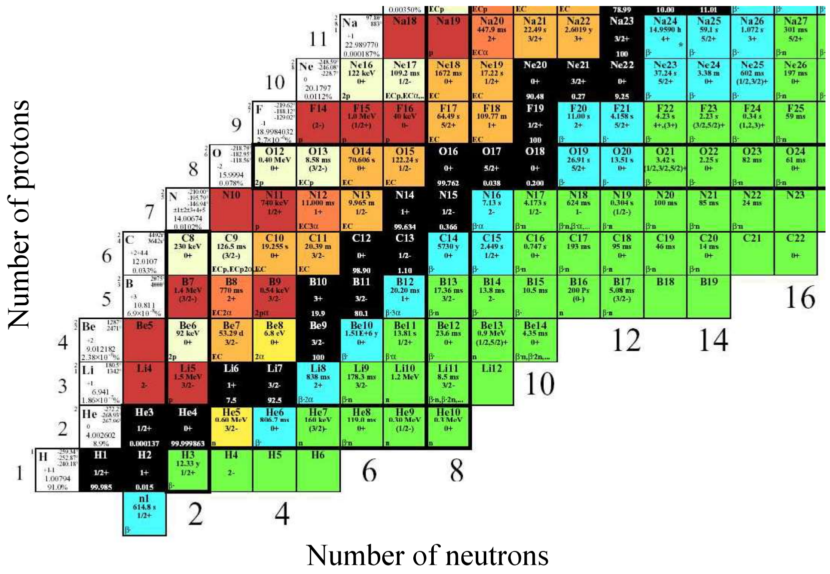
Pl: $^{18}_{9}$F unstable (radioactive) $^{19}_{9}$F stable $^{20}_{9}$F unstable (radioactive)

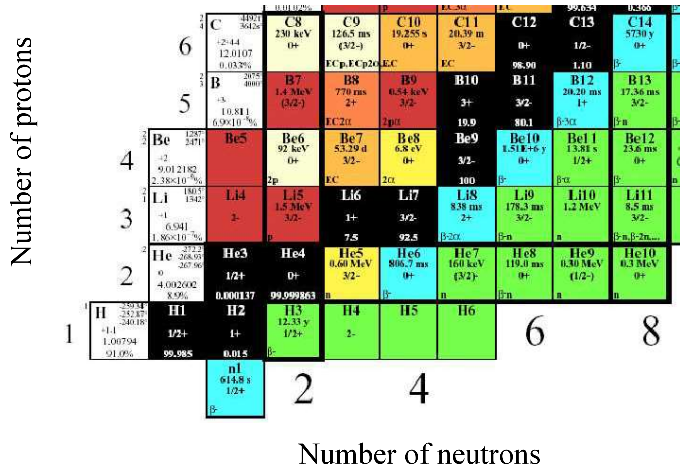
$^{18}_{9}$F	$^{19}_{9}$F	$^{20}_{9}$F
unstable (radioactive)	stable	unstable (radioactive)

isotope <-> radioactive isotope

Table of isotopes







Radioactive decays and particles

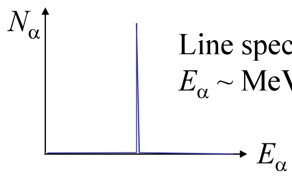
α - decay	α - particle =	${}^{4}_{2}\mathrm{He}$ nucleus
β - decay : β^-	β^- particle =	electron
β^+	β^+ particle =	positron
Isomeric transition		γ-ray
K-electron capture		characteristic x-ray photon

α - decay

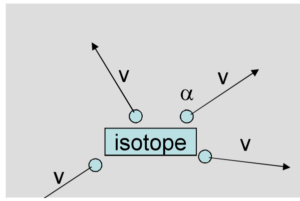
α - decay: an α particle (${}^{4}\mathrm{He}$ nucleus) will be emitted typical for the heavy atoms

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

e.g. $$ {}^{226}_{88}\mathrm{Ra} \longrightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\alpha $$

