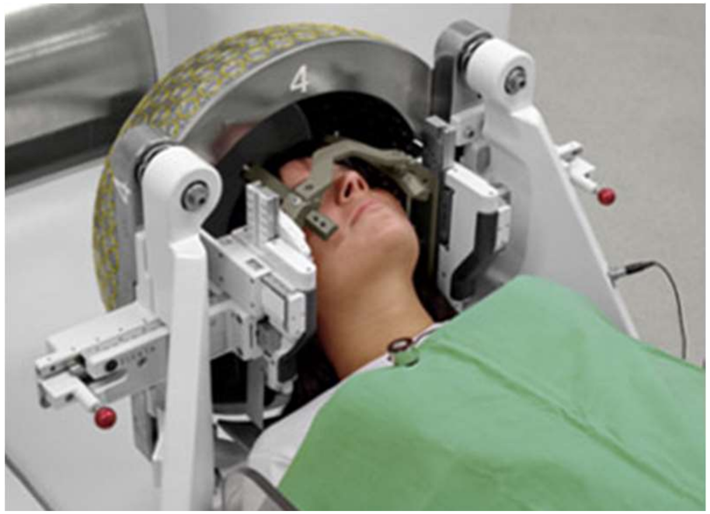
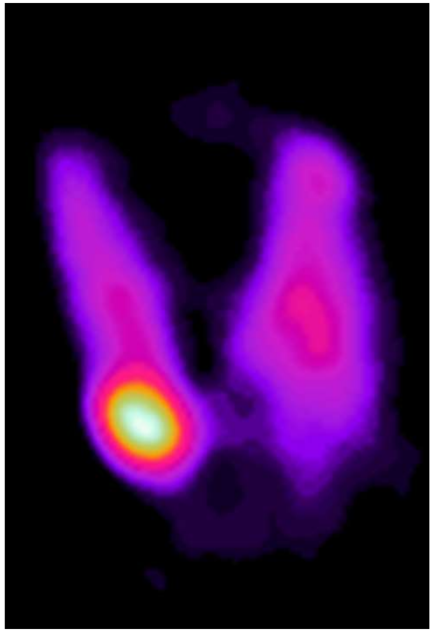
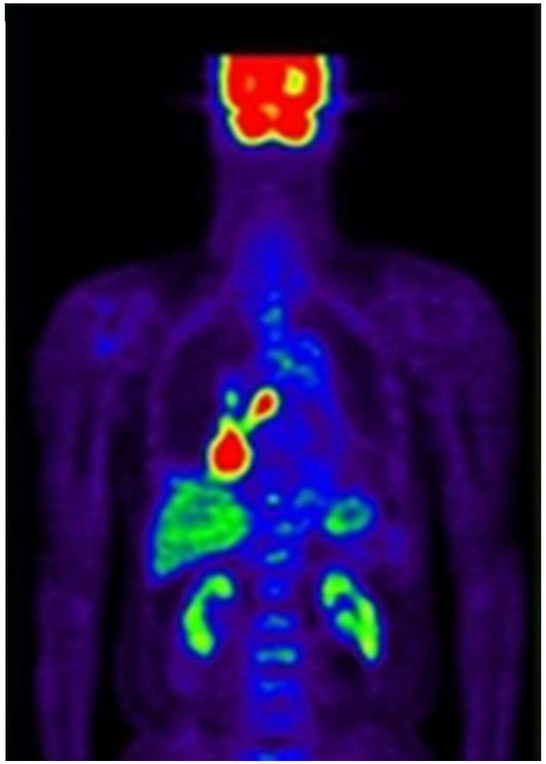
The atomic nucleus. Radioactivity. Nuclear radiations

László Smeller



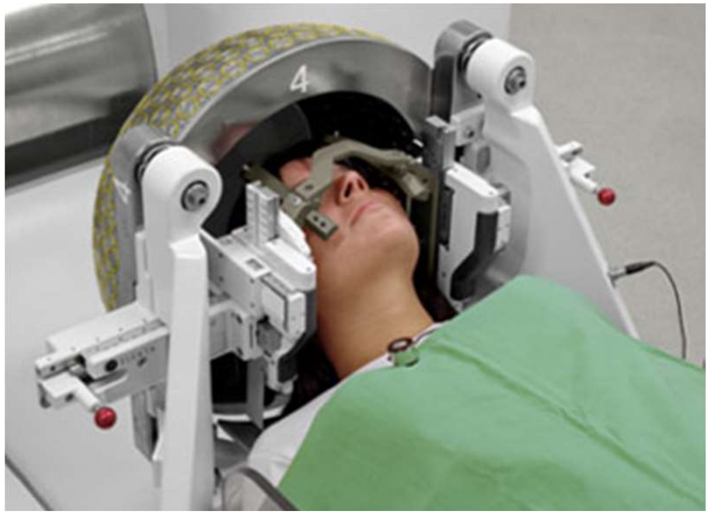


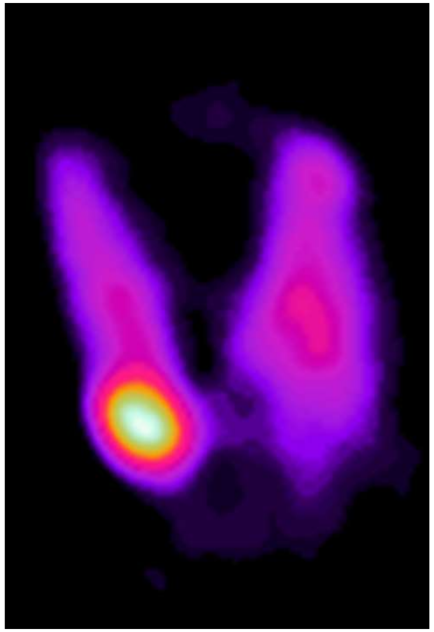


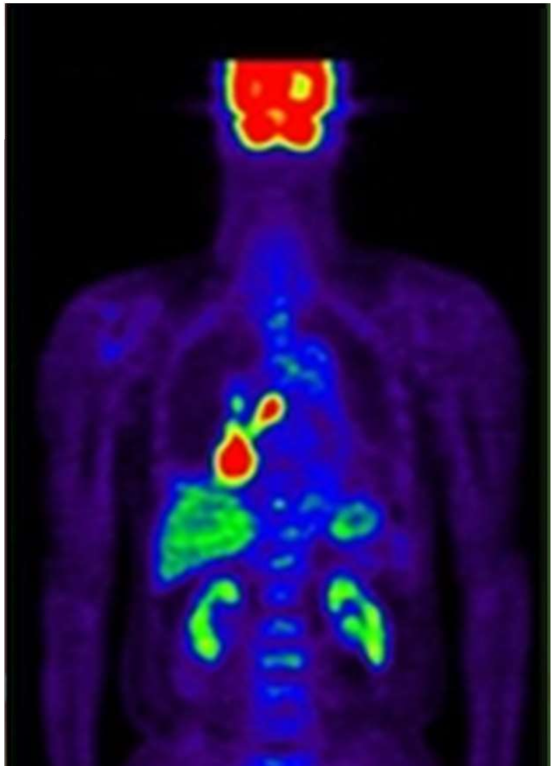
Why?

Medical applications of the nuclear radiation:

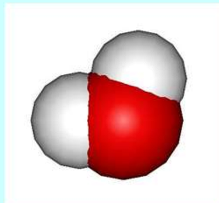
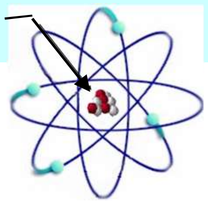
- Nuclear imaging
- Radiotherapy



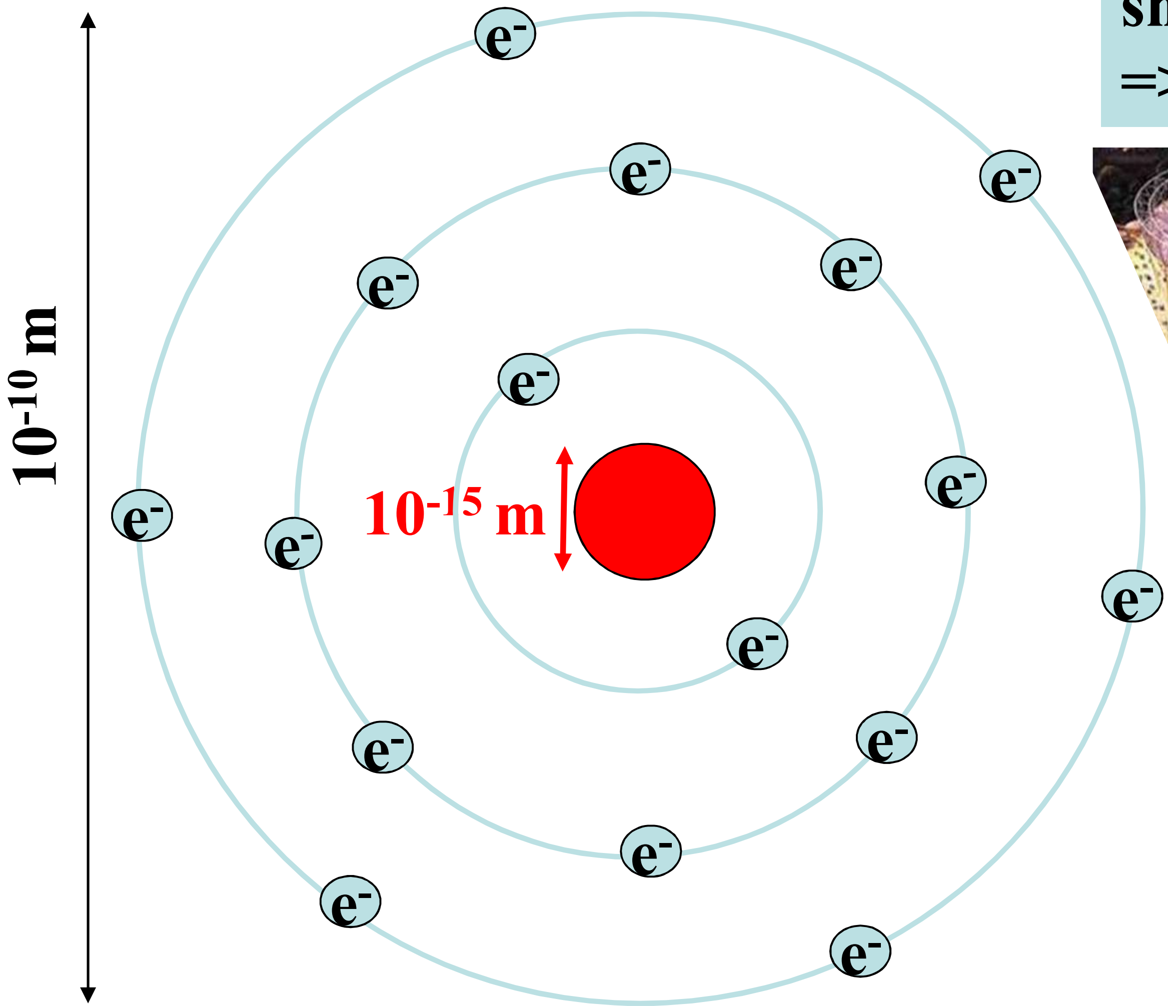




Length scale of the nature

m		
10^{0}	meter	men 
10^{-3}	millimeter	size of 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

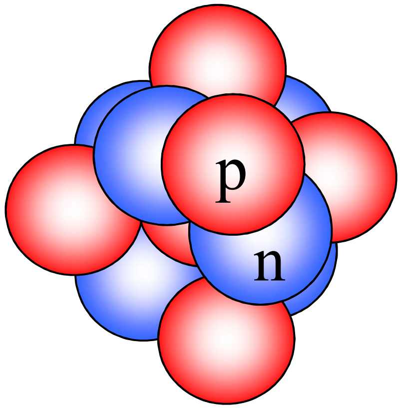


Changes in the electron shell:
=>chemical processes

Changes of the nucleus:
=> radioactivity

Structure of the nucleus

Elementary charge=$1.6 \cdot 10^{-19}$ 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

$^{99}_{43}\mathbf{Tc}$

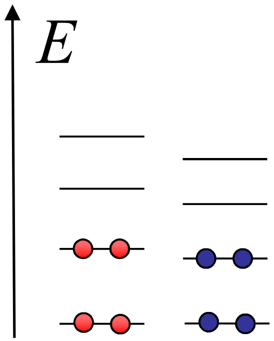
99 nucleon, 43 proton and 56 neutron

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.



