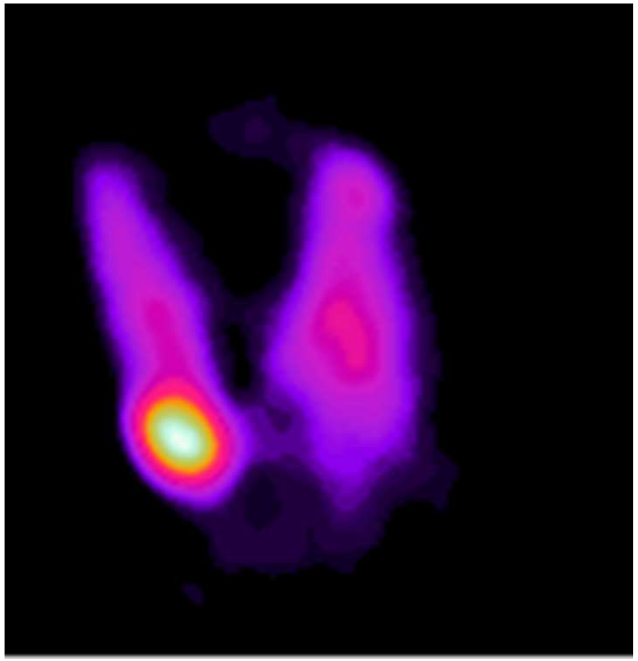
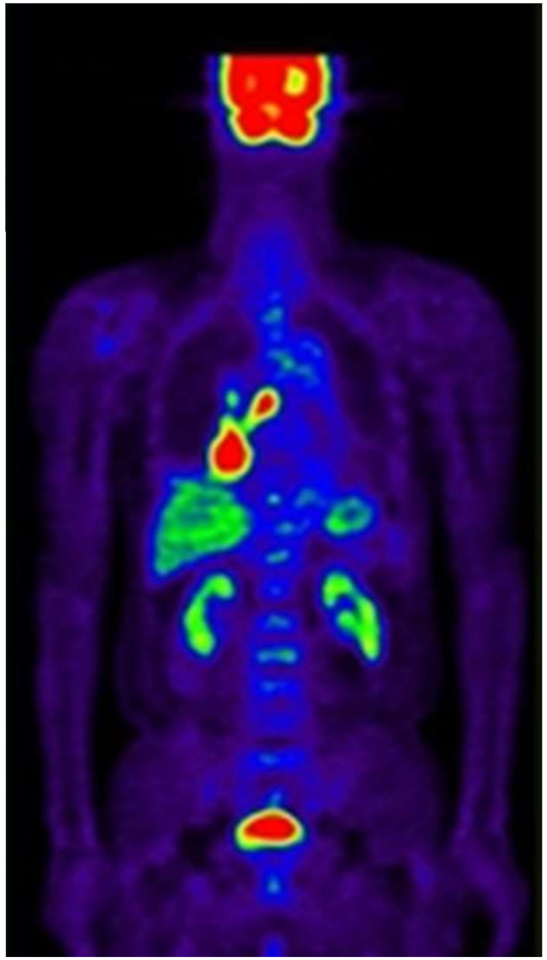
The atomic nucleus. Radioactivity. Nuclear radiations

László Smeller





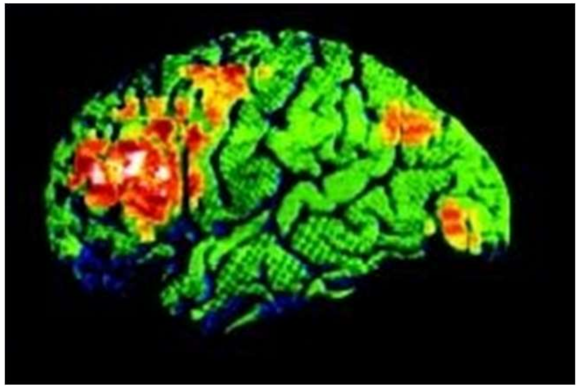
Why?

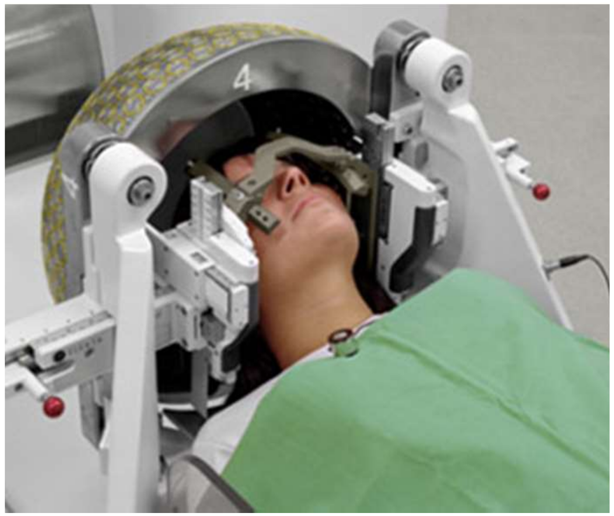
Medical/pharmaceutical applications of nuclear radiation:

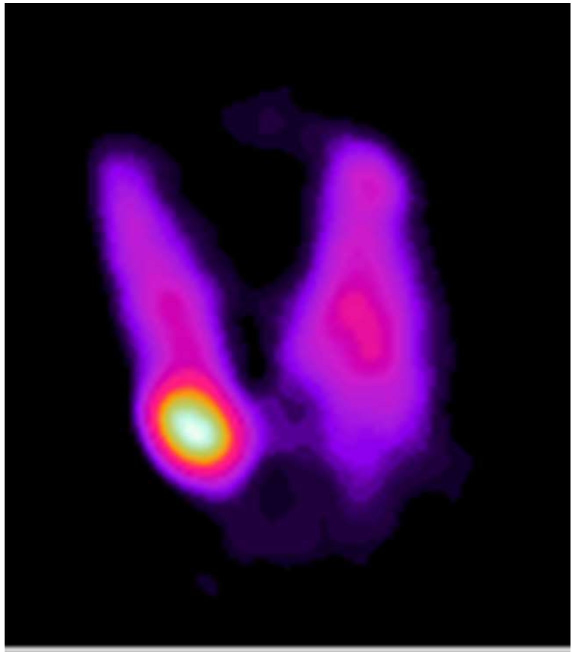
Nuclear imaging

Radiotherapy

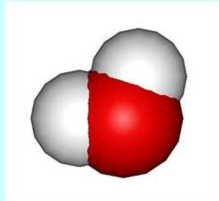
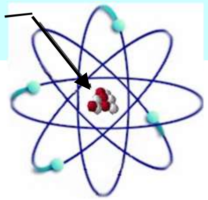
Pharmacokinetics



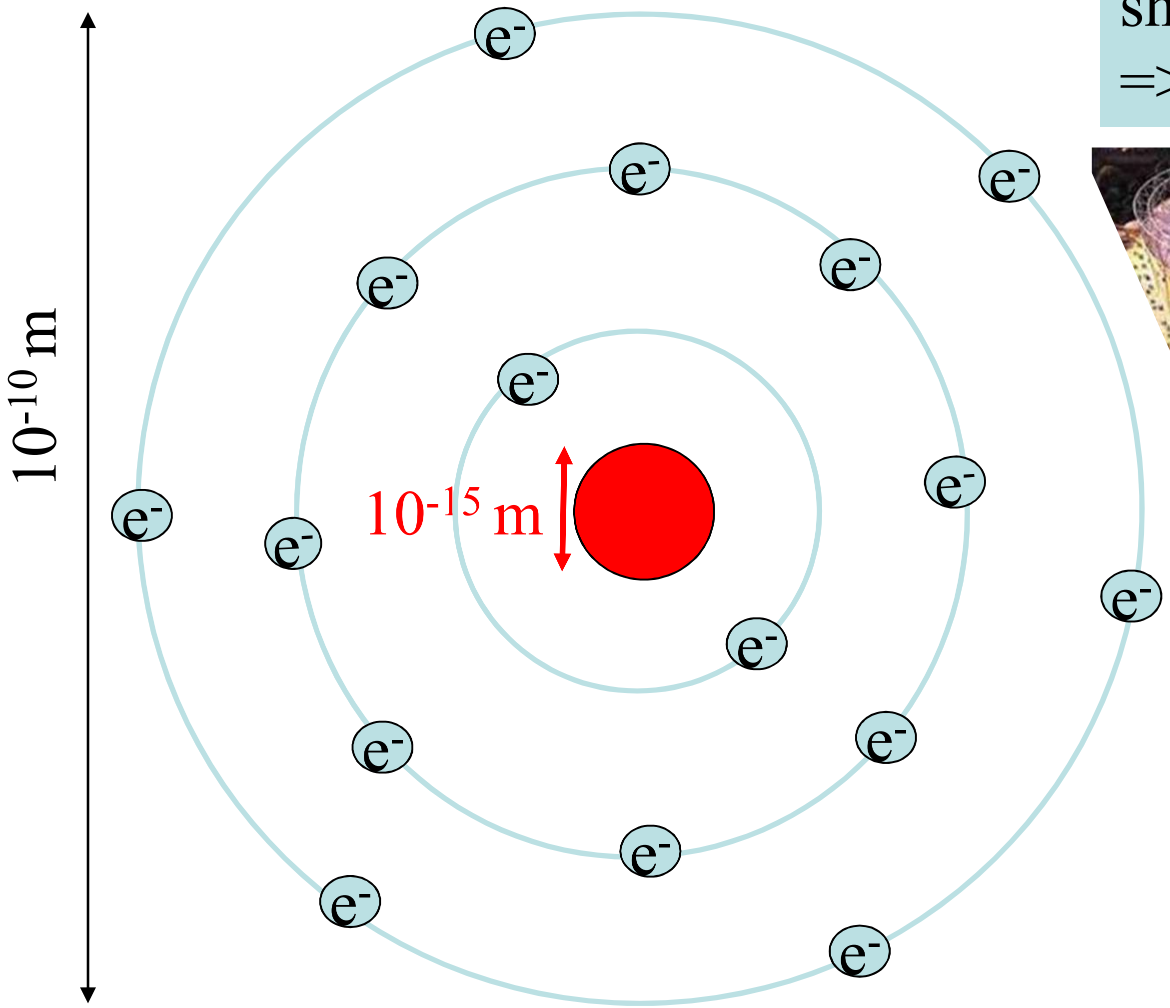




Length scale of the nature

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

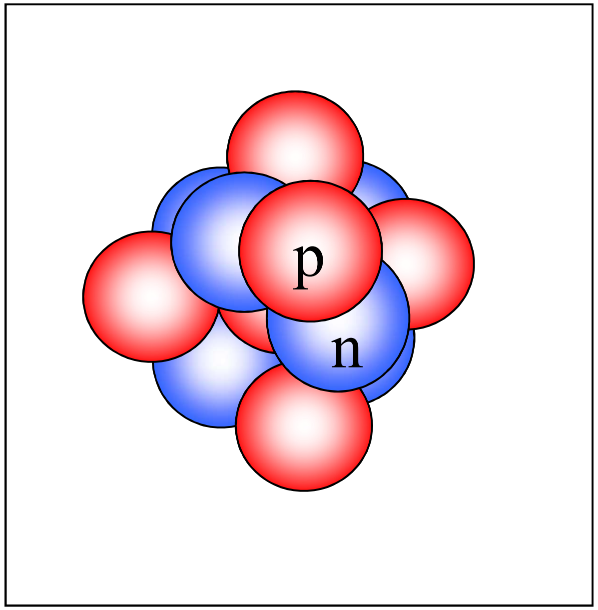


Changes in the electron shell:
=>chemical processes

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

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

99 nucleon, 43 proton and 56 neutron

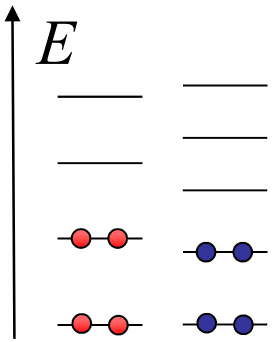
Stability of the nucleus

- Coulomb force: destabilization
  (electrostatic repulsion between the protons)

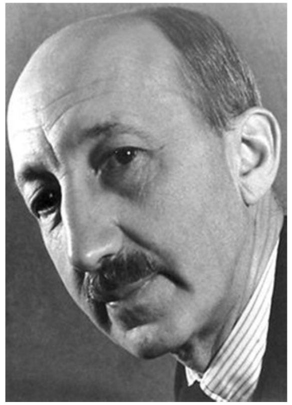
- Nuclear force: very strong
  attractive force
  acts only on short range (~fm)
  independent on the charge

- Quantized energy levels for the nucleus.