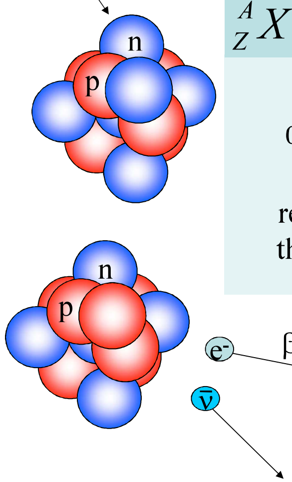


Line spectrum
$E_\alpha \sim$ MeV



β^- - decay

neutron surplus



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

$${}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}\beta + \bar{\nu}$$

remains in the nucleus — leave the nucleus

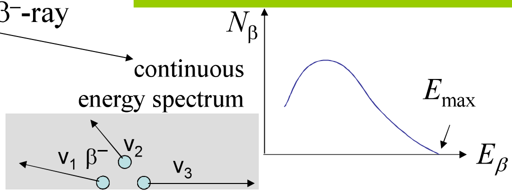
e.g.: ${}^{20}_{9}F$, ${}^{32}_{15}P$, ${}^{59}_{26}Fe$, ${}^{131}_{53}I$

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

β^--ray

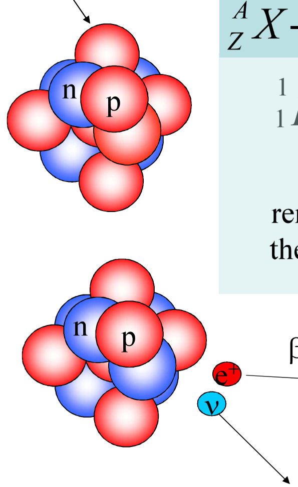
continuous energy spectrum

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



β^+ - decay

proton surplus



$${}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}\beta + \nu$$

$${}^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}\beta + \nu$$

remains in the nucleus — leave the nucleus

e.g.: ${}^{11}_{6}C$, ${}^{15}_{8}O$, ${}^{18}_{9}F$, ${}^{52}_{26}Fe$

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

β^+-ray

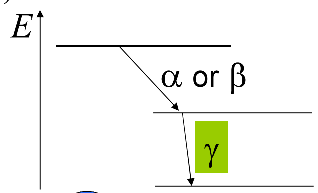
continuous energy spectrum

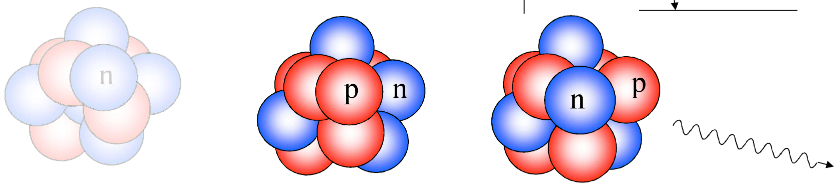
These isotopes must be produced artificially (e.g. in cyclotron)

Prompt γ-radiation

The daughter nucleus might have an energetically unfavoured arrangement of nucleons. (excited state)

The surplus energy will normally be emitted immediately (<ps) in form of the γ radiation





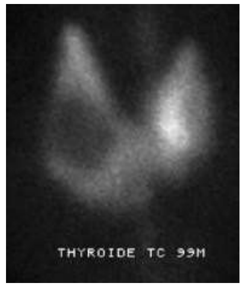
Atomic number, mass number are unchanged.

Isomeric transition

In some rare cases 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)