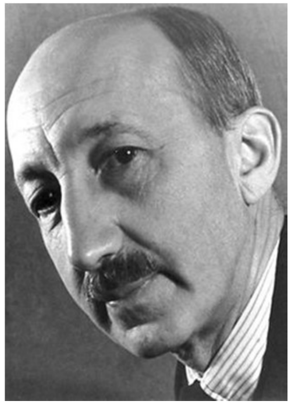
- Typical binding energy is in the MeV range
  $eV=1.6\cdot10^{-19}$ J

Isotopes

Variants of an element, wich differ in

- number of neutrons

=> mass number



György Hevesy
Nobel prize 1943

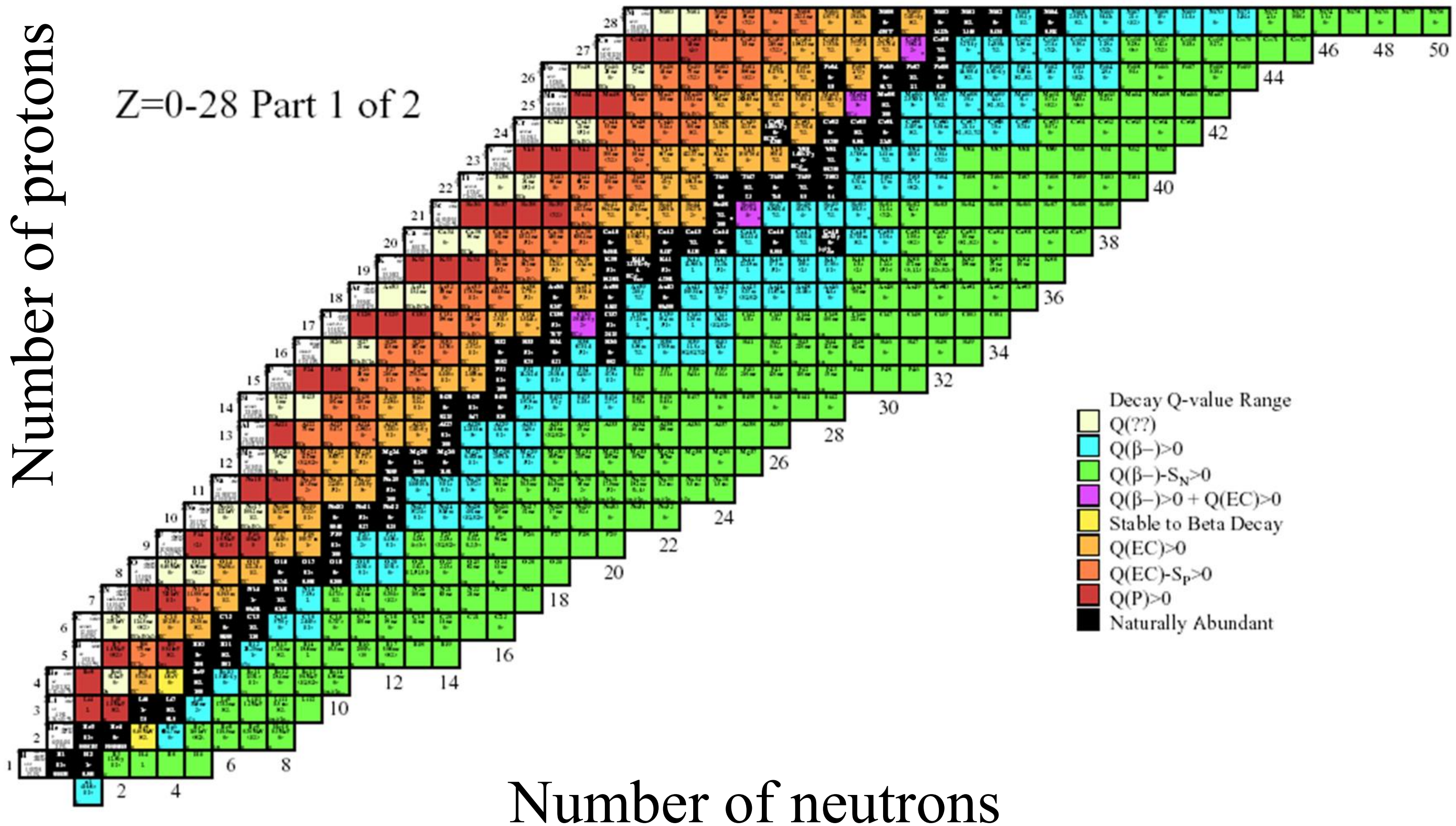
Remark:
The numbers of protons (=atomic numbers) are the same.

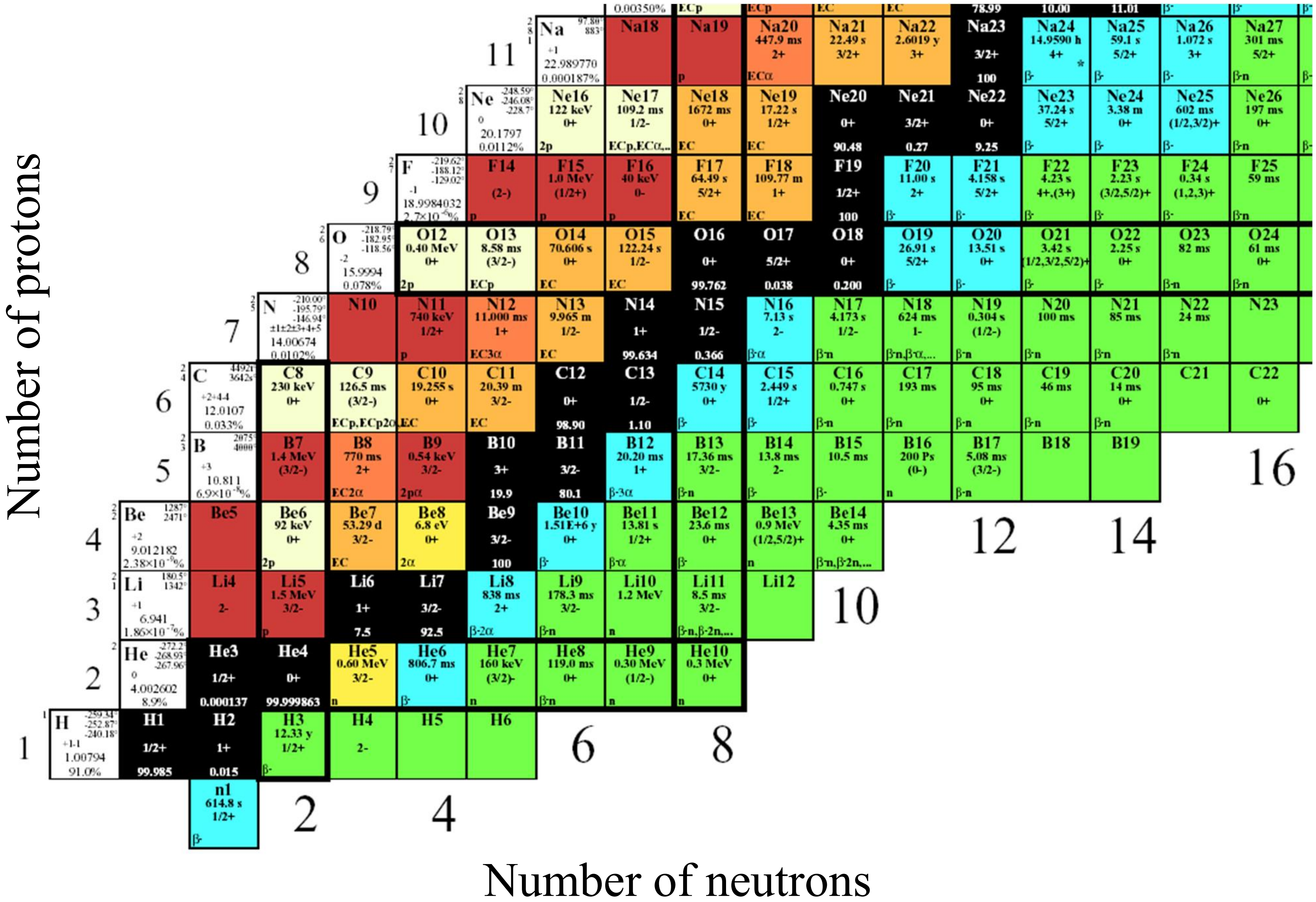
E.g.: ${}^{18}_{9}\mathrm{F}$ ${}^{19}_{9}\mathrm{F}$ ${}^{20}_{9}\mathrm{F}$

unstable (radioactive) | stable | unstable (radioactive)