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



Isotopes



Number of protons is the same

Number of neutrons is different

Variants of the same element

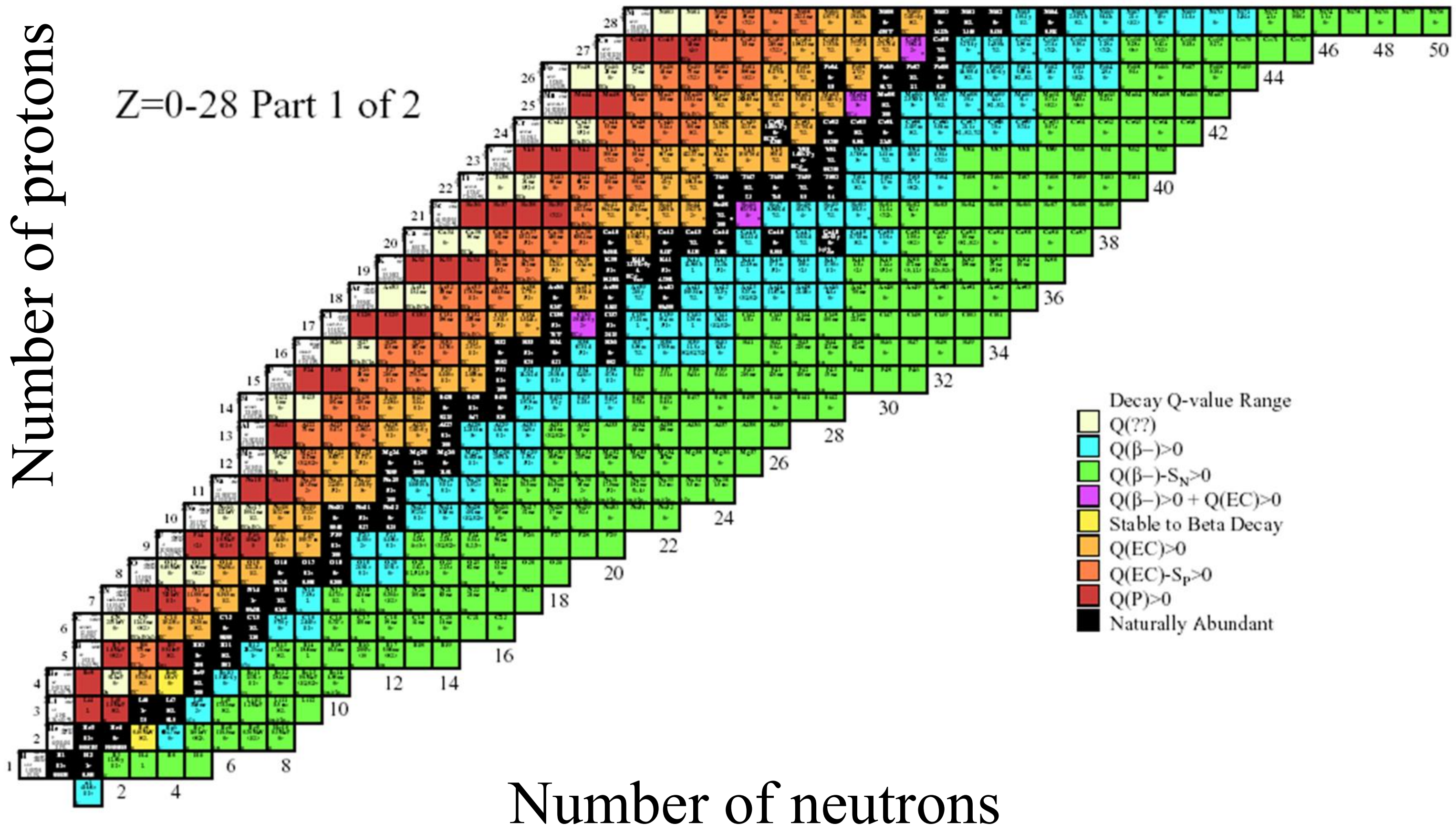
$\Rightarrow$ the chemical properties are identical.

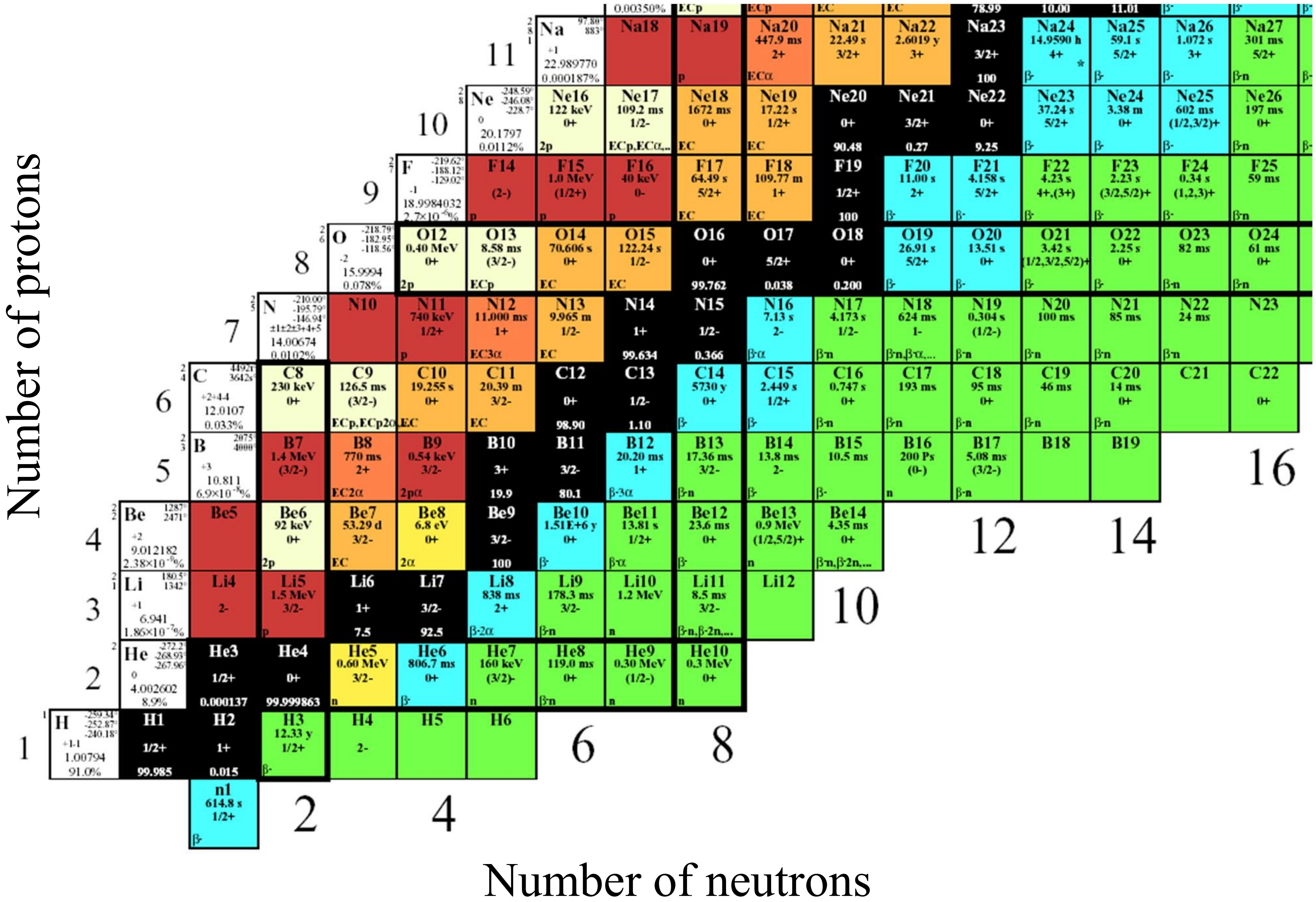
Pl: $^{18}_{9}\mathbf{F}$ $^{19}_{9}\mathbf{F}$ $^{20}_{9}\mathbf{F}$

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
H1
H2
H3
H4
H5
H6
n1
He
He3
He4
He5
He6
He7
He8
He9
He10
Li
Li4
Li5
Li6
Li7
Li8
Li9
Li10
Li11
Li12
Be
Be5
Be6
Be7
Be8
Be9
Be10
Be11
Be12
Be13
Be14
B
B7
B8
B9
B10
B11
B12
B13
B14
B15
B16
B17
B18
B19
C
C8
C9
C10
C11
C12
C13
C14
C15
C16
C17
C18
C19
C20
C21
C22
N
N10
N11
N12
N13
N14
N15
N16
N17
N18
N19
N20
N21
N22
N23
O
O12
O13
O14
O15
O16
O17
O18
O19
O20
O21
O22
O23
O24
F
F14
F15
F16
F17
F18
F19
F20
F21
F22
F23
F24
F25
Ne
Ne16
Ne17
Ne18
Ne19
Ne20
Ne21
Ne22
Ne23
Ne24
Ne25
Ne26
Na
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Na19
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Na22
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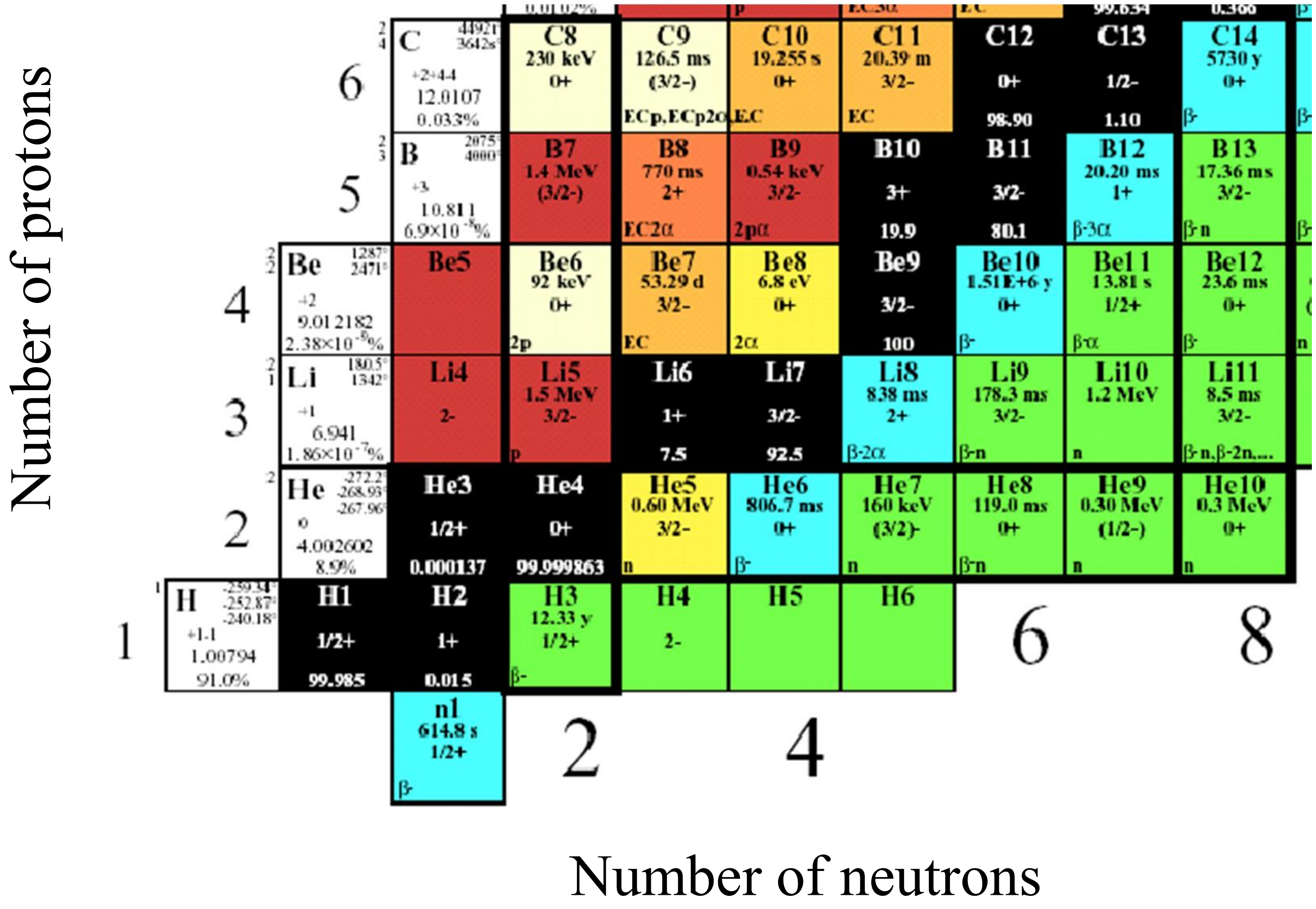
Na24
Na25
Na26
Na27