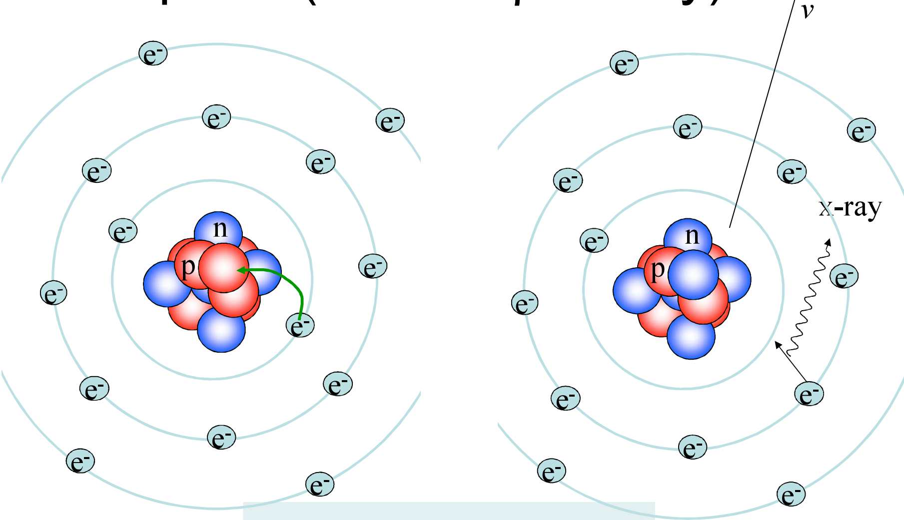


E.g.: ${}^{99m}\mathrm{Tc}$

$${}^{99}_{42}Mo \xrightarrow{\beta^-} {}^{99m}_{43}Tc \xrightarrow{\gamma} {}^{99}_{43}Tc$$

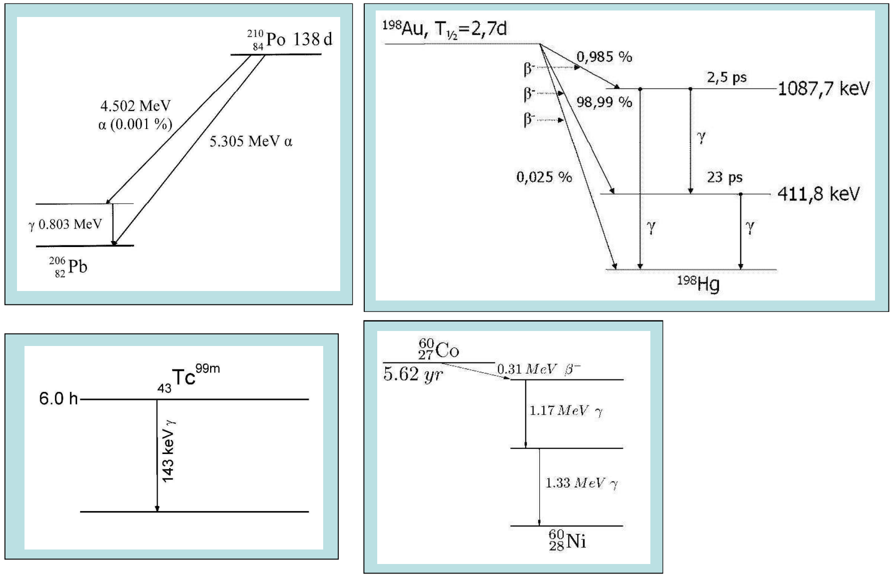
66 h — 6 h

K-capture (inverse β-decay)



$$ {}_{1}^{1}p + {}_{-1}^{0}\beta \rightarrow {}_{0}^{1}n + \nu $$

Some examples of the decay paths



How to produce radioactive isotopes?

β⁻ decaying:

n surplus → irradiate by neutrons
(in a nuclear reactor)

β⁺ decaying:

p surplus → irradiate by protons

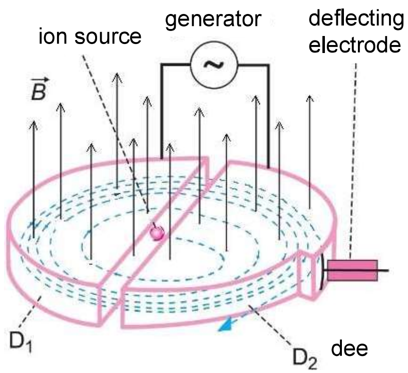
Coulomb repulsion → you need accelerated protons!

→ cyclotron

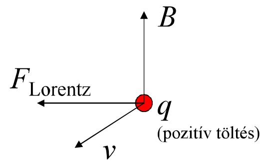
Cyclotron

Protons or alpha particles are accelerated on a spiral path.