isotope <-> radioactive isotope

Table of isotopes

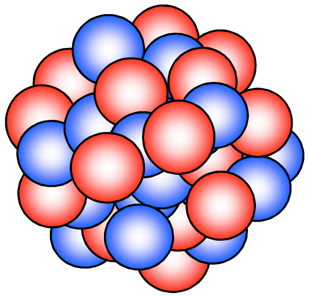




Number of protons
Number of neutrons
1
2
3
4
5
6
7
8
9
10
11
2
4
6
8
10
12
14
16
H 1.00794 91.0%
He 4.002602 8.9%
Li 6.941
Be 9.012182
B 10.811
C 12.0107 0.033%
N 14.00674
O 15.9994 0.078%
F 18.9984032
Ne 20.1797 0.0112%
Na 22.989770 0.000187%
n1 614.8 s 1/2+ β-
H1 1/2+ 99.985
H2 1+ 0.015
H3 12.33 y 1/2+ β-
H4 2-
H5
H6
He3 1/2+ 0.000137
He4 0+ 99.999863
He5 0.60 MeV 3/2- n
He6 806.7 ms 0+ β-
He7 160 keV (3/2)- n
He8 119.0 ms 0+ β-n
He9 0.30 MeV (1/2-) n
He10 0.3 MeV 0+ n
Li4 2-
Li5 1.5 MeV 3/2- p
Li6 1+ 7.5
Li7 3/2- 92.5
Li8 838 ms 2+ β-2α
Li9 178.3 ms 3/2- β-n
Li10 1.2 MeV n
Li11 8.5 ms 3/2- β-n,β-2n,...
Li12
Be5
Be6 92 keV 0+ 2p
Be7 53.29 d 3/2- EC
Be8 6.8 eV 0+ 2α
Be9 3/2- 100
Be10 1.51E+6 y 0+ β-
Be11 13.81 s 1/2+ β-α
Be12 23.6 ms 0+ β-
Be13 0.9 MeV (1/2,5/2)+ n
Be14 4.35 ms 0+ β-n,β-2n,...
B7 1.4 MeV (3/2-)
B8 770 ms 2+ EC2α
B9 0.54 keV 3/2- 2pα
B10 3+ 19.9
B11 3/2- 80.1
B12 20.20 ms 1+ β-3α
B13 17.36 ms 3/2- β-n
B14 13.8 ms 2- β-
B15 10.5 ms β-
B16 200 Ps (0-) n
B17 5.08 ms (3/2-) β-n
B18
B19
C8 230 keV 0+
C9 126.5 ms (3/2-) ECp,ECp2α
C10 19.255 s 0+ EC
C11 20.39 m 3/2- EC
C12 0+ 98.90
C13 1/2- 1.10
C14 5730 y 0+ β-
C15 2.449 s 1/2+ β-
C16 0.747 s 0+ β-n
C17 193 ms β-n
C18 95 ms 0+ β-n
C19 46 ms β-n
C20 14 ms 0+ β-n
C21
C22 0+
N10
N11 740 keV 1/2+ p
N12 11.000 ms 1+ EC3α
N13 9.965 m 1/2- EC
N14 1+ 99.634
N15 1/2- 0.366
N16 7.13 s 2- β-α
N17 4.173 s 1/2- β-n
N18 624 ms 1- β-n,β-α,...
N19 0.304 s (1/2-) β-n
N20 100 ms β-n
N21 85 ms β-n
N22 24 ms β-n
N23
O12 0.40 MeV 0+ 2p
O13 8.58 ms (3/2-) ECp
O14 70.606 s 0+ EC
O15 122.24 s 1/2- EC
O16 0+ 99.762
O17 5/2+ 0.038
O18 0+ 0.200
O19 26.91 s 5/2+ β-
O20 13.51 s 0+ β-
O21 3.42 s (1/2,3/2,5/2)+ β-
O22 2.25 s 0+ β-
O23 82 ms β-n
O24 61 ms 0+ β-n
F14 (2-) p
F15 1.0 MeV (1/2+) p
F16 40 keV 0- p
F17 64.49 s 5/2+ EC
F18 109.77 m 1+ EC
F19 1/2+ 100
F20 11.00 s 2+ β-
F21 4.158 s 5/2+ β-
F22 4.23 s 4+,(3+) β-
F23 2.23 s (3/2,5/2)+ β-
F24 0.34 s (1,2,3)+ β-
F25 59 ms β-n
Ne16 122 keV 0+ 2p
Ne17 109.2 ms 1/2- ECp,ECα,...
Ne18 1672 ms 0+ EC
Ne19 17.22 s 1/2+ EC
Ne20 0+ 90.48
Ne21 3/2+ 0.27
Ne22 0+ 9.25
Ne23 37.24 s 5/2+ β-
Ne24 3.38 m 0+ β-
Ne25 602 ms (1/2,3/2)+ β-
Ne26 197 ms 0+ β-n
Na18
Na19 p
Na20 447.9 ms 2+ ECα
Na21 22.49 s 3/2+
Na22 2.6019 y 3+
Na23 3/2+ 100
Na24 14.9590 h 4+ β-
Na25 59.1 s 5/2+ β-
Na26 1.072 s 3+ β-
Na27 301 ms 5/2+ β-n

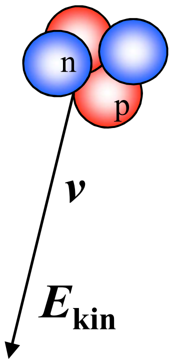
Radioactive decays and particles

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



α - decay

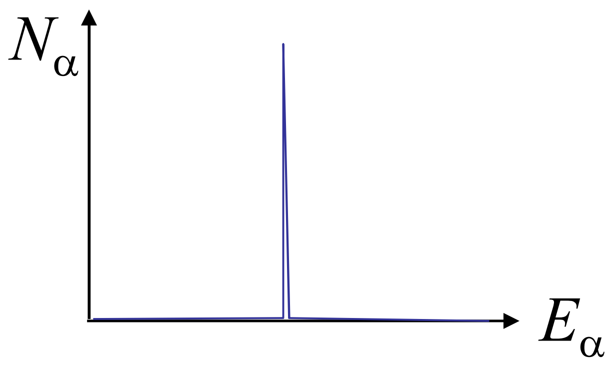
an α particle (^{4}He nucleus) will be emitted
typical for the heavy atoms



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

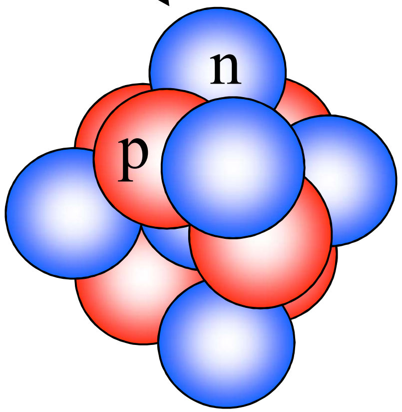
e.g. $$ {}^{226}_{88}\mathrm{Ra} \longrightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\alpha $$

Line spectrum
$E_{\alpha} \sim$ MeV



β^{-} - decay

neutron surplus



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

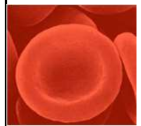
$$^{1}_{0}n \rightarrow {}^{1}_{1}p + {}_{-1}\beta + \overline{\nu}$$

remains in the nucleus

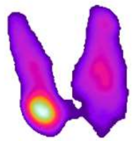
leave the nucleus

e.g.: $^{20}_{9}F$

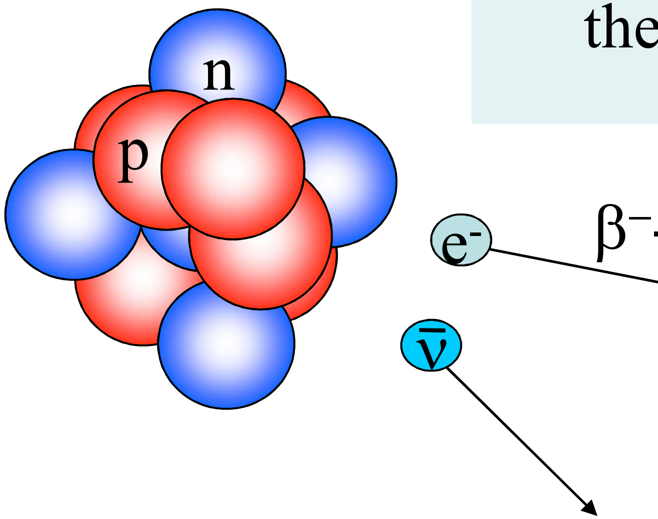
$^{32}_{15}P$



$^{59}_{26}Fe$



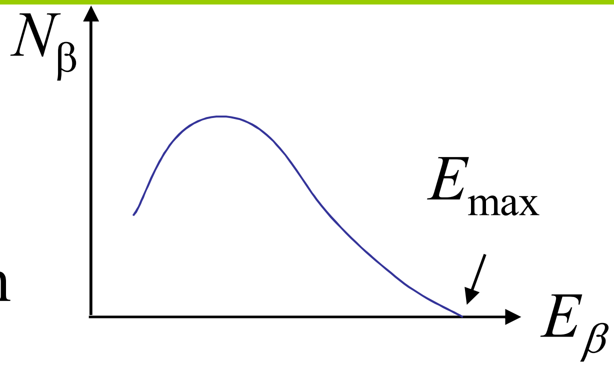
$^{131}_{53}I$



β^{-}-ray

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

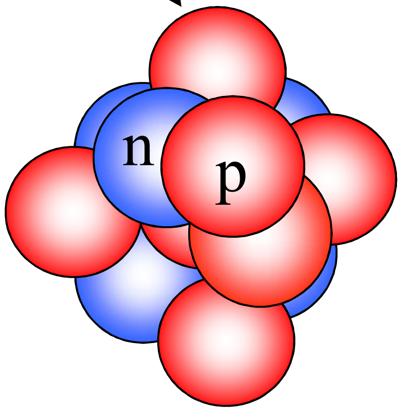
continous energy spectrum



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

β^+ - decay

proton surplus



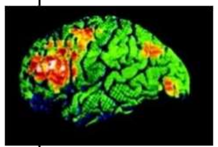
$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y + {}_{+1}\beta + \nu $$