Number of protons
Number of neutrons
1
2
3
4
5
6
2
4
6
8
C 12.0107
B 10.811
Be 9.012182
Li 6.941
He 4.002602
H 1.00794
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-
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
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-
Li4 2- p
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,...
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
H1 1/2+ 99.985
H2 1+ 0.015
H3 12.33 y 1/2+ β-
H4 2-
H5
H6
n1 614.8 s 1/2+ β-

Radioactive decays and particles

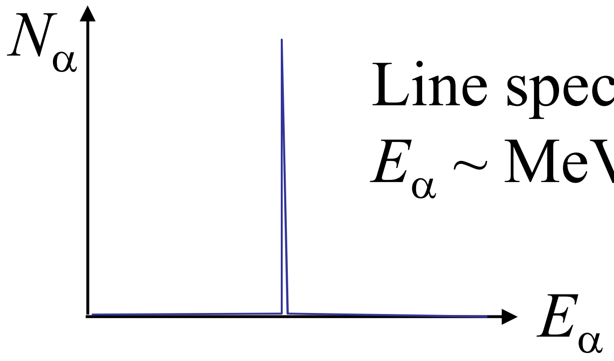
α - decay	α - particle	=	${}^{4}_{2}He$ nucleus
β - decay : β^-	β^- particle	=	electron
β^+	β^+ particle	=	positron
Isomeric transition	γ-ray		
K-electron capture	characteristic x-ray photon		

α - decay

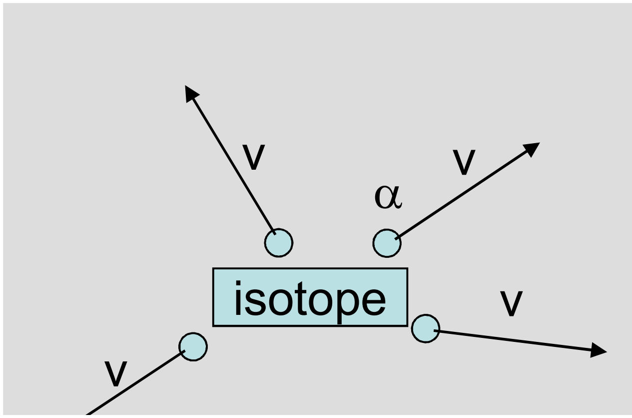
α - decay: an α particle (^{4}He nucleus) will be emitted typical for the heavy atoms

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

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

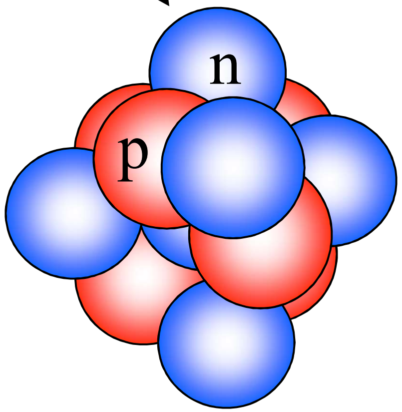


Line spectrum
$E_\alpha \sim$ MeV



β^- - decay

neutron surplus



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

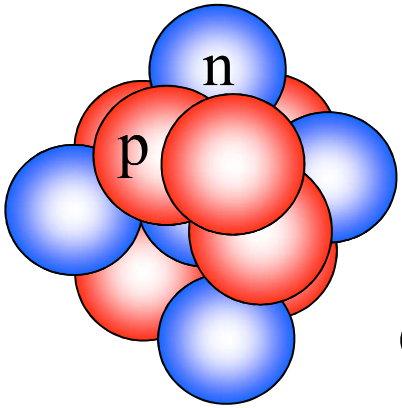
$${}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}\beta + \bar{\nu}$$

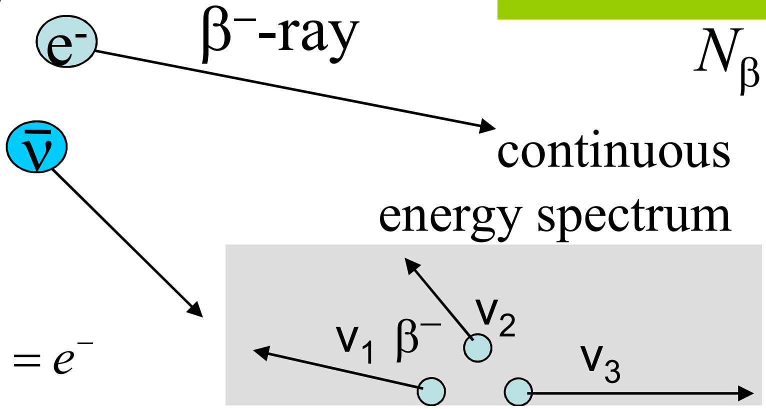
remains in the nucleus

leave the nucleus

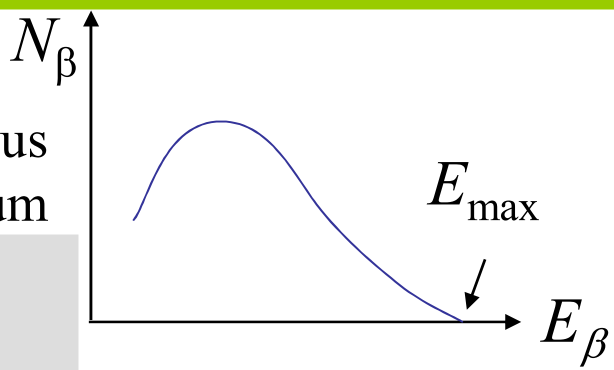
e.g.: ${}^{20}_{9}F$ ${}^{32}_{15}P$ ${}^{59}_{26}Fe$ ${}^{131}_{53}I$

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



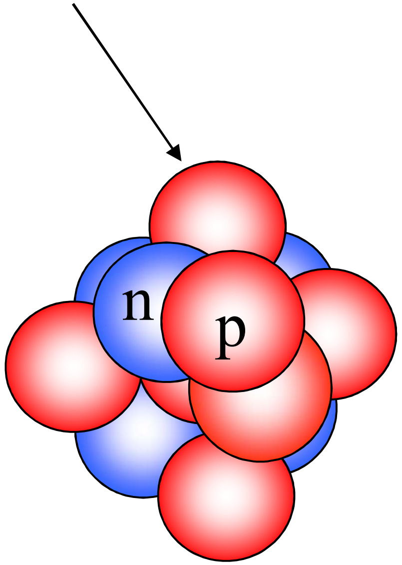


$\beta^- = {}^{0}_{-1}\beta = e^-$



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

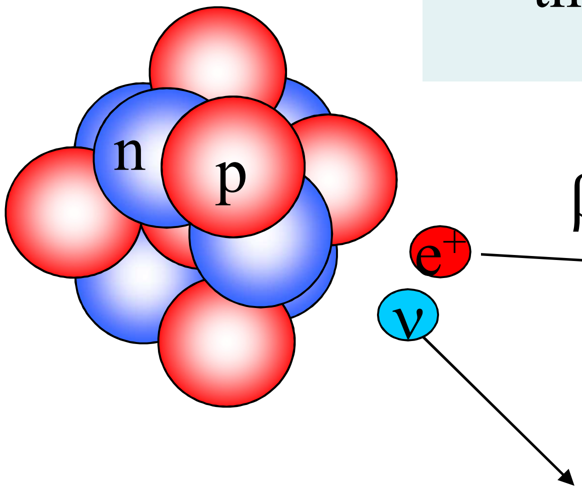
e.g.: $^{11}_{6}C$

$^{15}_{8}O$

$^{18}_{9}F$

$^{52}_{26}Fe$

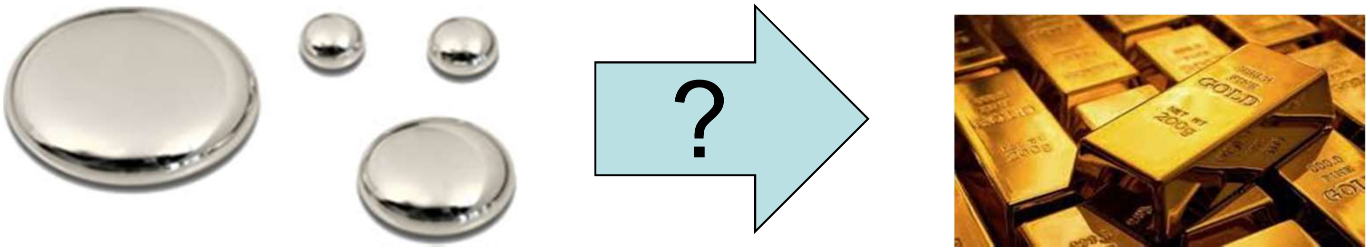
e.g.: $^{30}_{15}\mathrm{P} \longrightarrow {}^{30}_{14}\mathrm{Si} + {}^{0}_{+1}\beta + \nu$



β^+-ray

continuous energy spectrum

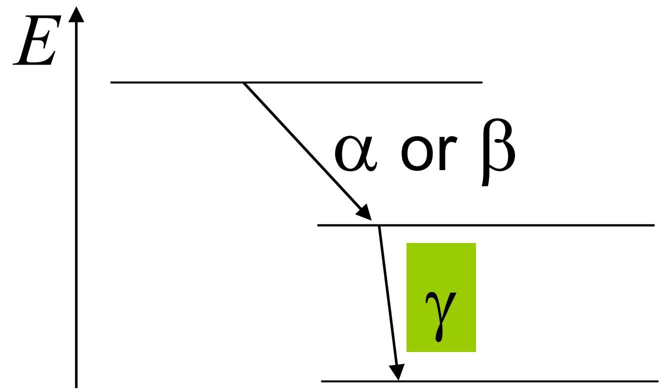
These isotopes must be produced artificially (e.g. in cyclotron)

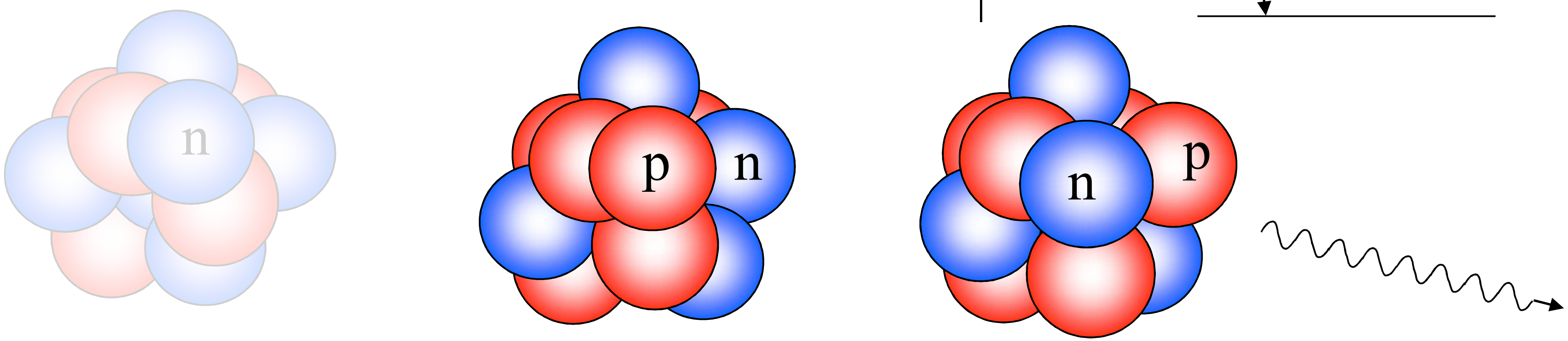


Prompt γ-radiation

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





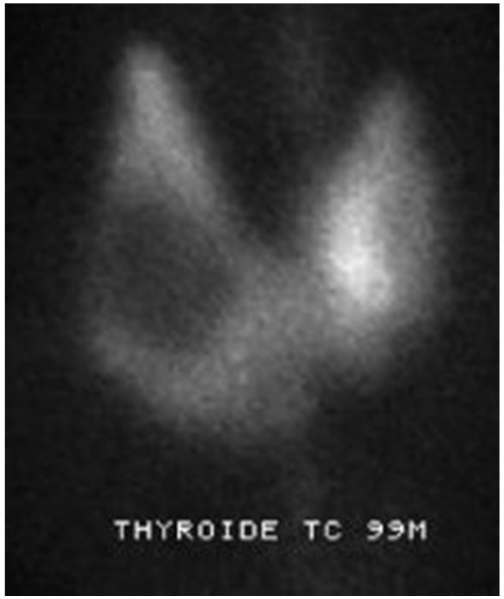
Atomic number, mass number are unchanged.