Tipical energy: few 10 MeV (max 50 MeV)



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



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

Characteristics of radioactive decays in general

activity	characterizes the source
decay type	characterizes the source* (see above)
half life time	characterizes the speed of the decay*
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

immeasurably small

kBq, MBq, GBq, TBq

level of natural activity — in vivo diagn. — careful work with it! — activity applied in radiotherapy

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

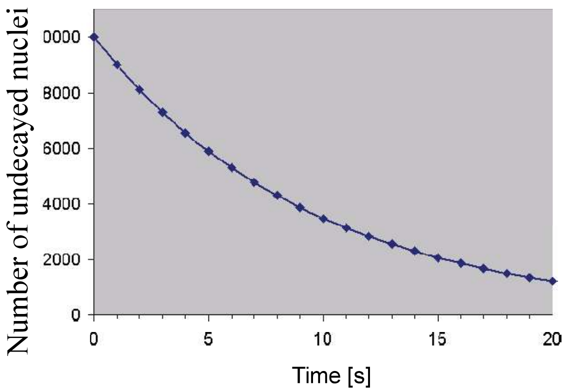
number of undecayed atoms at t=0

An example

- N_0=10000 λ=0.1 $^1/_s$
- After 1 sec : 9000 (10000x0.1=1000 decayed)
- After 2 sec : 8100 (9000x0.1=900 decayed)
- After 3 sec : 7290 (8100x0.1=810 decayed)
- After 4 sec : 6561 (7290x0.1=729 decayed)
- ….

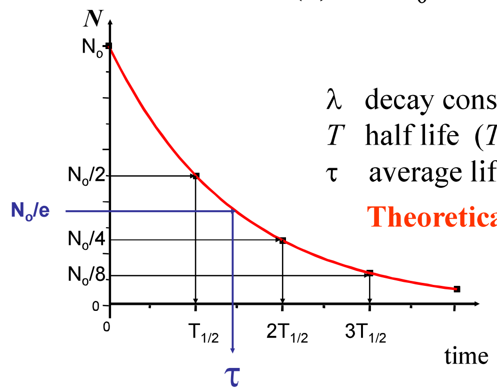
An example

- N_0=10000 λ=0,1 $^1/_s$
- 1 sec 9000
- 2 sec 8100
- 3 sec 7290
- 4 sec 6561
- ....



Law of radioactive decay

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



λ decay constant (probability of the decay)

T half life ($T_{1/2}$)

τ average lifetime

Theoretically never decreases to zero !

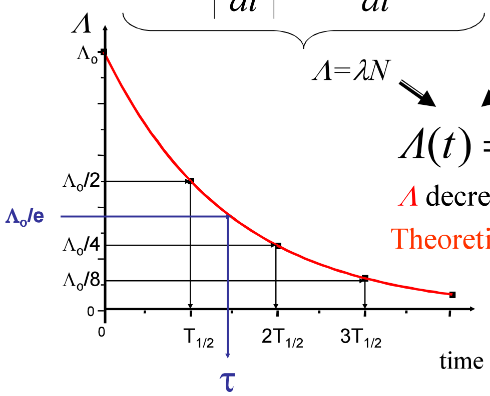
$$\lambda = \frac{\ln 2}{T} = \frac{0{,}693}{T}$$

Decrease of the activity as a function of time

$$\Lambda = \left|\frac{dN}{dt}\right| \qquad \frac{dN}{dt} = -\lambda N \qquad N(t) = N_0 e^{-\lambda t}$$

$\Lambda = \lambda N$

$$\Lambda(t) = \Lambda_0 e^{-\lambda t} = \Lambda_0 2^{-\frac{t}{T}}$$



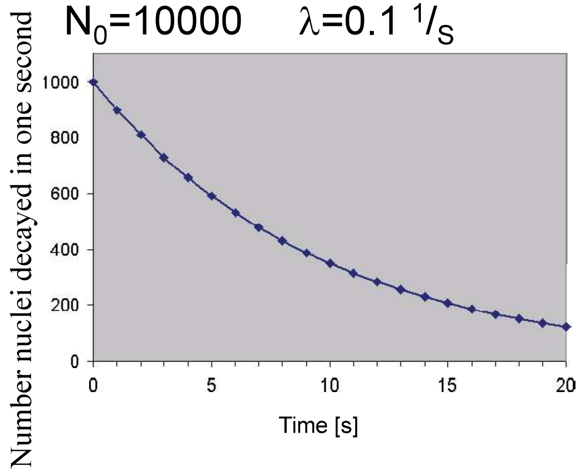
Λ decreases on the same mode as N!

Theoretically never decreases to zero!