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

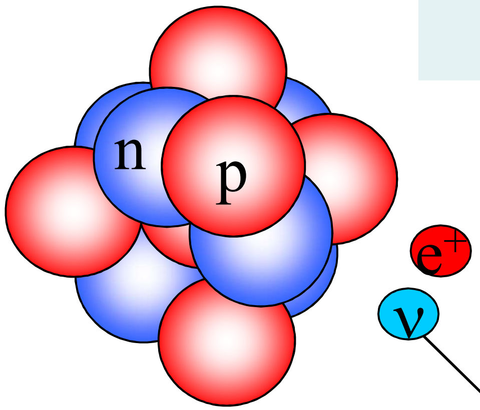
remains in the nucleus

leave the nucleus

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



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

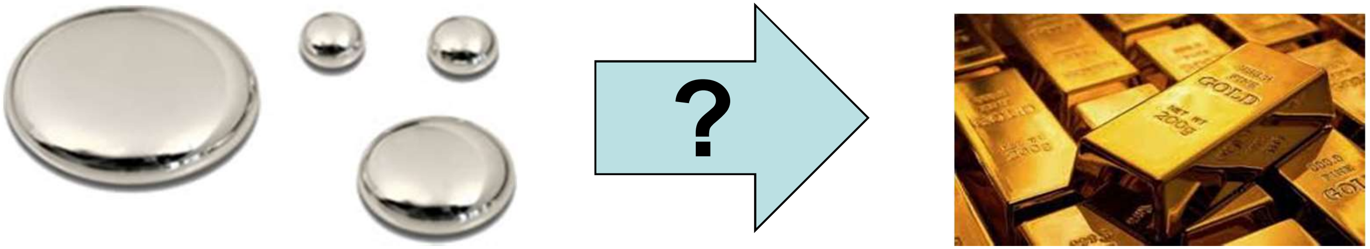


β^+-ray

continous energy spectrum

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

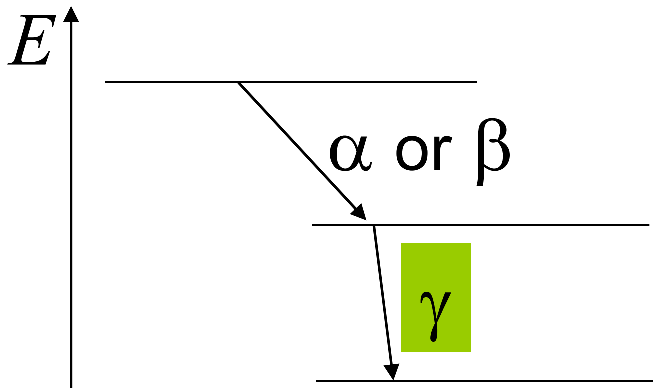
Mecial application: PET

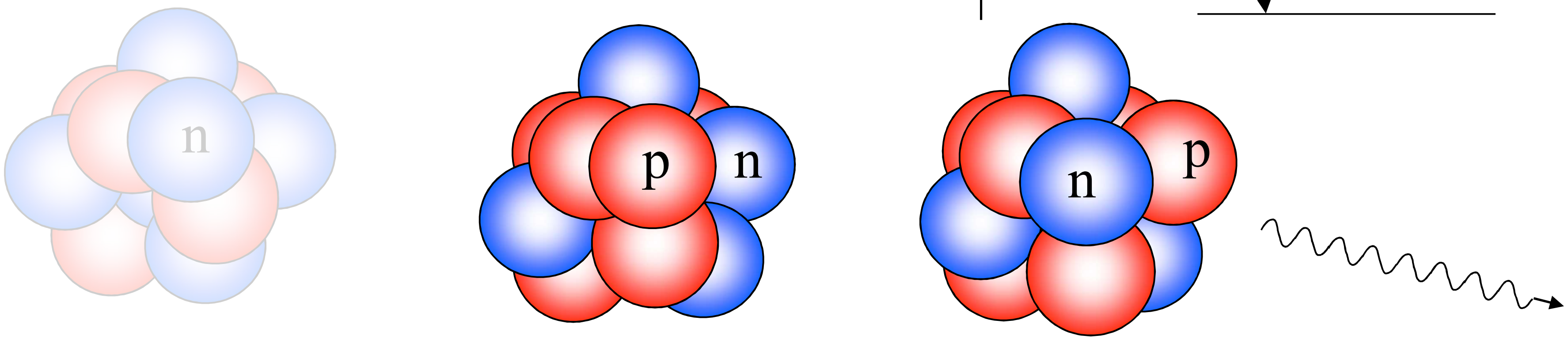


Prompt γ-radiation

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





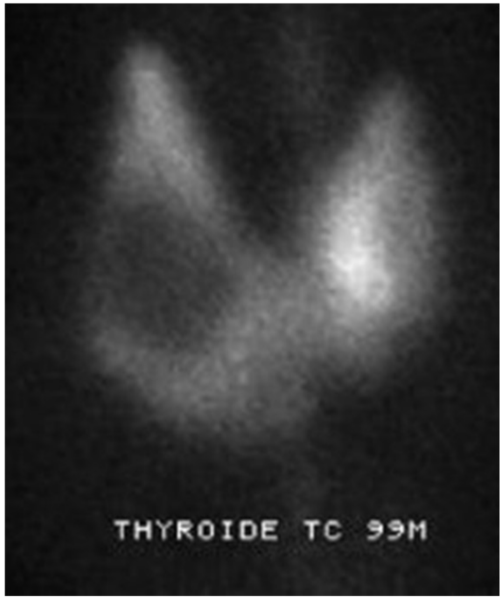
Atomic number, mass number are unchanged.

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)

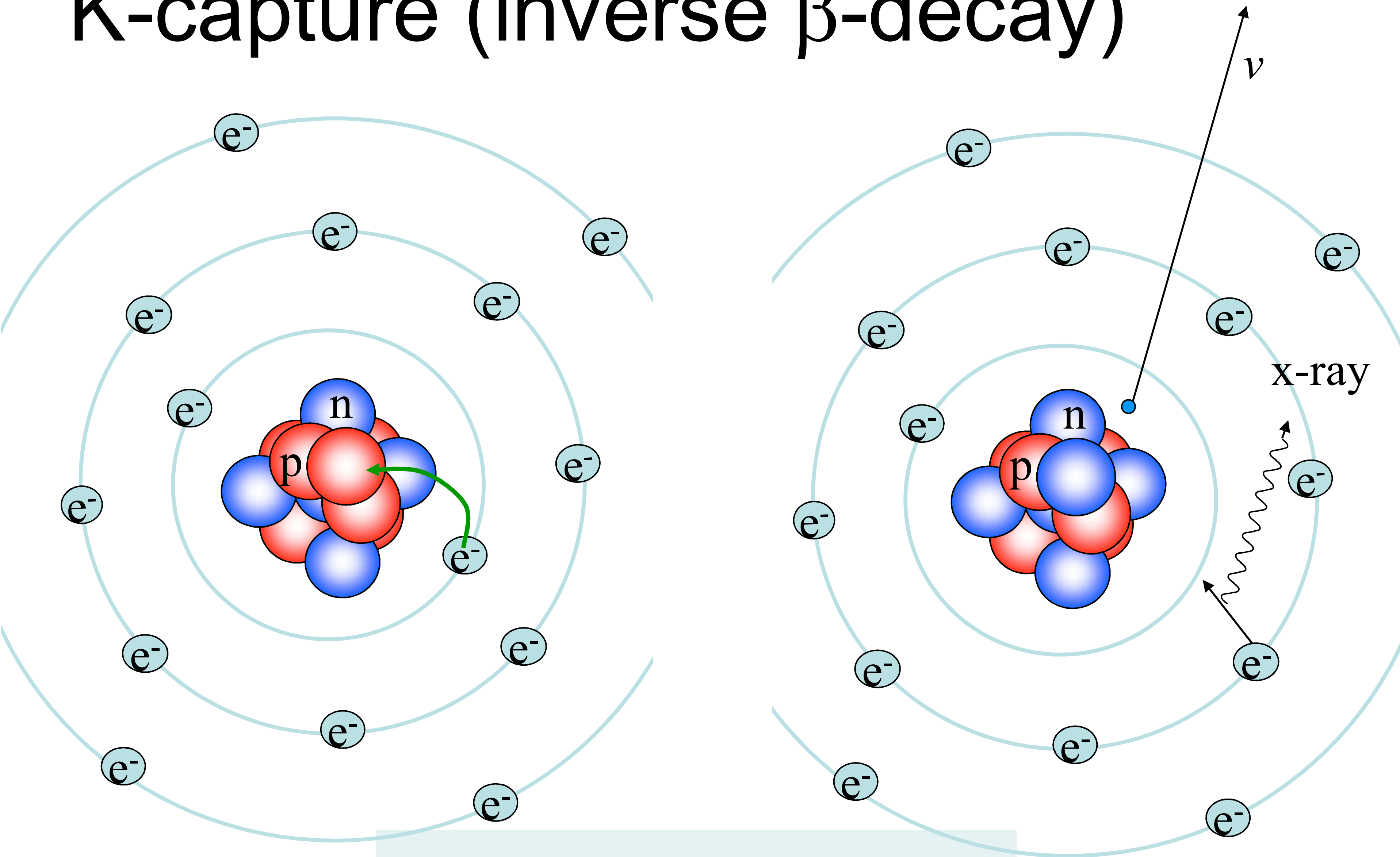


E.g.: ^{99m}Tc

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

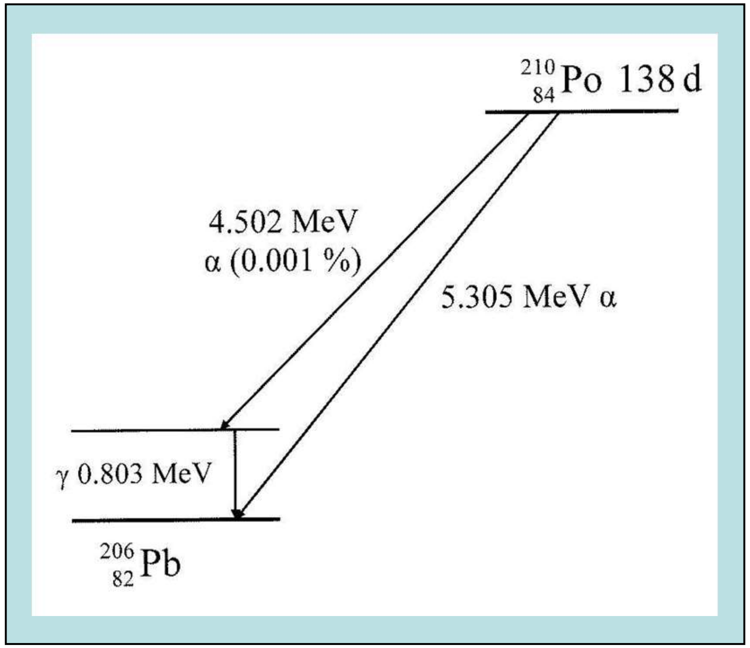
66 h 6 h

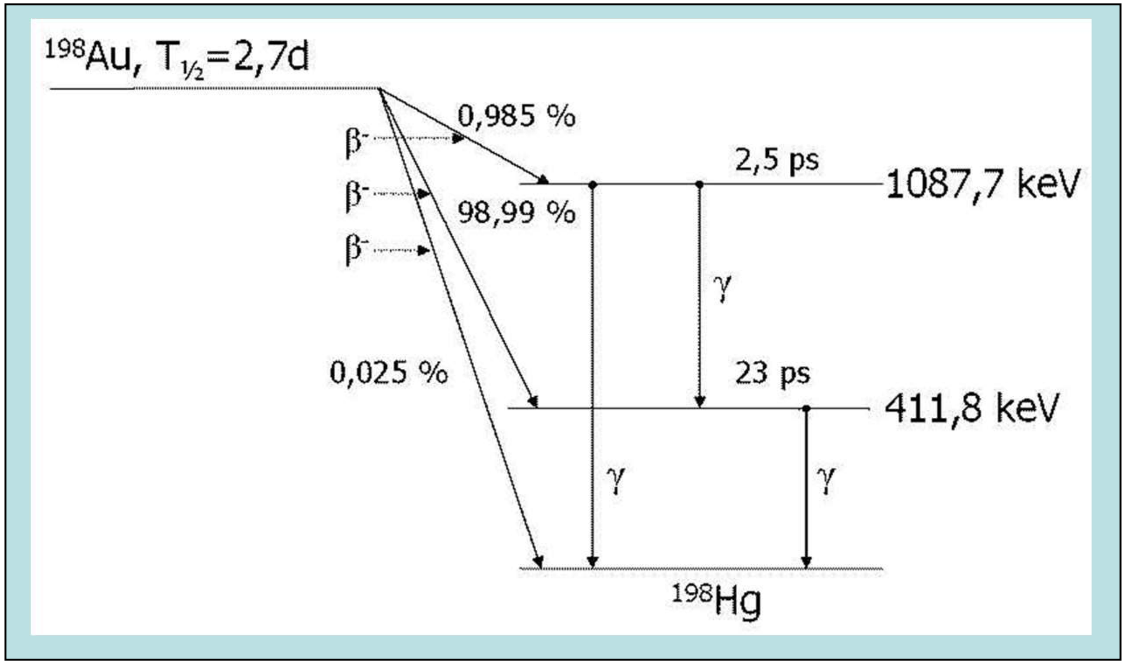
K-capture (inverse β-decay)

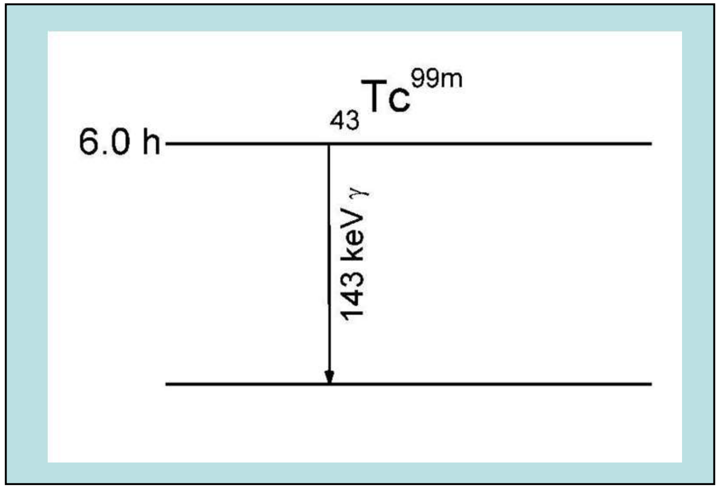


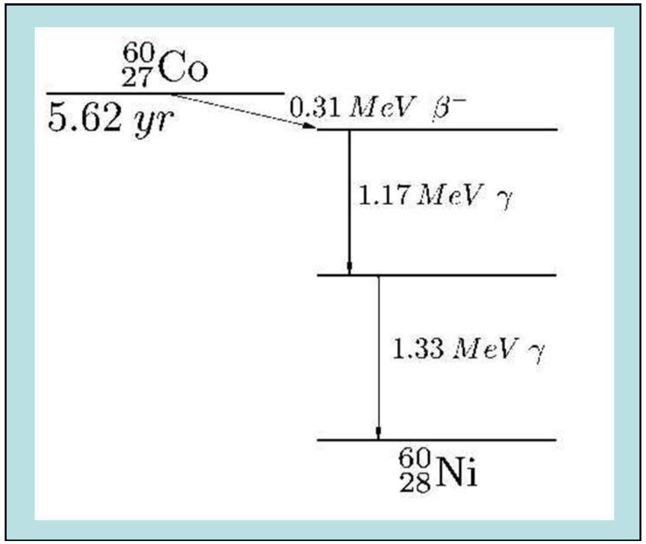
$$ {}_{1}^{1}p + {}_{-1}\beta \rightarrow {}_{0}^{1}n + \nu $$