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)

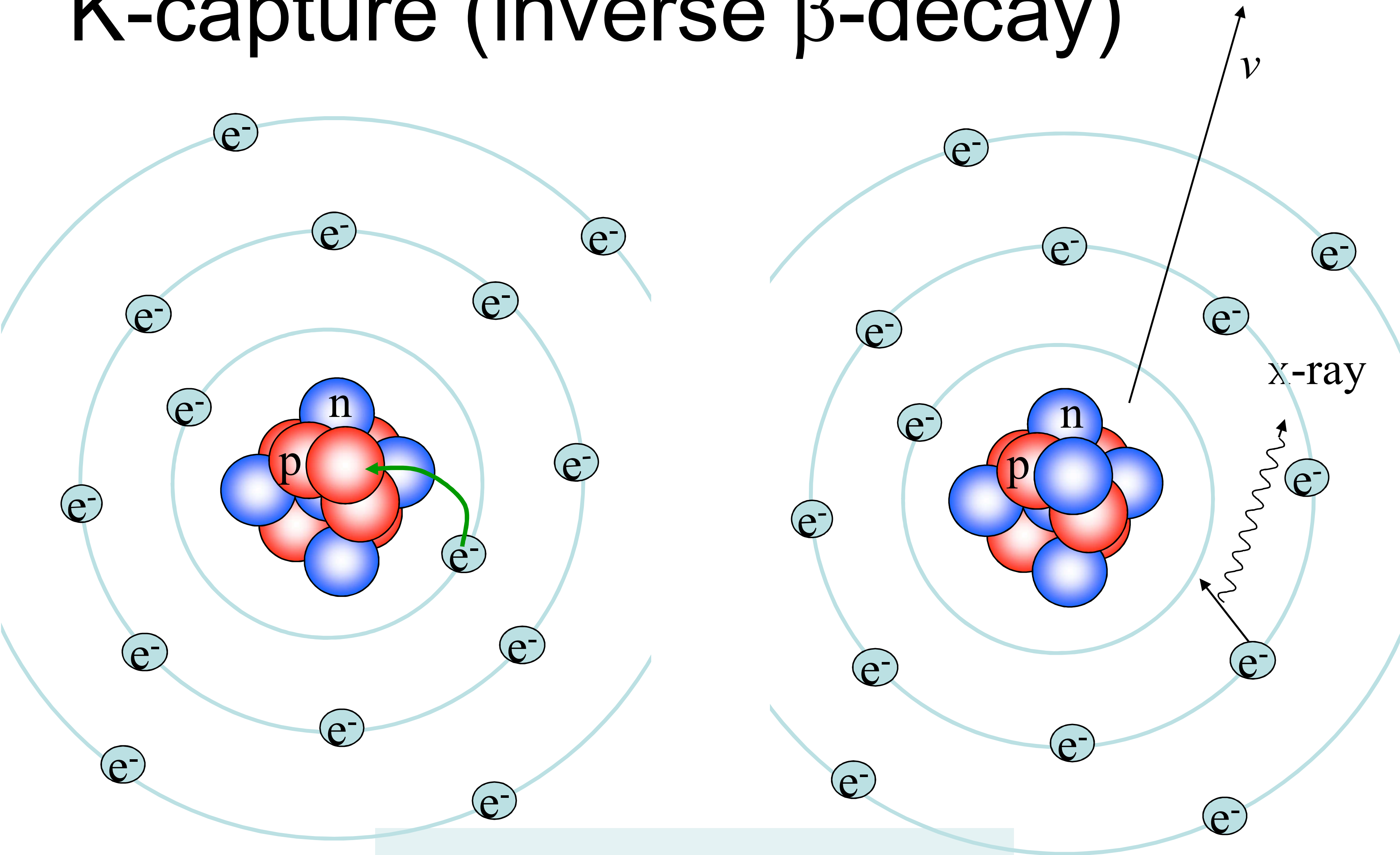


E.g.: ^{99m}Tc

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

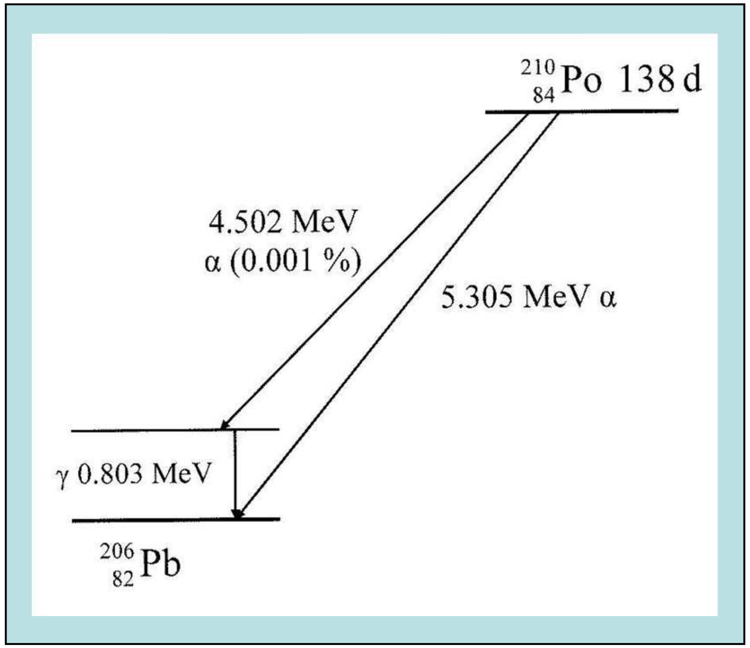
66 h 6 h

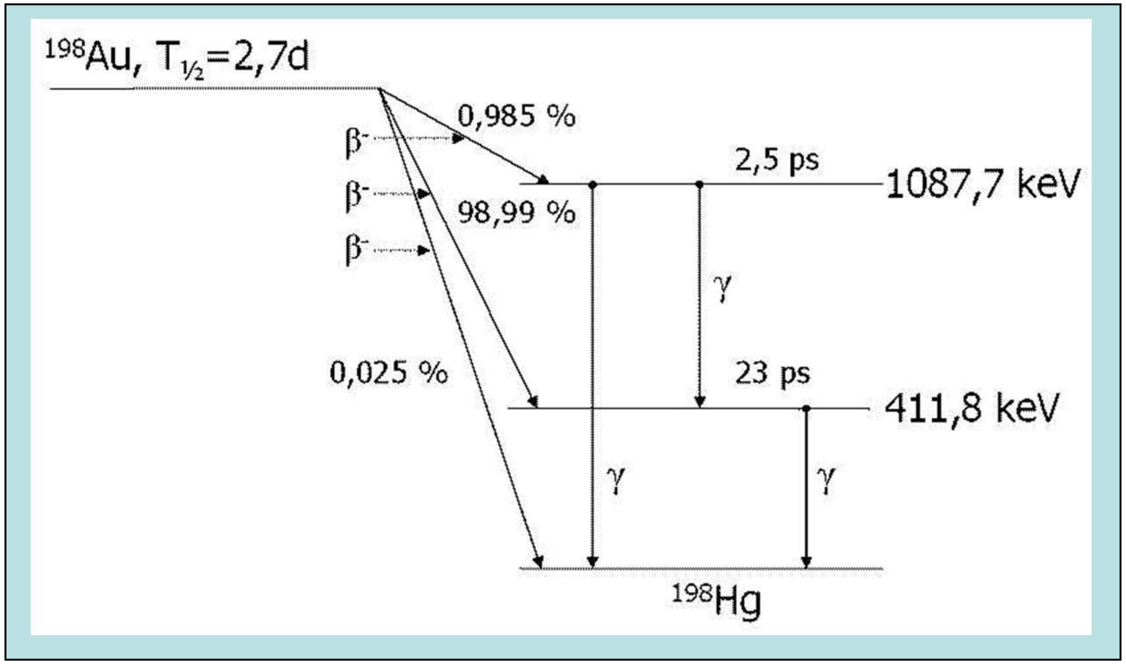
K-capture (inverse β-decay)

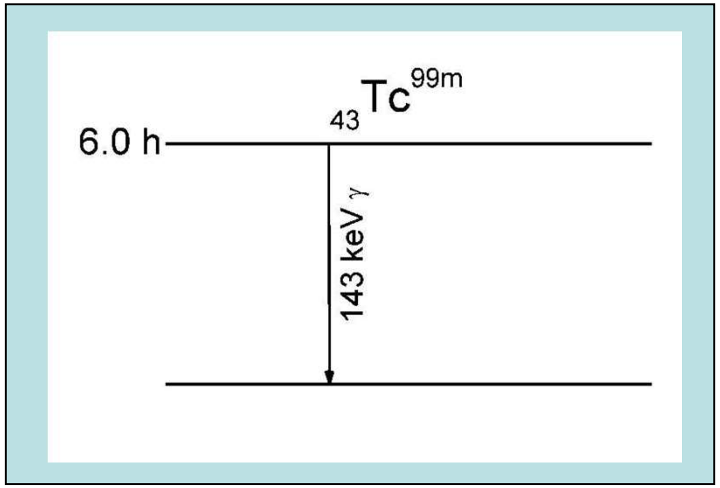


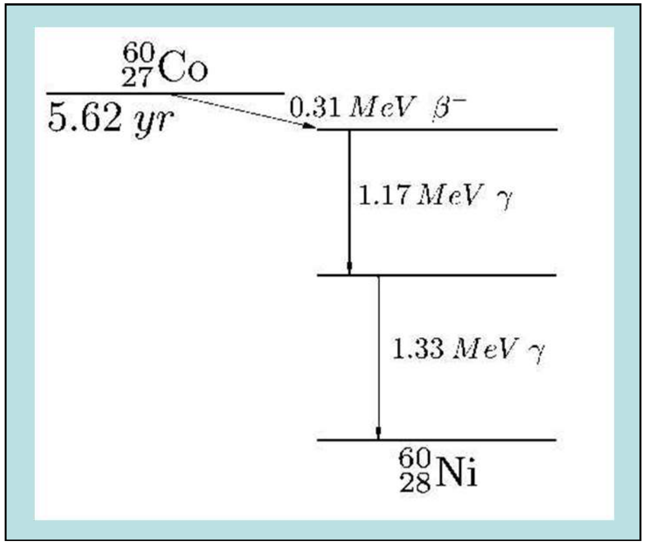
$$ {}^{1}_{1}p + {}^{0}_{-1}\beta \rightarrow {}^{1}_{0}n + \nu $$