During about 10 T the activity decreases to its 1/1000 (e.g GBq->MBq)

Example

N_0=10000 λ=0.1 $^1/_s$



1000 decayed)

900 decayed)

810 decayed)

729 decayed)

Few examples for half life

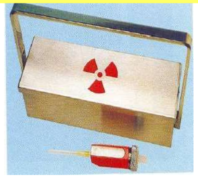
^{232}Th	$1,4 \cdot 10^{10}$ y	^{60}Co	5,3 y
^{238}U	$4,5 \cdot 10^{9}$ y	^{59}Fe	1,5 m
^{40}K	$1,3 \cdot 10^{9}$ y	^{56}Cr	1 m (28 d)
^{14}C	5736 y	^{131}I	8 d
^{137}Cs	30 y	^{99m}Tc	6 h
^{3}H	12,3 y	^{18}F	110 min
		^{11}C	20 min
		^{15}O	2 min
		^{222}Th	2,8 ms

Don’t learn these numbers!

Typical energy levels in the microworld

Excitation of the outer electrons	Electron transition between inner electrons	Transformation of the nucleus (decay)
eV (aJ)	keV (fJ)	MeV (pJ)
light	X-ray	Nuclear radiation α, β, γ





Absorption of the nuclear radiation

α, β⁻, β⁺ — particles with electric charge — direct ionisation

different types of interactions with matter!

Different attenuation characteristics!

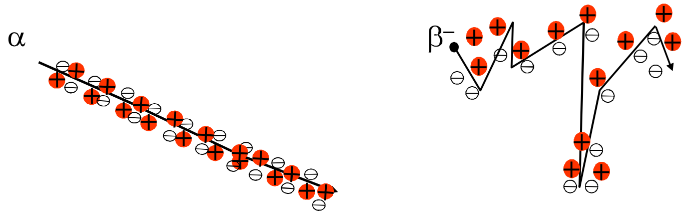
γ, (x-ray) — uncharged particles (photons) — indirect ionisation

not a nuclear radiation, but its absorption is similar to that of the γ radiation

Absorption of the charged particles

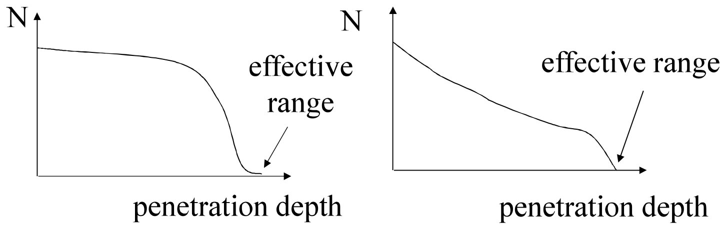
Ionizing during the path => continuous decrease of the particle energy
The energy after a given path length decreases to the thermal value

effective range



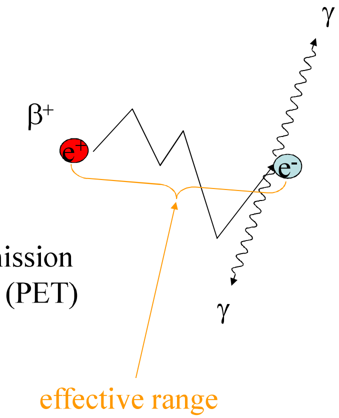
Effective range

	α-particle	β⁻-particle
in air	**few cm**	**~ m**
in tissue	**0,01-0,1 mm**	**~ cm**



β^+-radiation

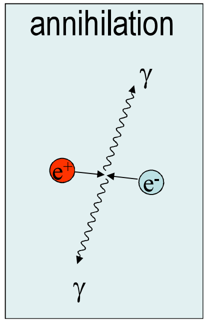
annihilation



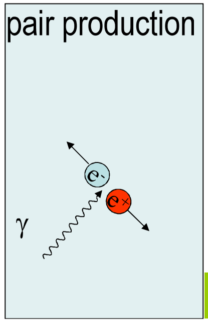
see: Positron Emission Tomography (PET)