Some examples of the decay paths









Characteristics of radioactive decays in general

activity	characterizes the source
half life time	characterizes the speed of the decay*
particle energy	characterizes the radiation*

*depends on the type of the isotope

Activity (Λ)

$$\Lambda = \left| \frac{\Delta N}{\Delta t} \right|$$

N = Number of undecayed atoms

t = time

$-\Delta N$ = Number of decays during Δt time

Activity= number of decays in a unit time

unit: becquerel Bq

1 Bq= 1 decay/sec

old unit: Ci=37GBq

kBq, MBq, GBq, TBq, PBq

immeasurably small (→ 1 Bq)

level of natural activity (→ kBq)

in vivo diagn. (→ MBq)

work carefully with it! (→ GBq)

activity applied in radiotherapy (→ TBq, PBq)

Law of radioactive decay

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

$$\frac{\Delta N}{\Delta t} = -\lambda N$$

N: Number of undecayed nuclei
($-\Delta N$ = Number of decays during Δt time)
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 $t=0$

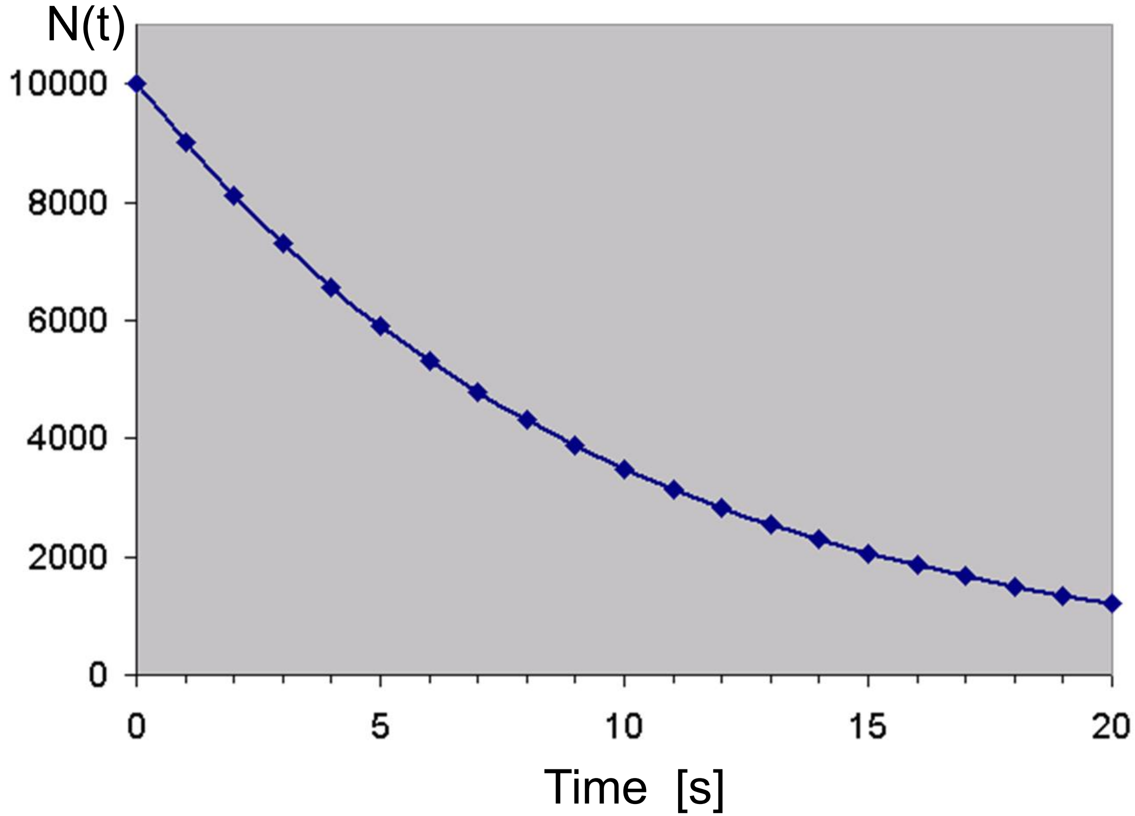
An example

- At start: N_0=10000 (number of atoms)
  λ=0.1 $^1/_s$ (decay probability)
  $\Delta N = -\lambda N \Delta t$
- 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

- At start: N_0=10000 (number of atoms
  λ=0.1 $^1/_s$ (decay probability)

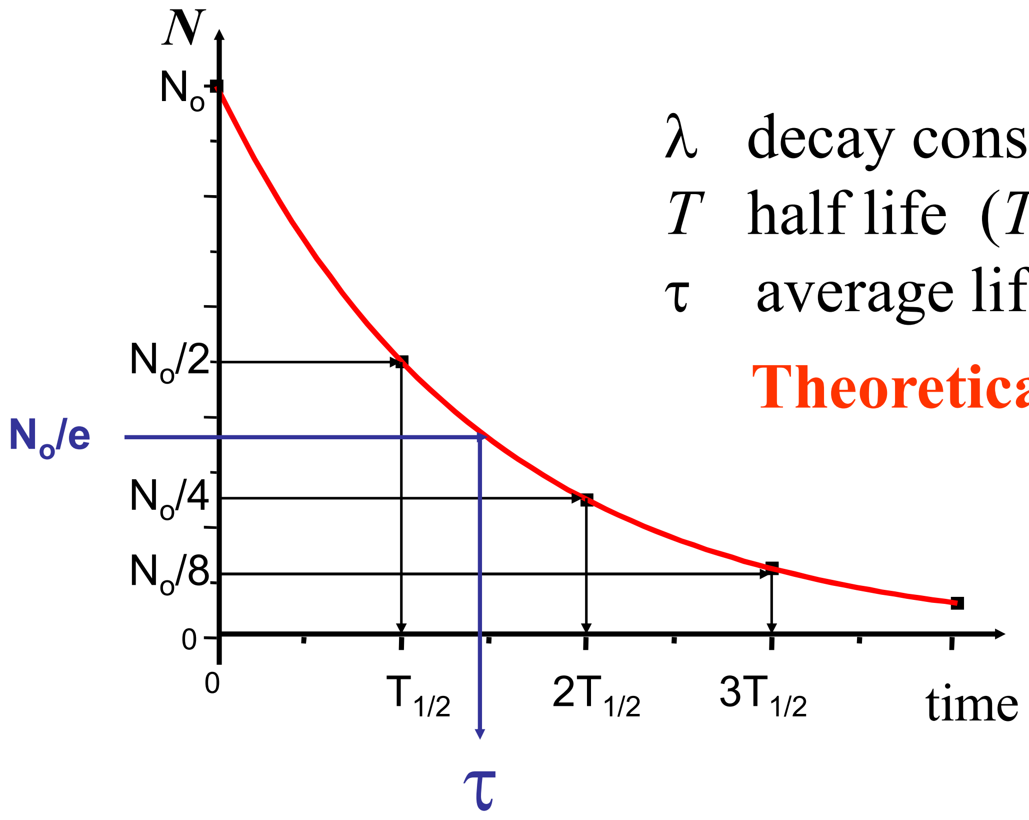
- after 1 s: 9000
- after 2 s: 8100
- after 3 s: 7290
- after 4 s: 6561
- ….



Law of radioactive decay

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

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



λ decay constant (probability of the decay)

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

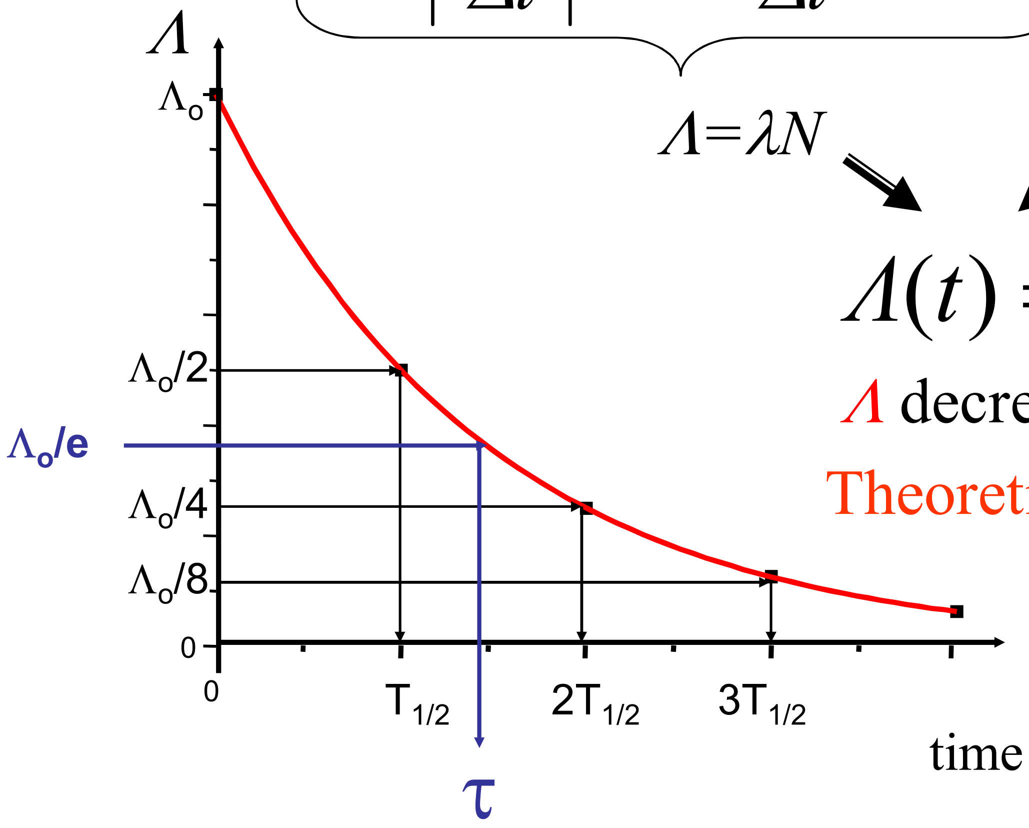
τ average lifetime

Theoretically never decreases to zero !