Some examples of the decay paths

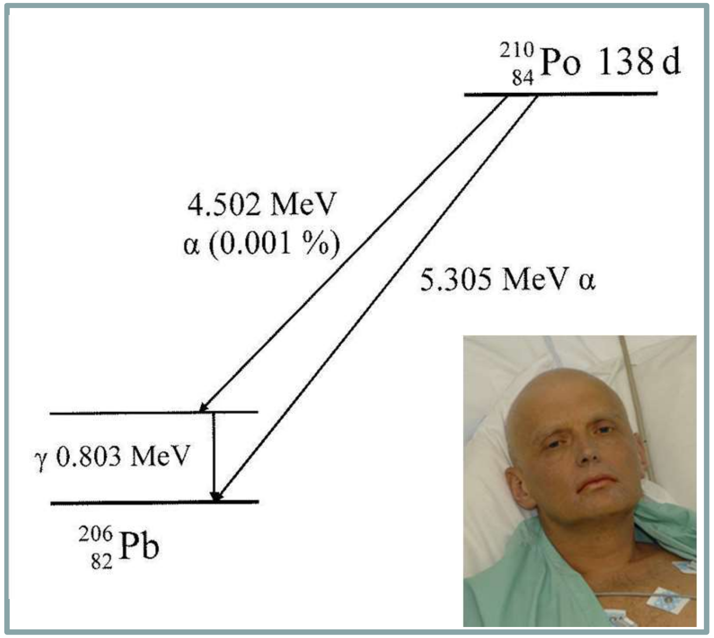


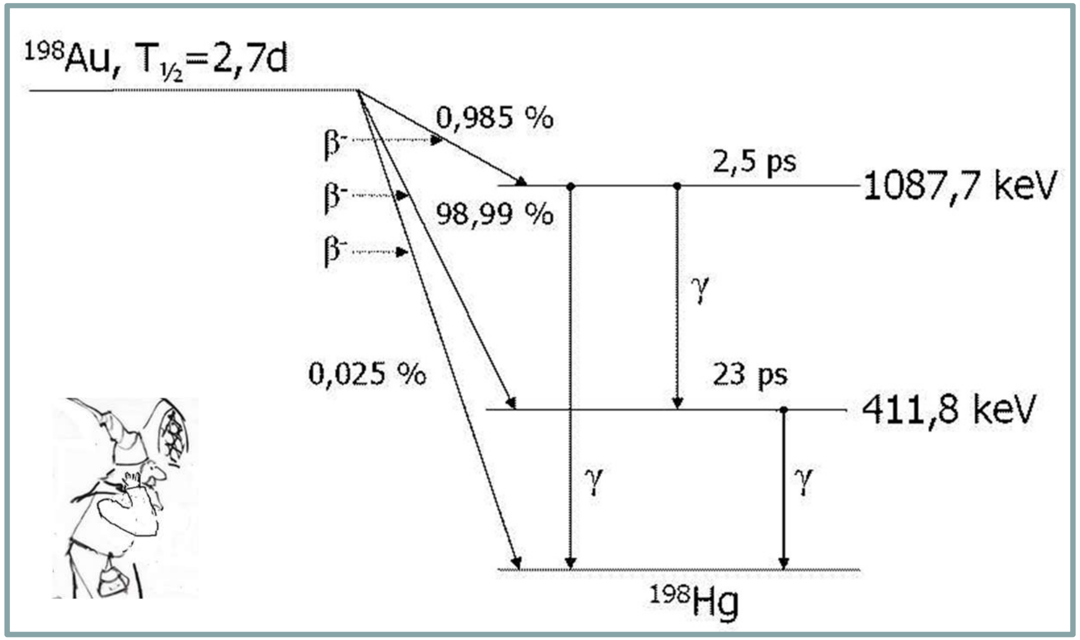


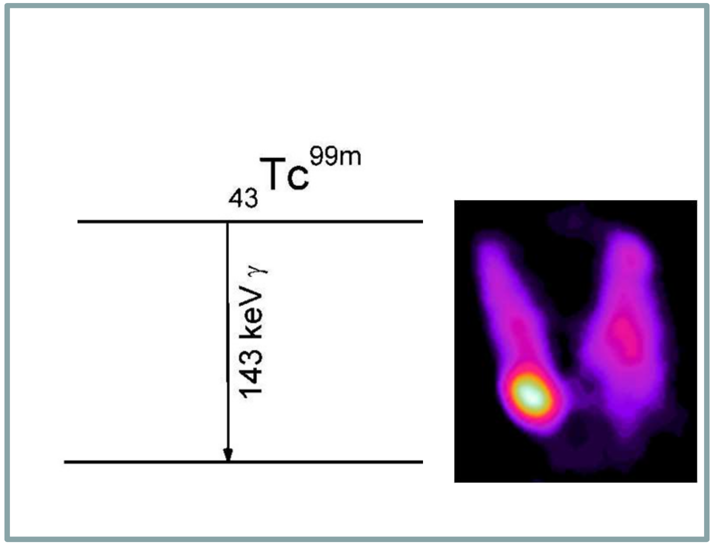


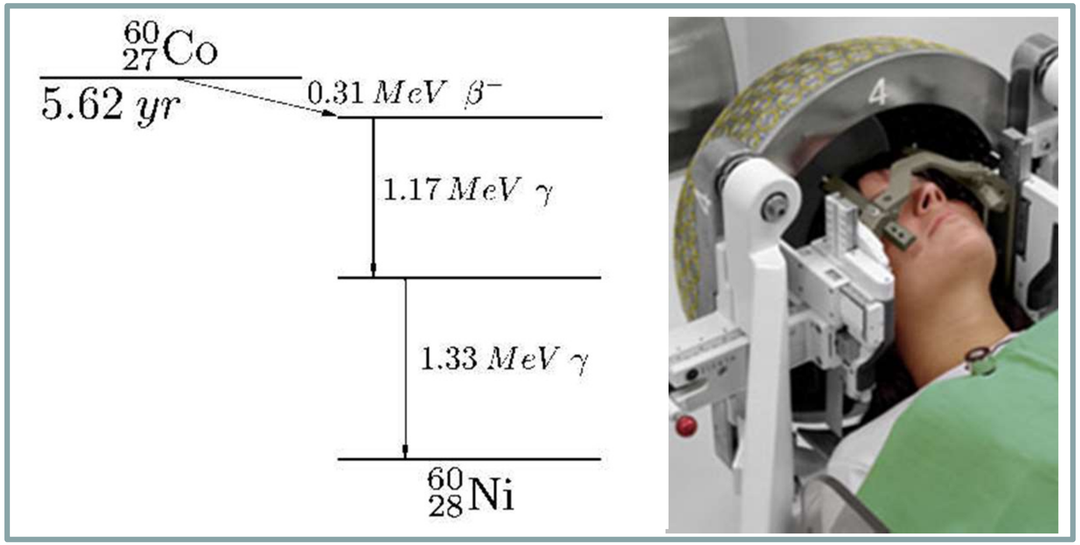


Some examples of the decay paths









How to produce radioactive isotopes?

β^- decaying:

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

β^+ decaying:

p surplus → irradiate by protons

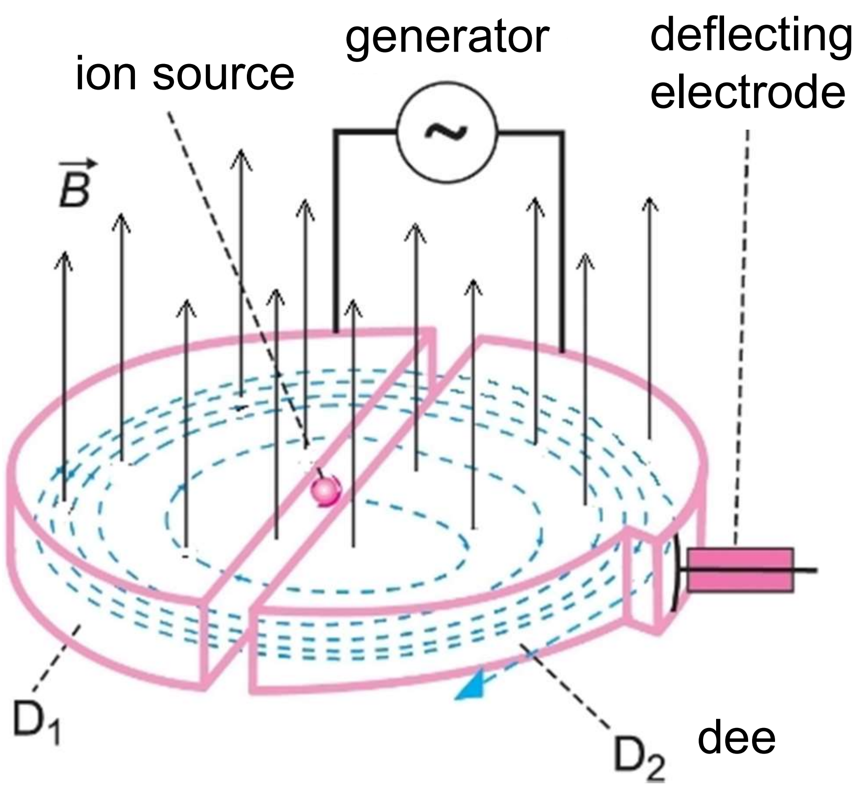
Coulomb repulsion → you need accelerated protons!

→ cyclotron

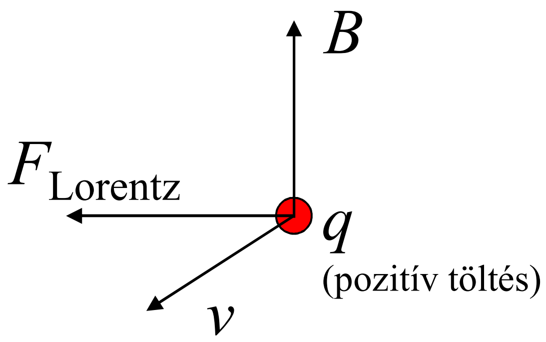
Cyclotron

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

kBq, MBq, GBq, TBq

immeasurably small

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

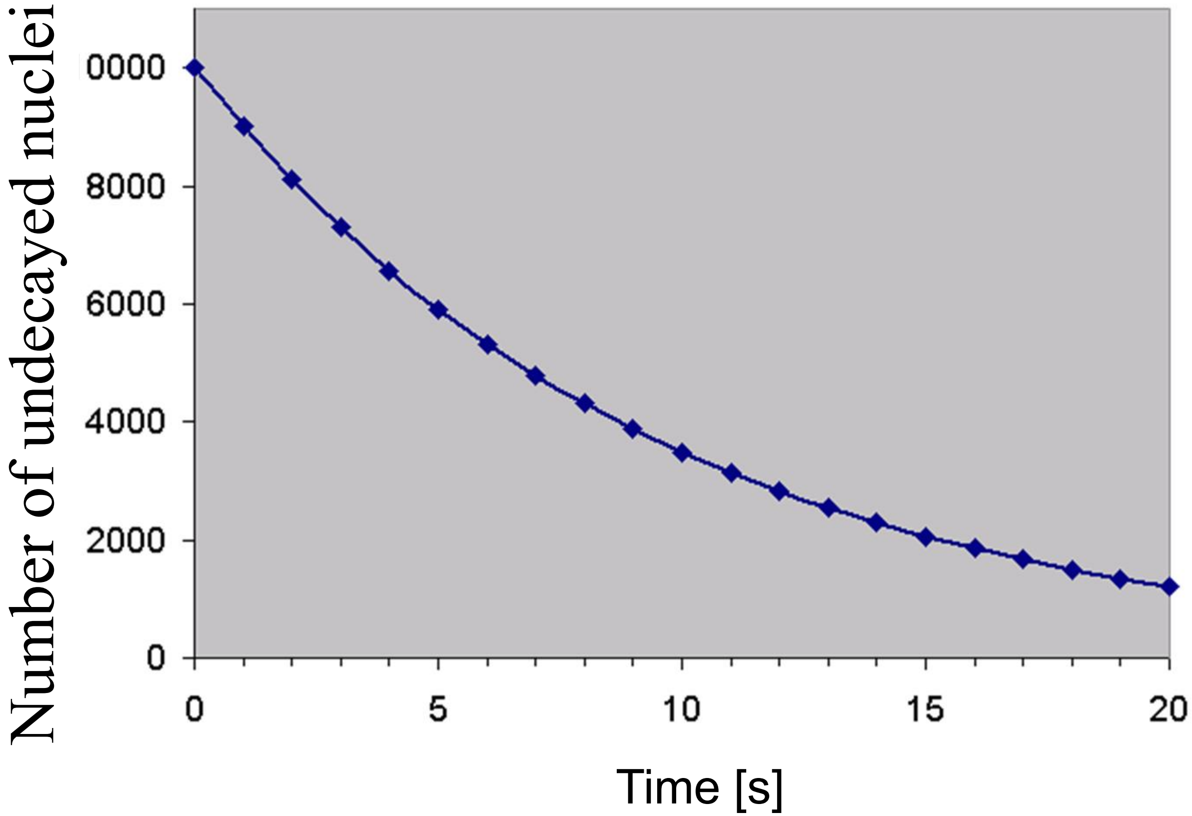
number of undecayed atoms at t=0

An example

- $N_0=10000$ $\lambda=0.1\ ^1/_s$
- 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)
- ….

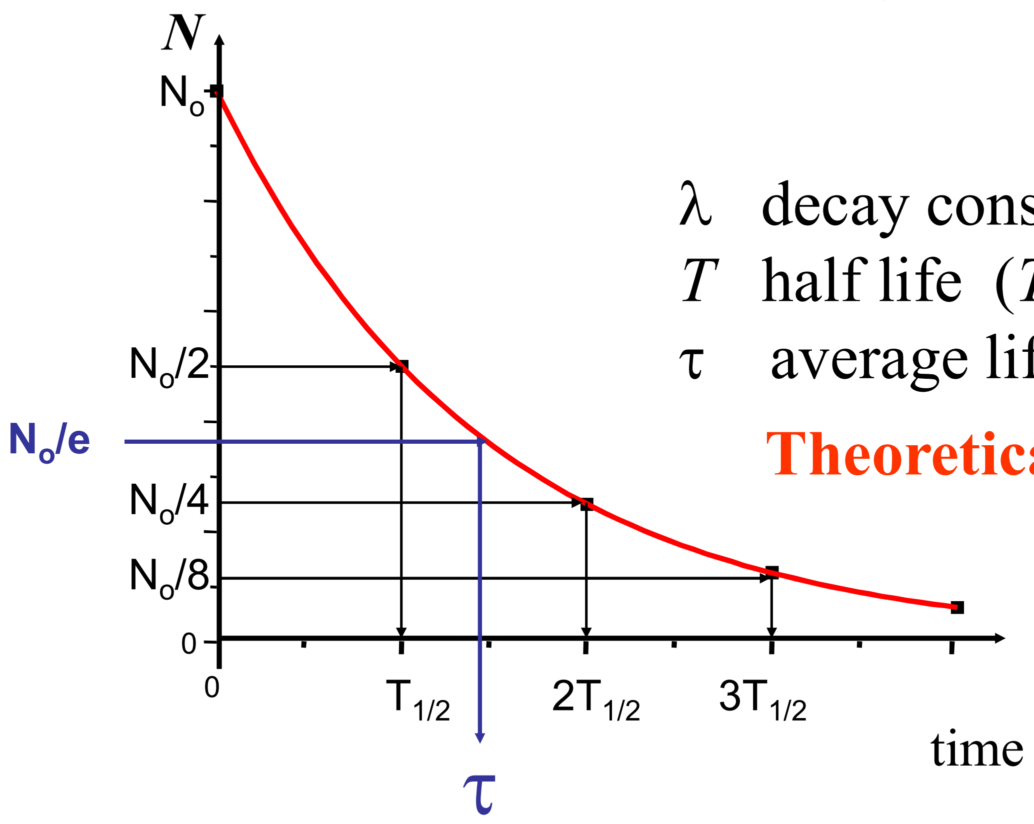
An example

- 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 !