Electron and positron

- particle - antiparticle
- same mass,
- charge: same value, but differen [redacted]



and



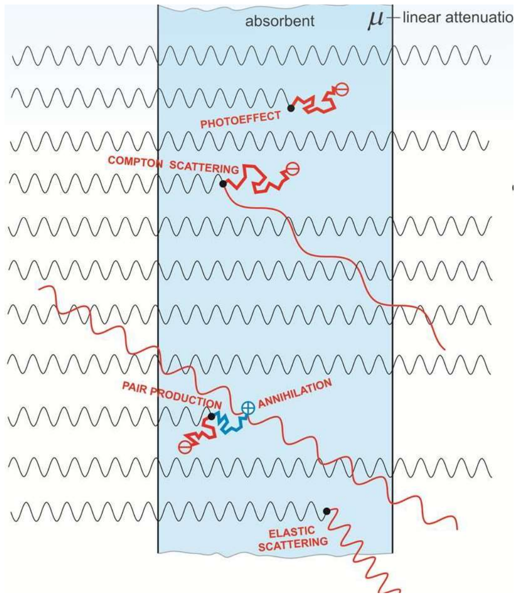
Einstein:

mass-energy ekvivalence

$$E=mc^2$$

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

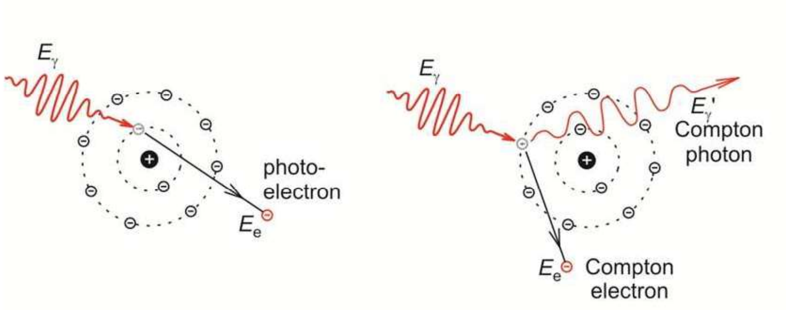
Absorption of the γ-radiation (and x-ray)



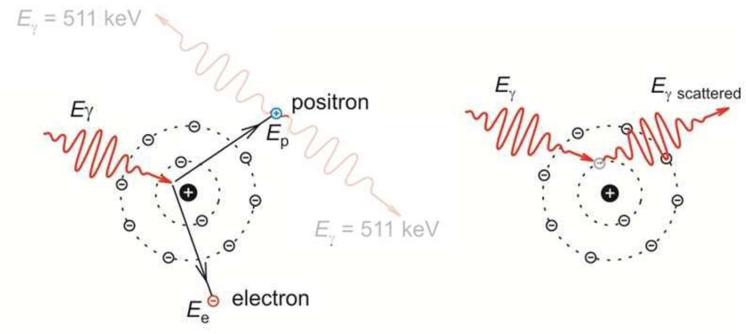
Absorption processes happen accidentally :

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

Photoeffect | **Compton effect Compton-scattering**

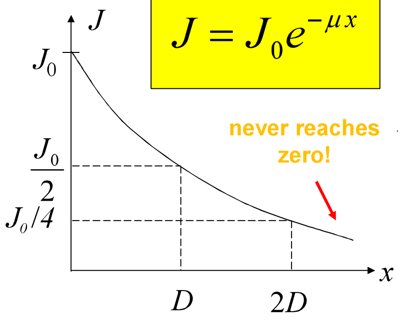


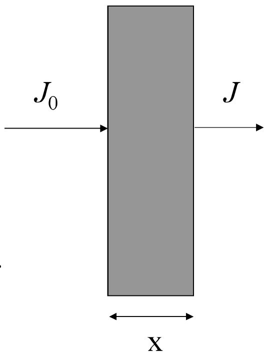
Pair production | **elastic scattering**



Attenuation of the γ–radiation and x-ray

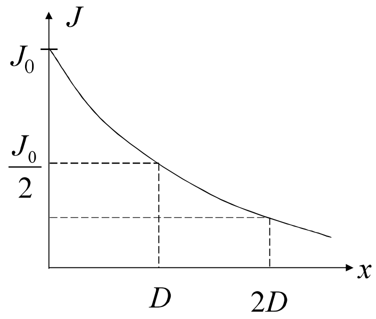
$$J = J_0 e^{-\mu x}$$





no limited effective range!