Decrease of the activity as a function of time

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

$$\Lambda = \lambda N$$



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

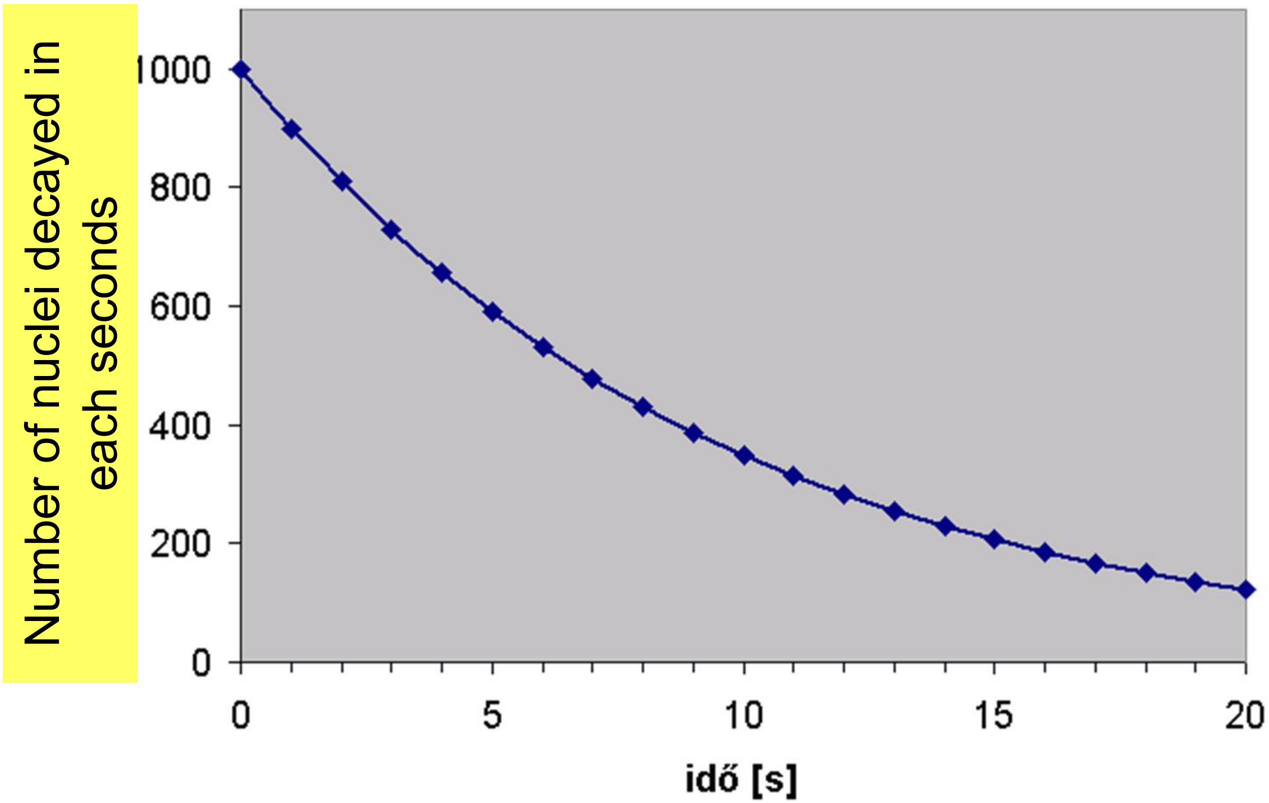
Λ decreases on the same way as N!

Theoretically never decreases to zero!

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

An example

- At start: N_0=10000 (number of atoms
  λ=0.1 $^1/_s$ (decay probability)



=1000 decayed)

=900 decayed)

=810 decayed)

=729 decayed)

Few examples for half life

^{232}Th	$1.4 \cdot 10^{10}$ y
^{238}U	$4.5 \cdot 10^{9}$ y
^{40}K	$1.3 \cdot 10^{9}$ y
^{14}C	5736 y
^{137}Cs	30 y
^{3}H	12.3 y

^{60}Co	5.3 y
^{59}Fe	1.5 m
^{56}Cr	1 m (28 d)
^{131}I	8 d
^{99m}Tc	6 h
^{18}F	110 min
^{11}C	20 min
^{15}O	2 min
^{222}Th	2.8 ms

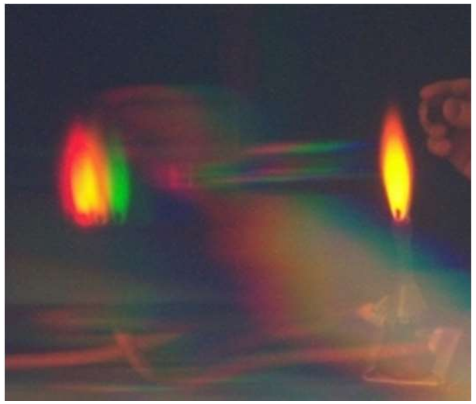
Don’t learn these numbers!

Typical energy levels in the microworld

Excitation of the outer electrons

eV (aJ)

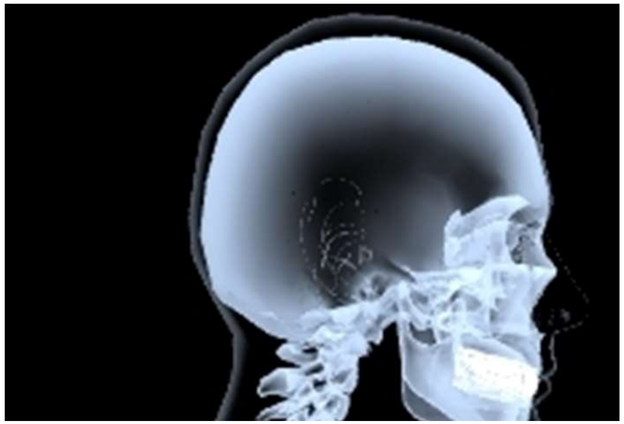
light



Electron transition between inner electrons

keV (fJ)

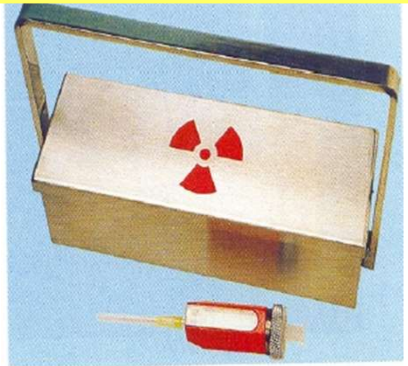
X-ray



Transformation of the nucleus (decay)

MeV (pJ)

Nuclear radiation α, β, γ



Absorption of the nuclear radiation

α

β^-

β^+

particles with electric charge

direct ionisation

different types of interactions with matter!

Different attenuation characteristics!

γ

(x-ray)

uncharged particles (photons)

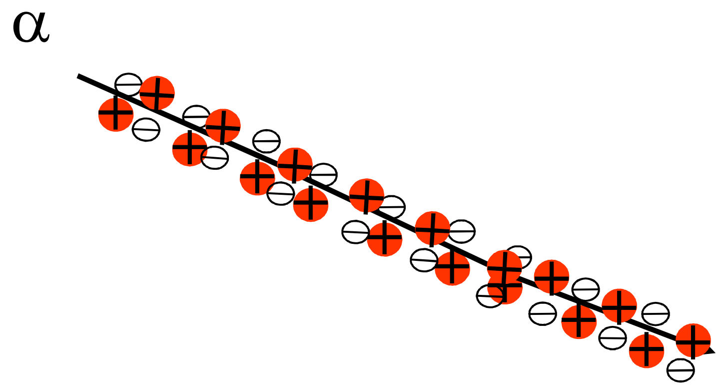
indirect ionisation

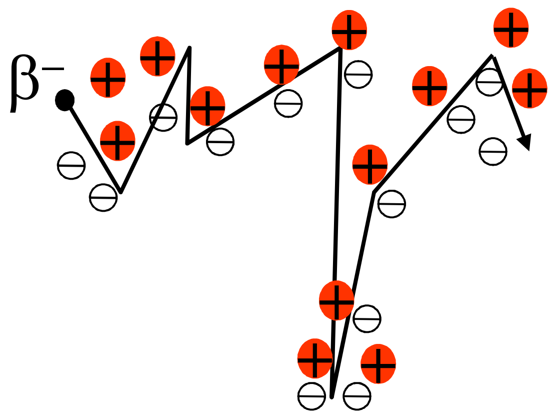
not a nuclear radiation, but its absorption is similar to that of the γ radiation

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

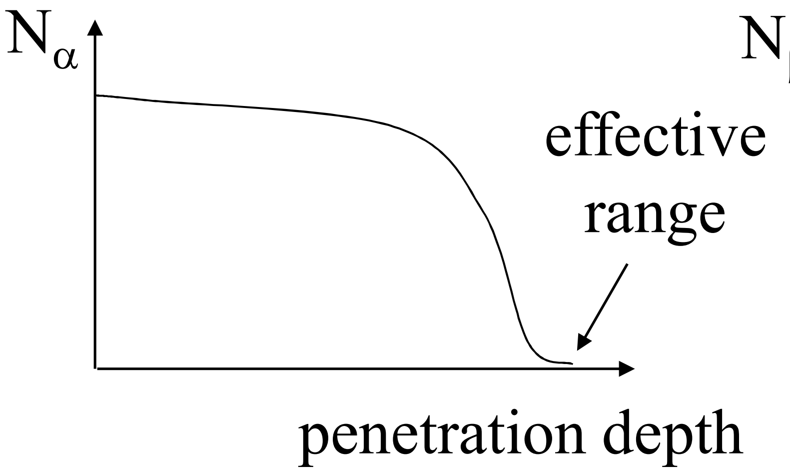
effective range

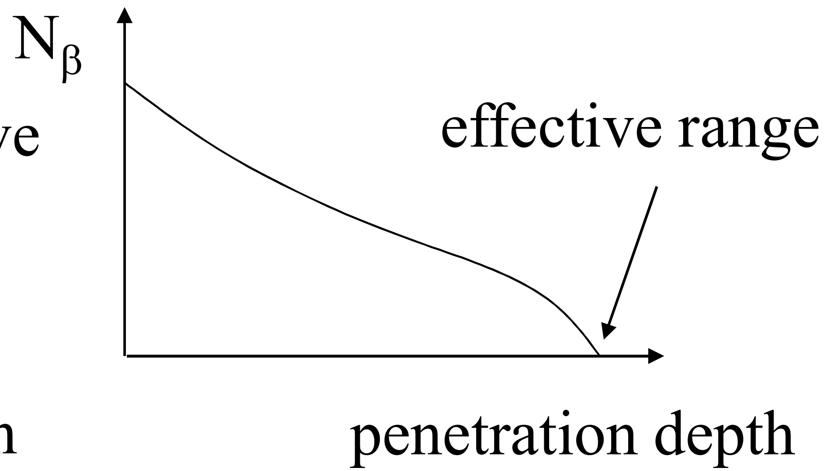




Effective range

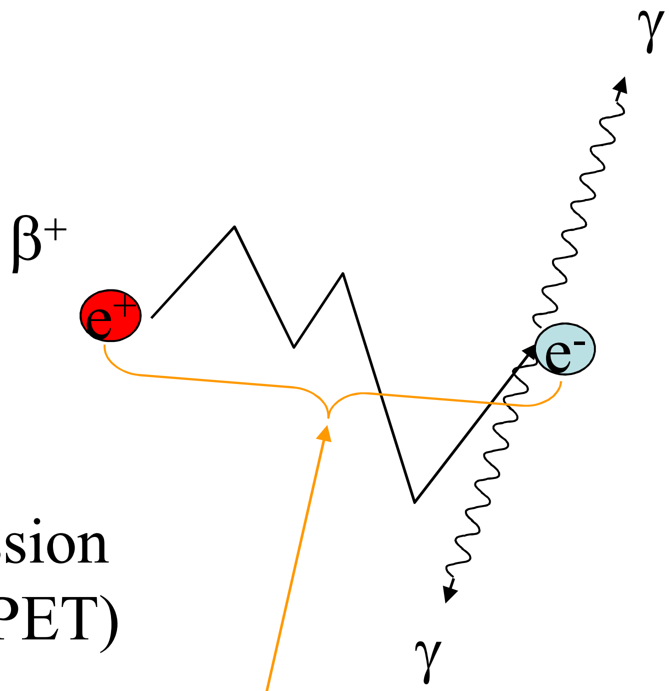
	α-particle	β^--particle
in air	**few cm**	**~ m**
in tissue	**0,01-0,1 mm**	**~ cm**