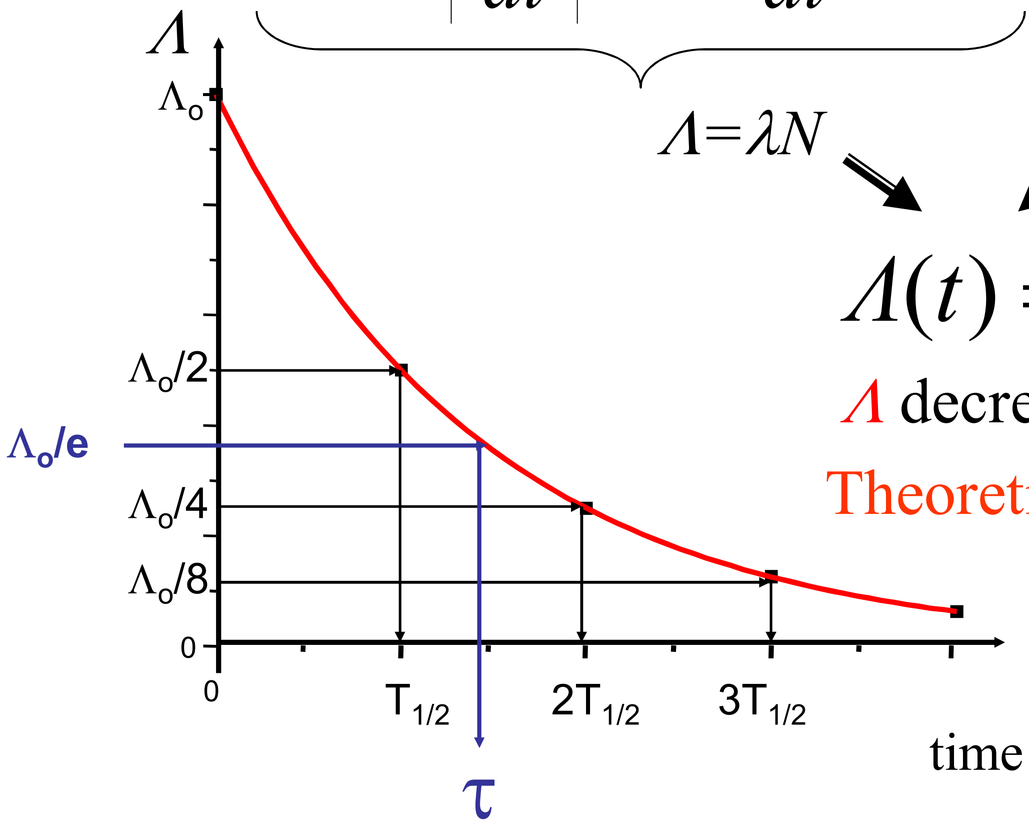
$$\lambda = \frac{\ln 2}{T} = \frac{0{,}693}{T}$$

Decrease of the activity as a function of time

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

$$\Lambda = \lambda N$$

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



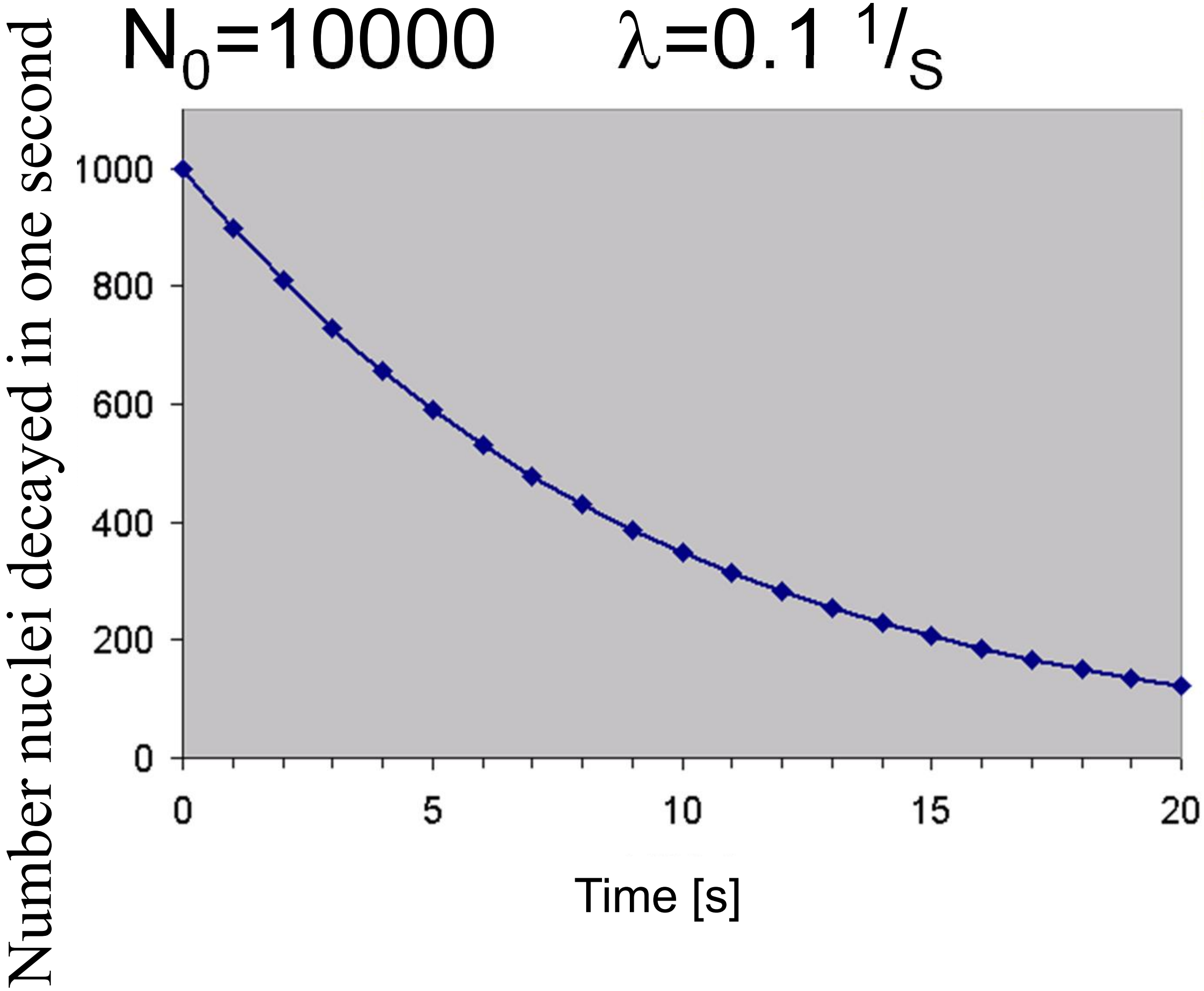
Λ decreases on the same mode as N!

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
^{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

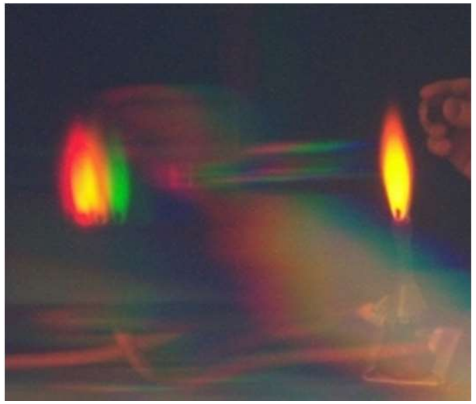
Don't learn these numbers!

Typical energy levels in the microworld

Excitation of the outer electrons

eV (aJ)

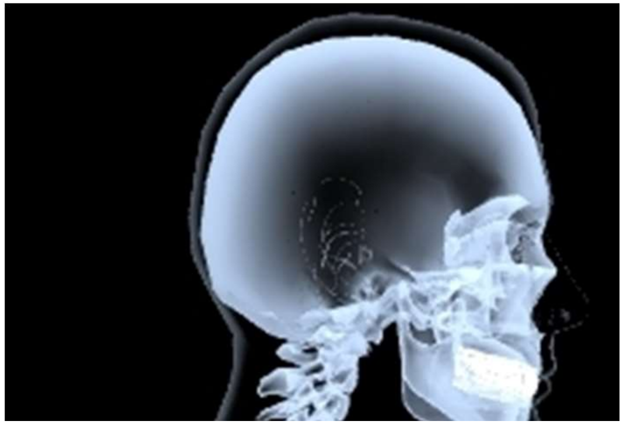
light



Electron transition between inner electrons

keV (fJ)

X-ray

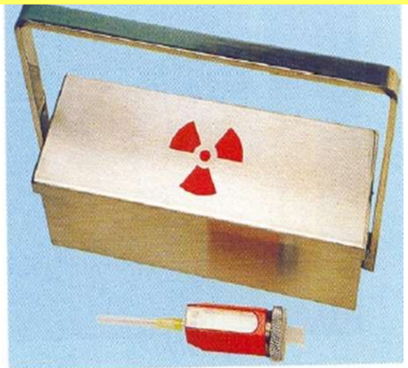


Transformation of the nucleus (decay)

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!

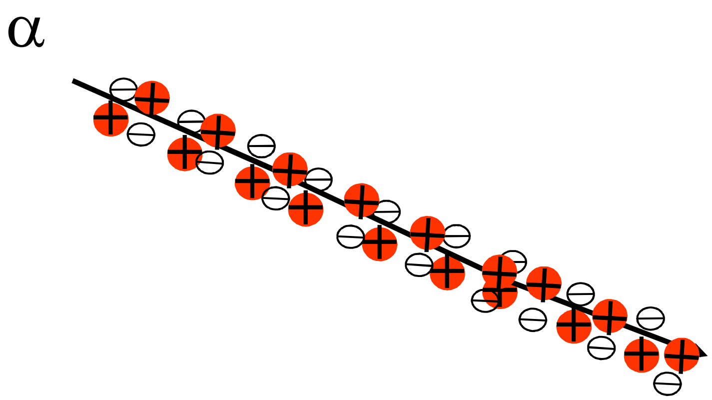
γ, (x-ray) — uncharged particles (photons) — indirect ionisation

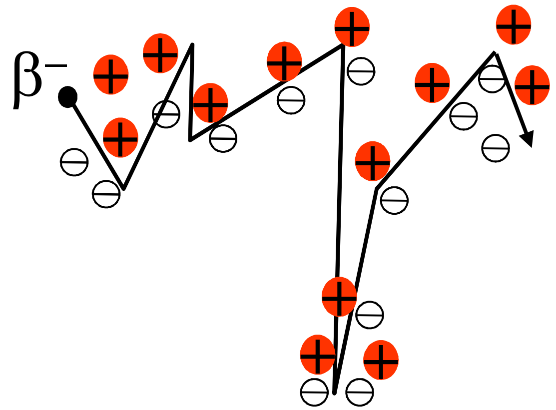
not a nuclear radiation, but its absorption
is similar to that of the γ radiation