few rules of thumb: $x_{1/10}$=3,33 D $x_{1/1000}$=10 D



$$J = J_0 e^{-\mu x}$$

μ: (linear) attenuation coefficient

its units are: 1/m, 1/cm

$\delta = \frac{1}{\mu}$ „penetration depth"

Intensity decreases to the *e*-th part (c.a. 37%)

μ(material, number of absorbing centers, energy of the radiation)

=μ(material,ρ,E_{photon}) ~ ρ

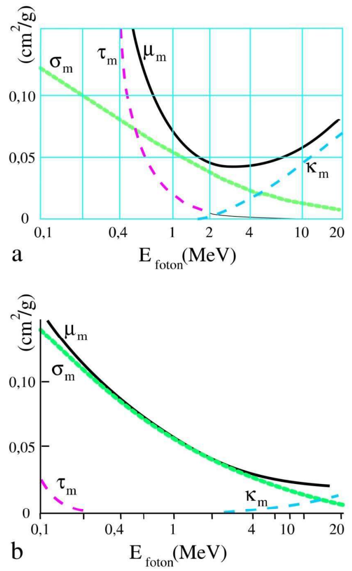
$$\mu_m = \frac{\mu}{\rho}$$ mass attenuation coefficient

mass attenuation coeff.

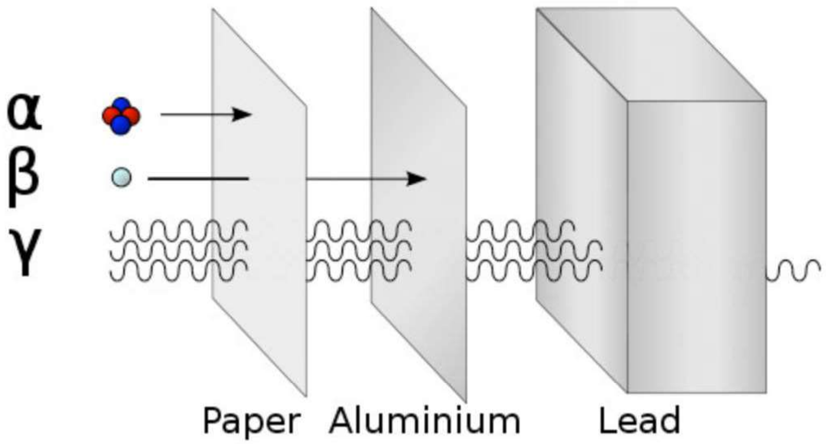
$$\mu_m = \frac{\mu}{\rho}$$

$$\mu_m = \tau_m + \sigma_m + \kappa_m$$

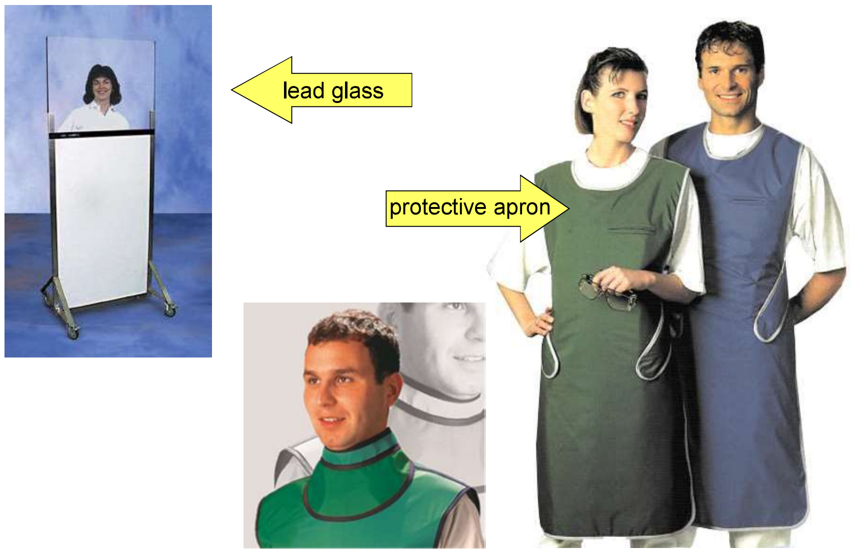
$$\tau_m = c\lambda^3 Z^3$$



Summary of the absorption of α, β and γ radiation



Applications (attenuation)



Applications: isotopes and nuclear radiation