β⁺-radiation

annihilation



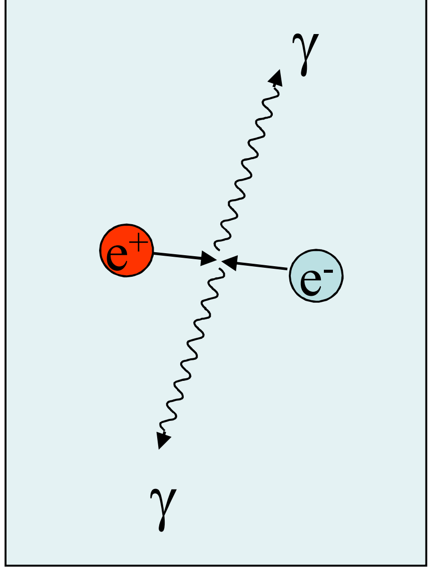
see: Positron Emission Tomography (PET)

effective range

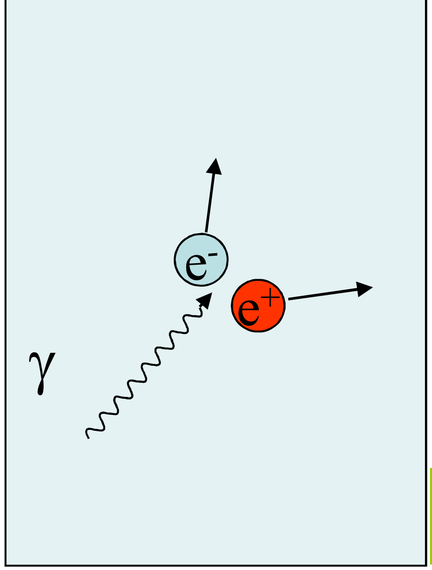
Electron and positron

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

annihilation



and pair production



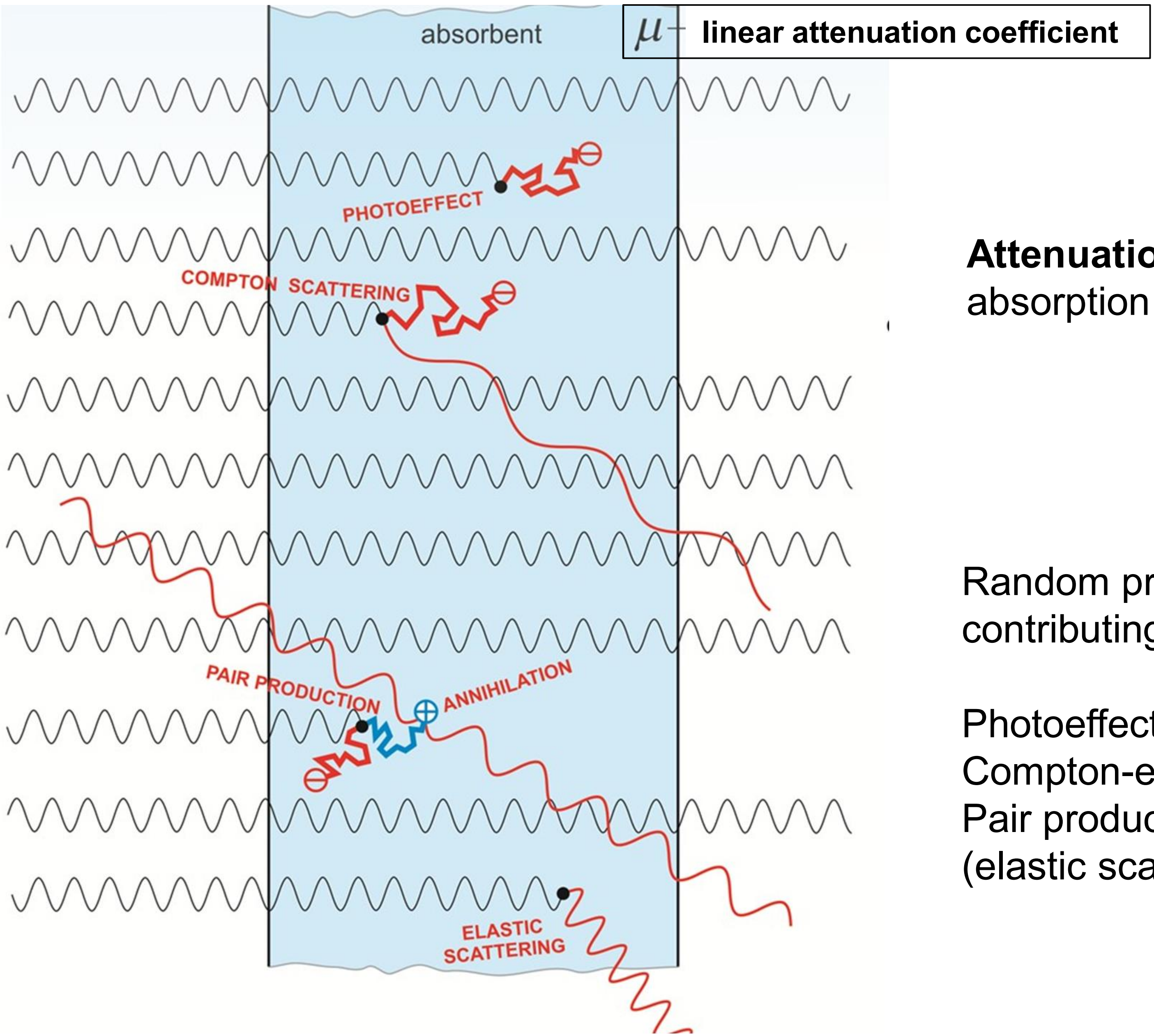
Einstein:

mass-energy ekvivalence

$$E=mc^2$$

$m_e c^2$=511 keV≈0.5 MeV

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

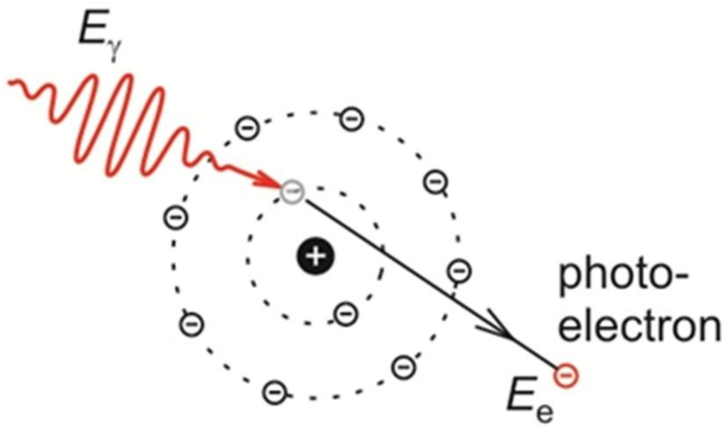


Attenuation:
absorption + scattering

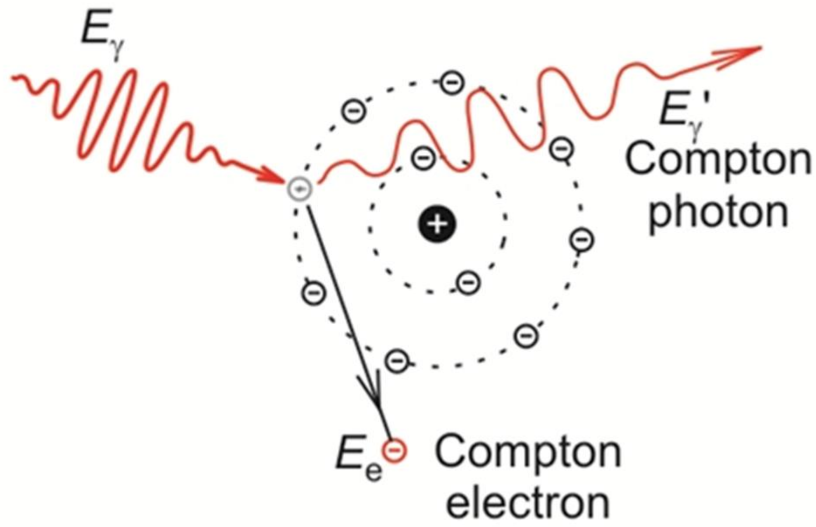
Random processes contributing:

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

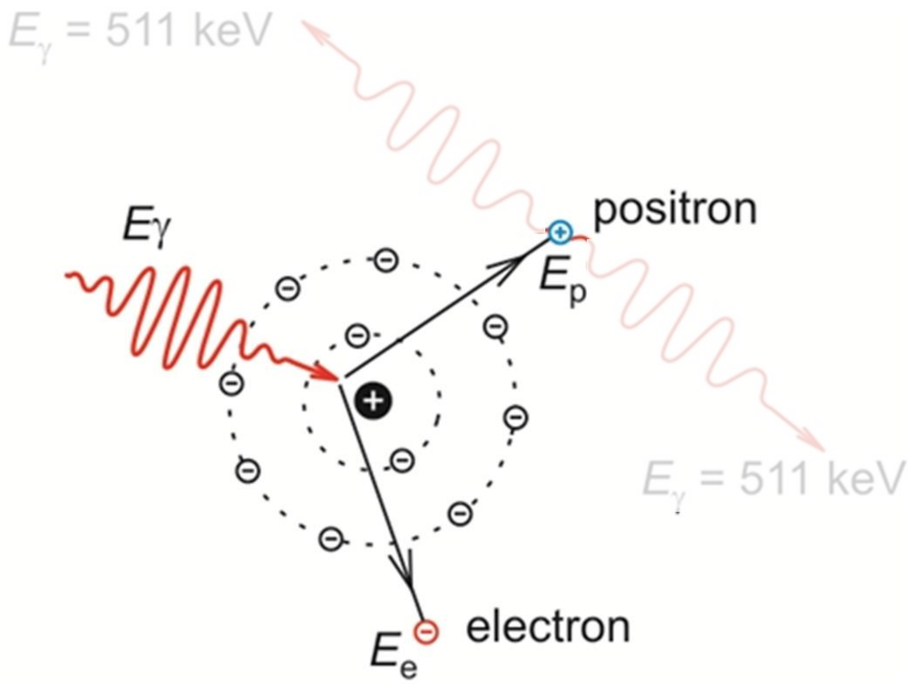
Photoeffect



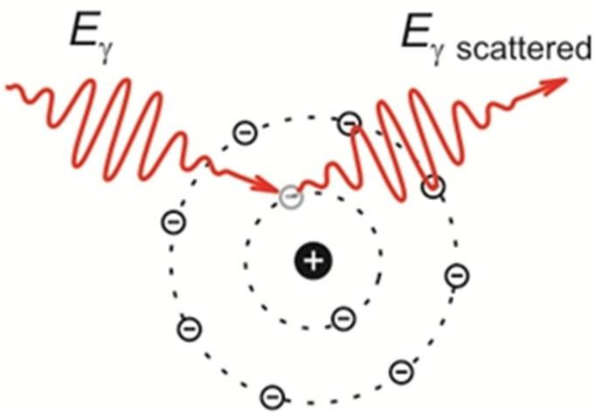
Compton effect
Compton-scattering



Pair production

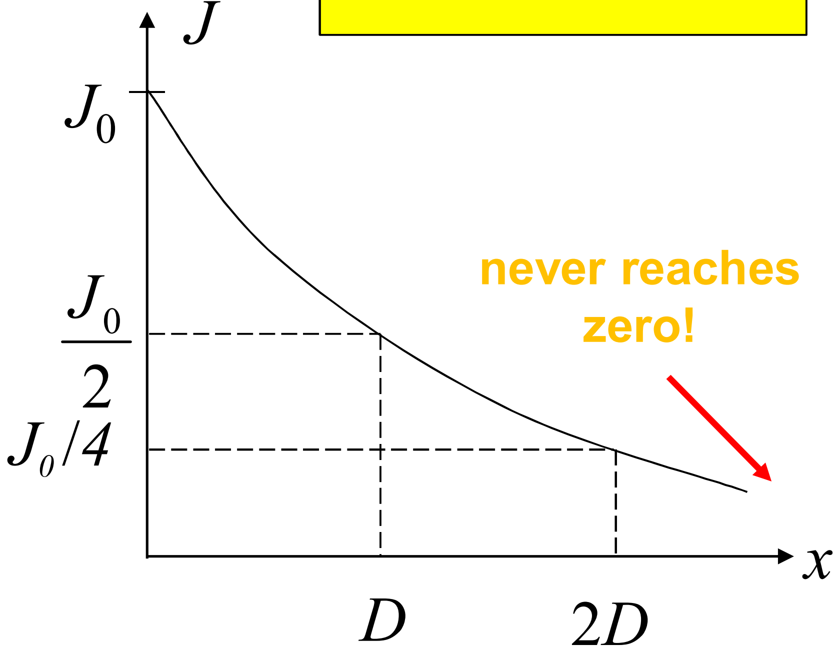


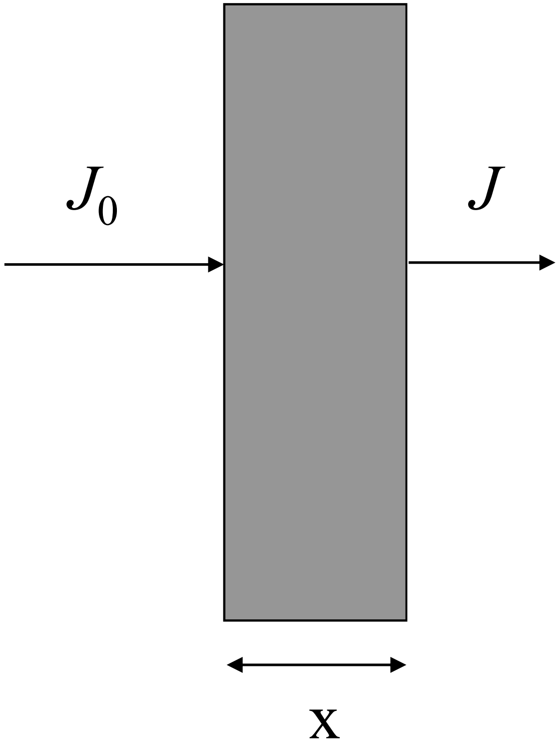
elastic scattering



Attenuation of the γ–radiation and x-ray

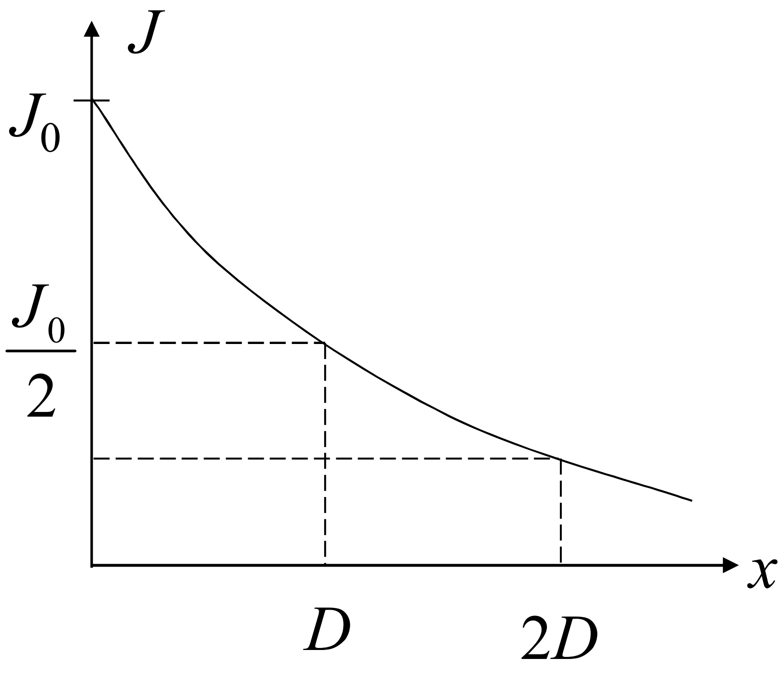
$$J = J_0 e^{-\mu x}$$





no finite effective range!

few rules of thumb: $x_{1/10}$=3,32 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)

$=\mu(\text{material}, \rho, E_{photon}) \sim \rho$

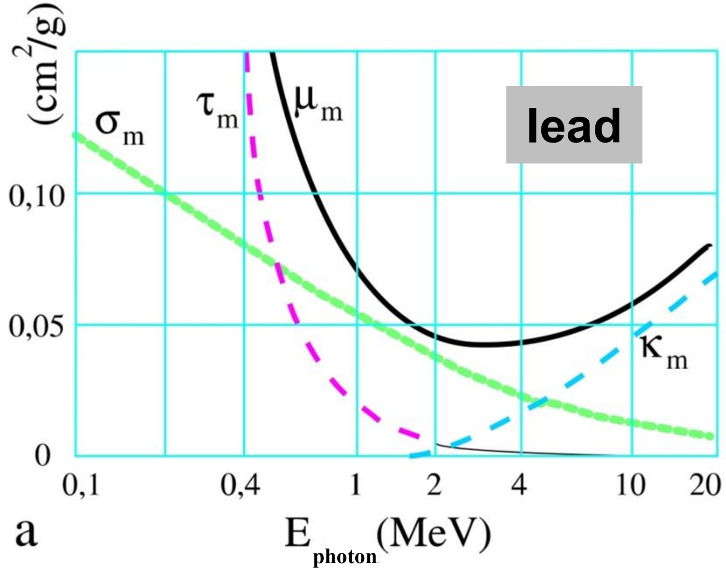
$$\mu_m = \frac{\mu}{\rho}$$ mass attenuation coefficient

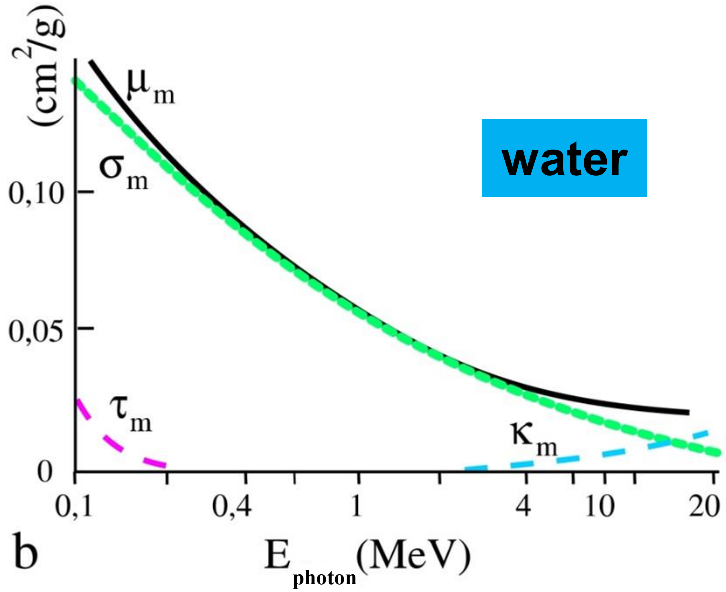
mass attenuation coeff.

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

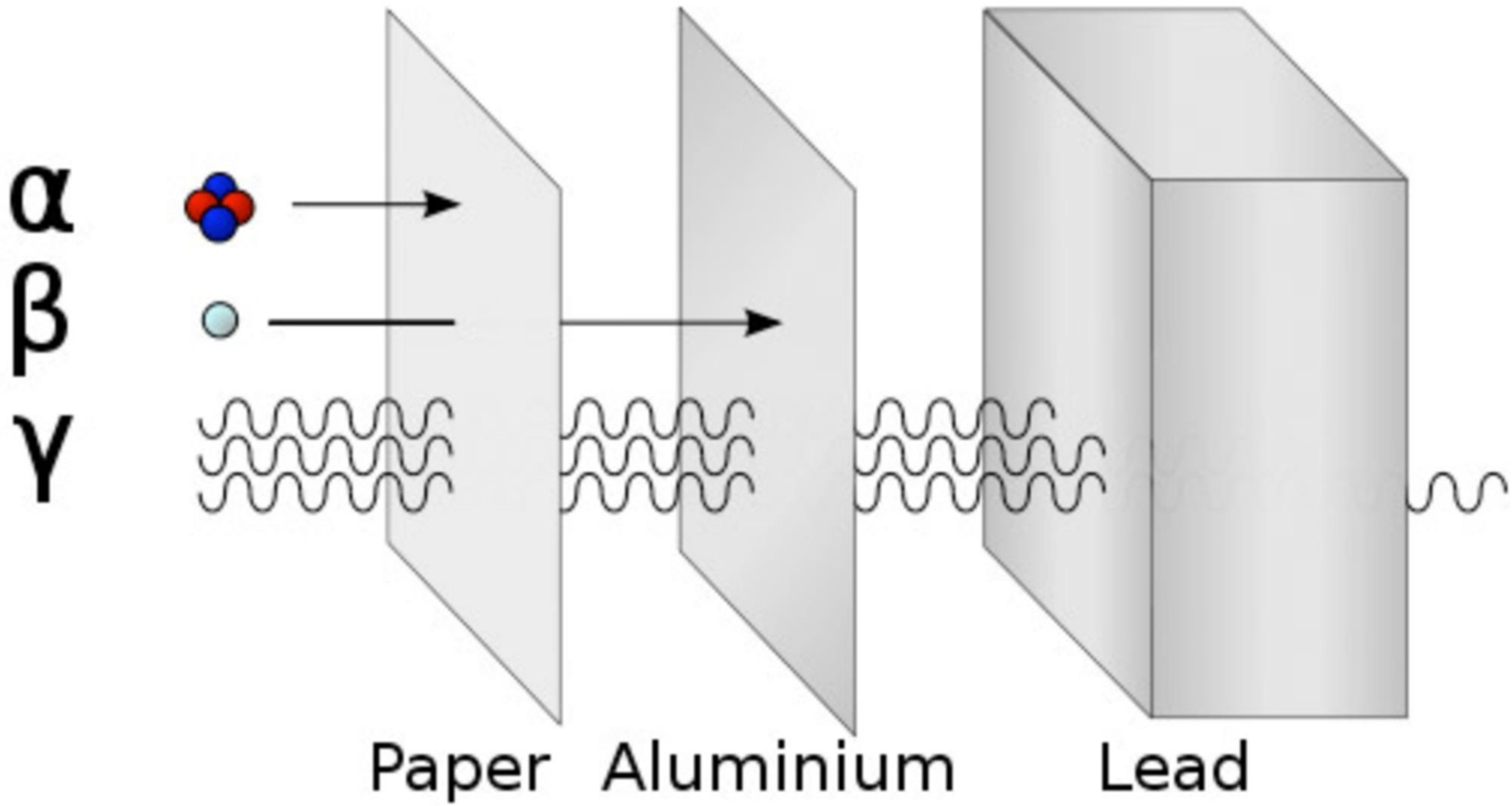
$$\mu_m = \tau_m + \sigma_m + \kappa_m$$

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





Summary of the absorption of α, β and γ radiation



Applications (attenuation)

lead glass

protective apron

Applications: isotopes and nuclear radiation