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

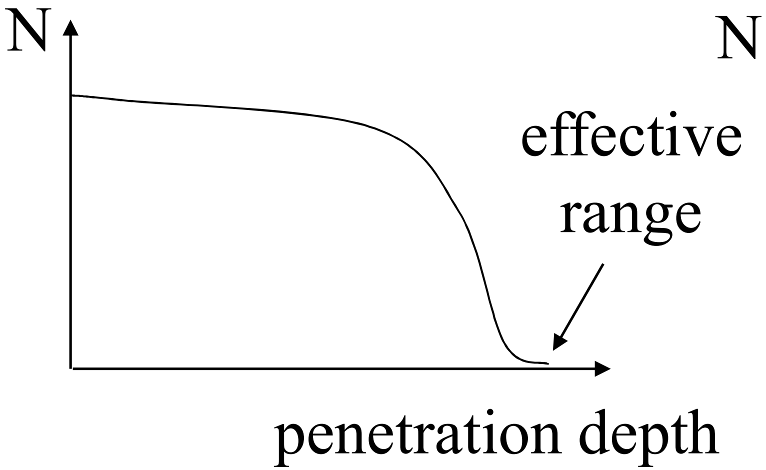
effective range

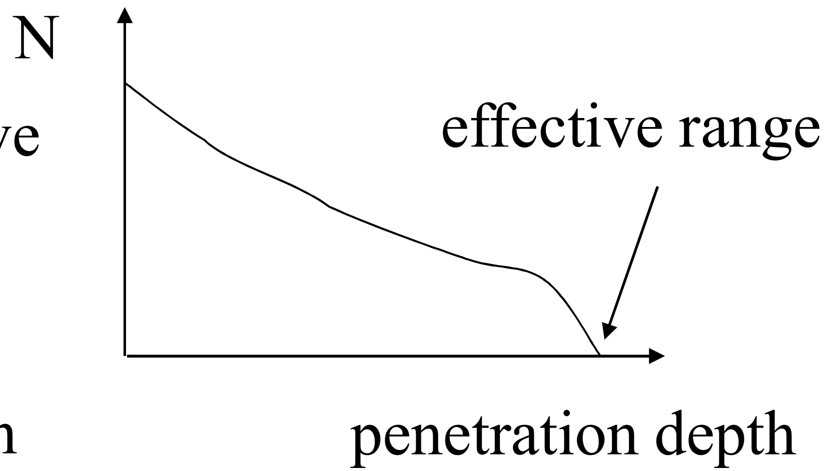




Effective range

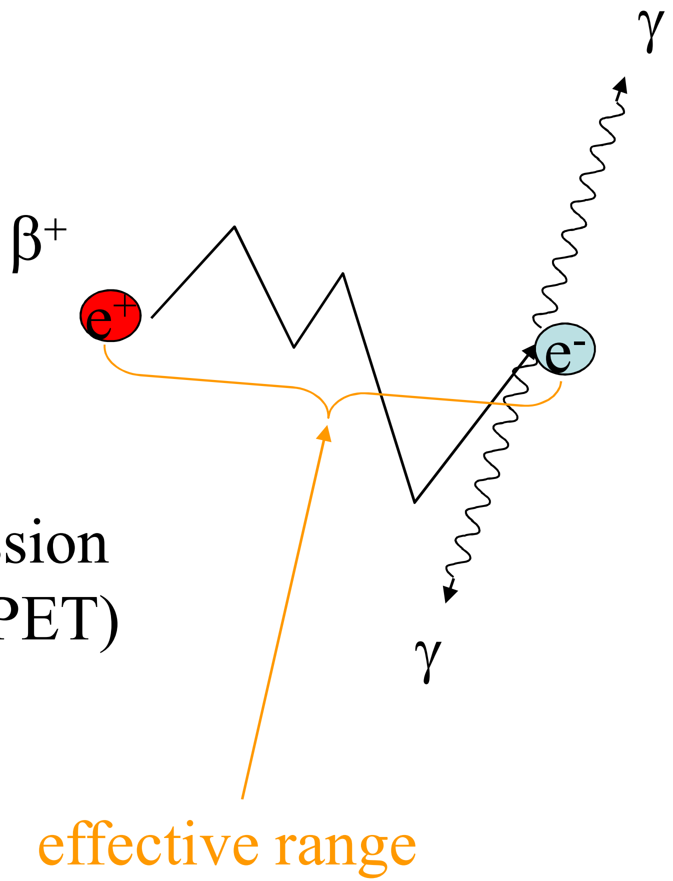
	α-particle	β^--particle
in air	**few cm**	**~ m**
in tissue	**0,01-0,1 mm**	**~ cm**





β^+-radiation

annihilation

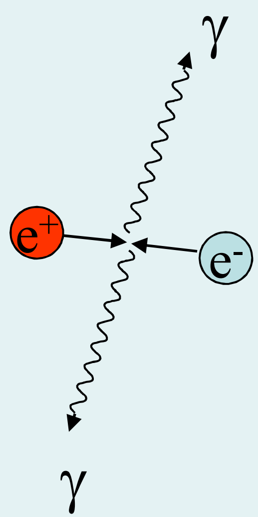


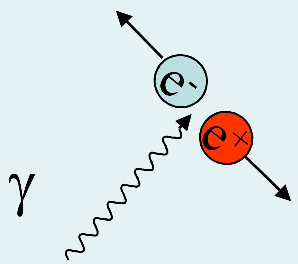
see: Positron Emission
Tomography (PET)

Electron and positron

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

annihilation and pair production





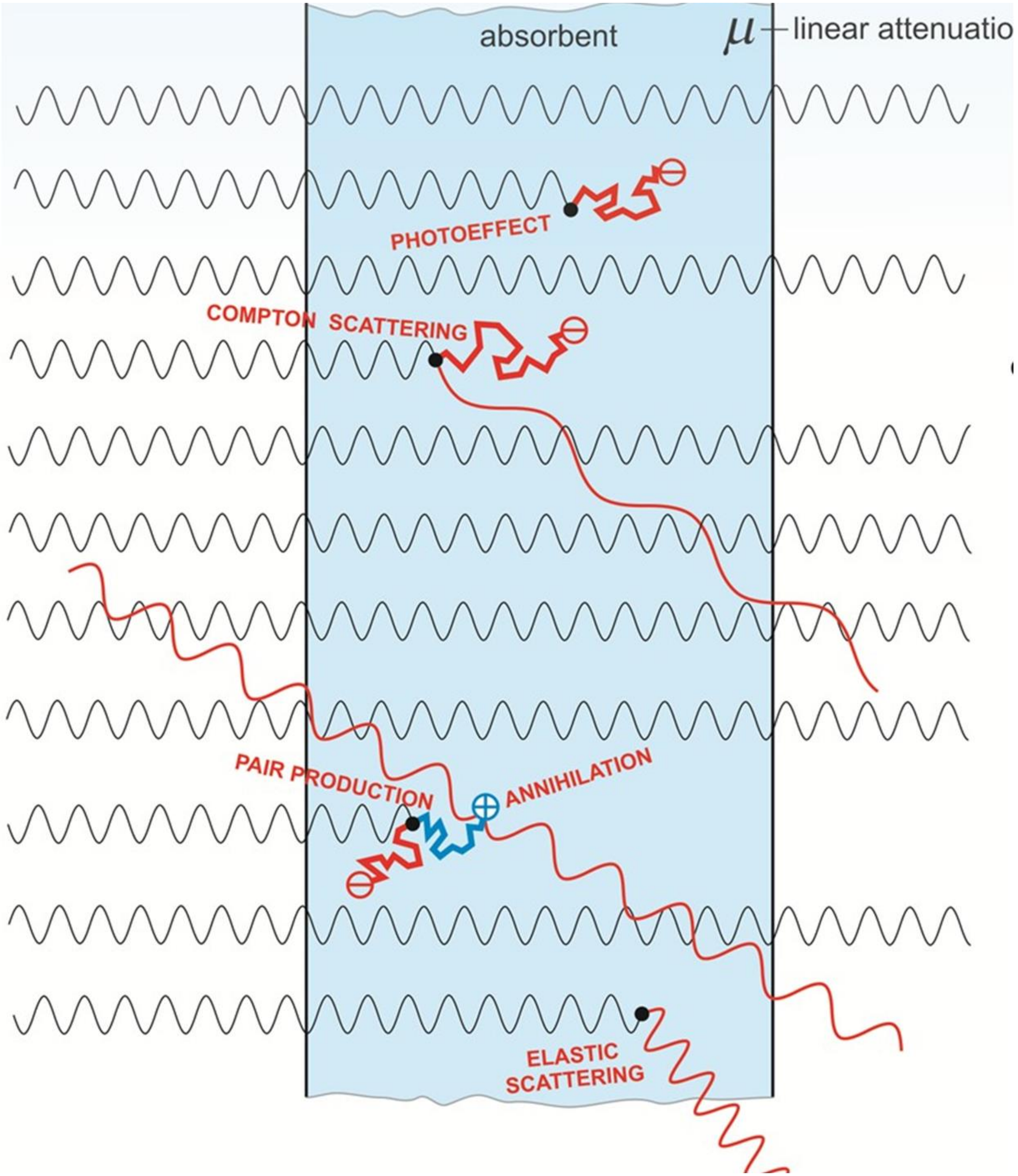
Einstein:

mass-energy ekvivalence

$$E=mc^2$$

$m_e c^2$=511 keV≈0,5 MeV

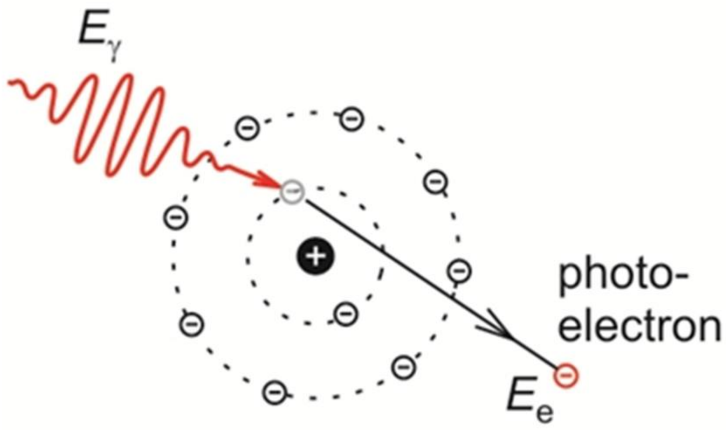
Absorption of the γ-radiation (and x-ray)



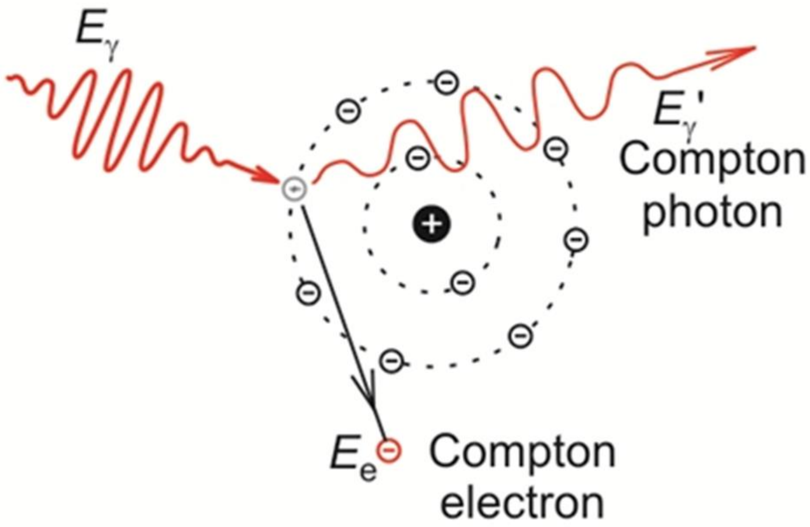
Absorption processes happen accidentally :

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

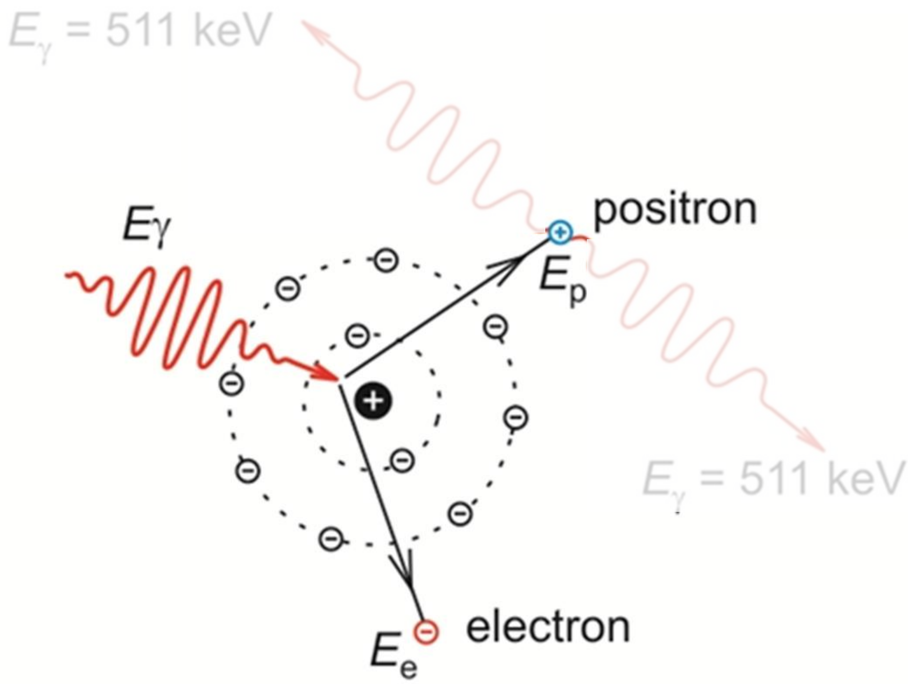
Photoeffect



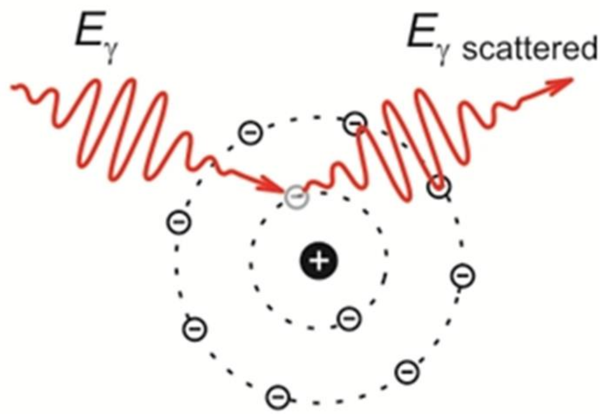
Compton effect
Compton-scattering



Pair production

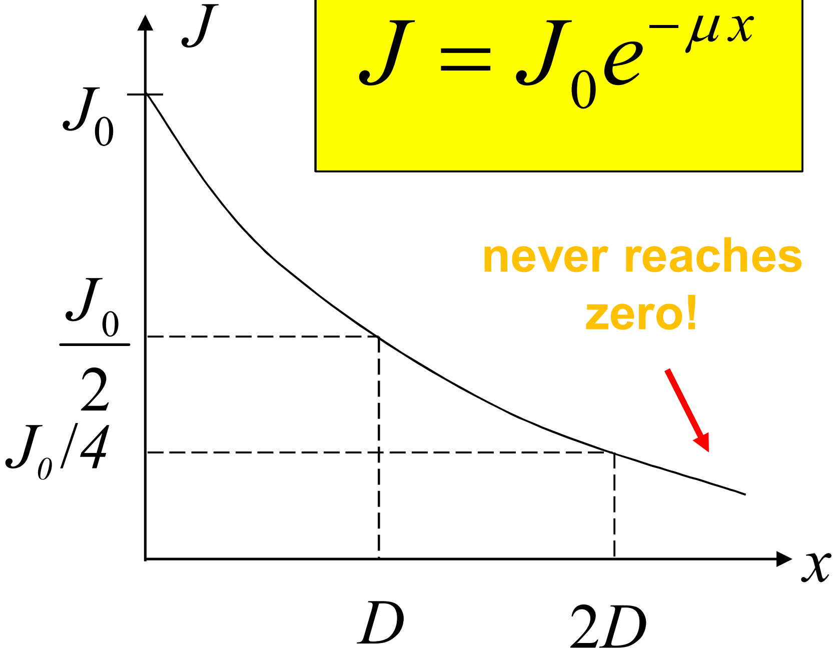


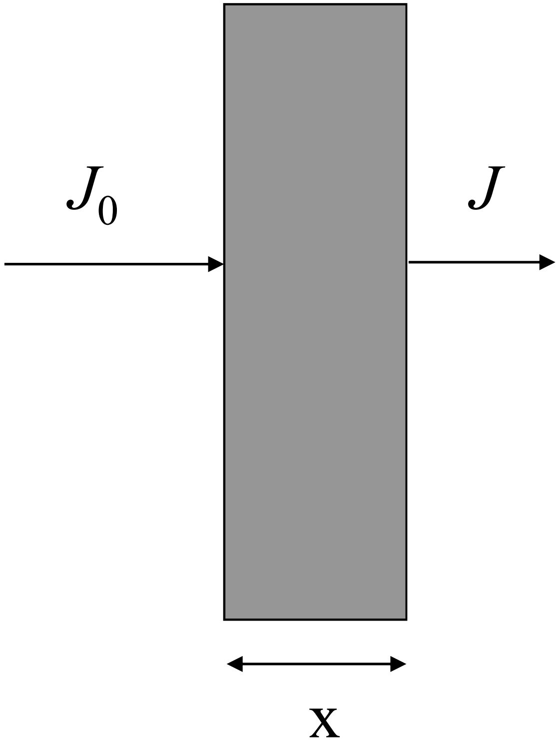
elastic scattering



Attenuation
of the γ–radiation and x-ray

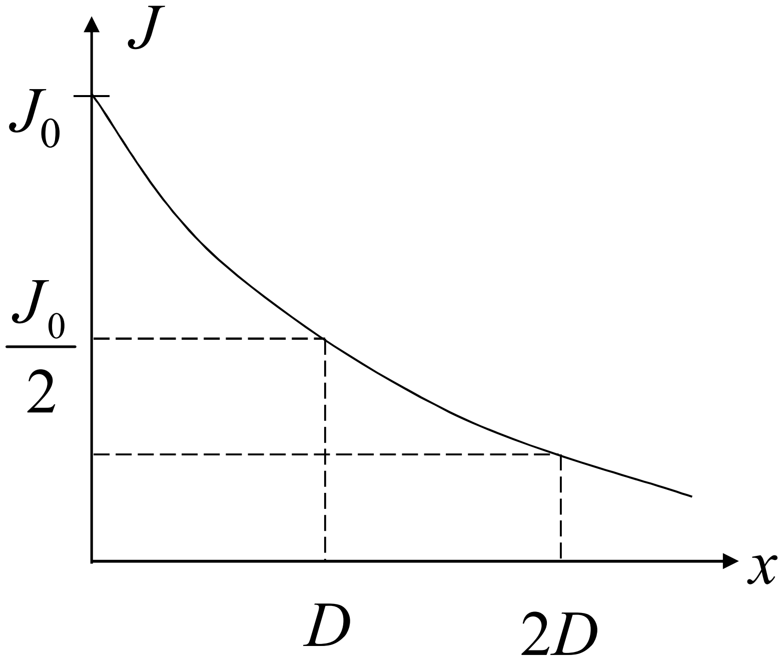
$$J = J_0 e^{-\mu x}$$





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

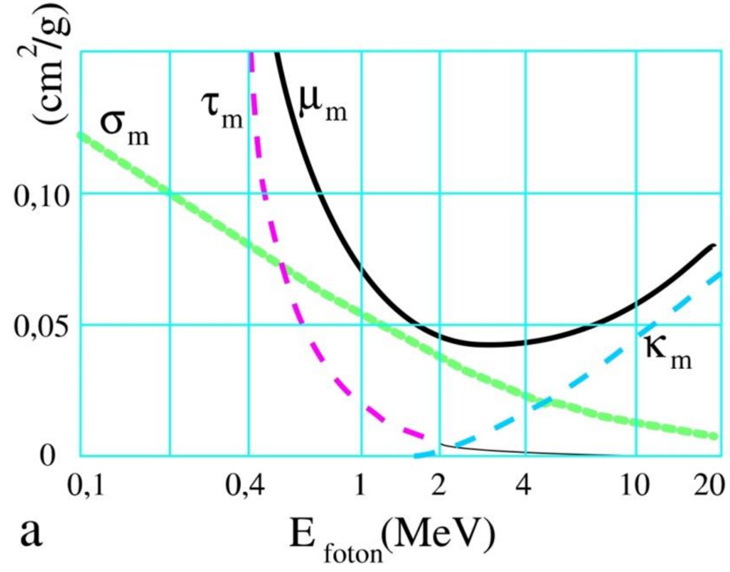
$$\mu_m = \frac{\mu}{\rho}$$ mass attenuation coefficient

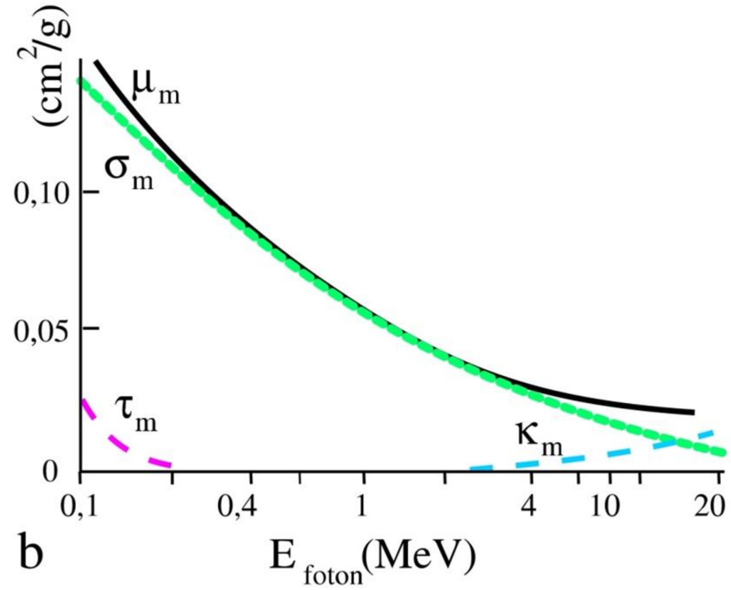
mass attenuation coeff.

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

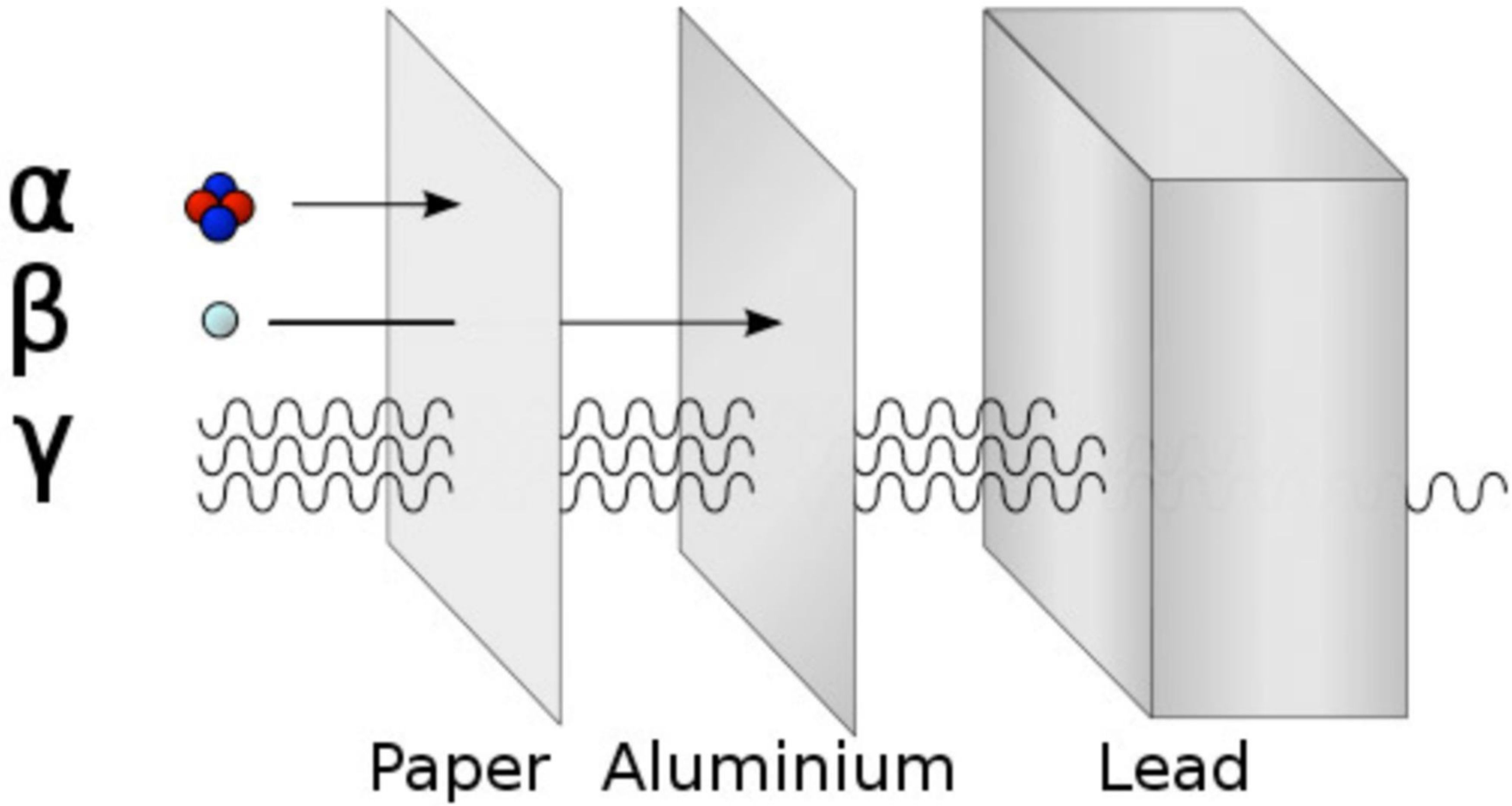
$$\mu_m = \tau_m + \sigma_m + \kappa_m$$

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





Summary of the absorption of α, β and γ radiation



Applications (attenuation)

lead glass

protective apron

Applications: isotopes and nuclear radiation