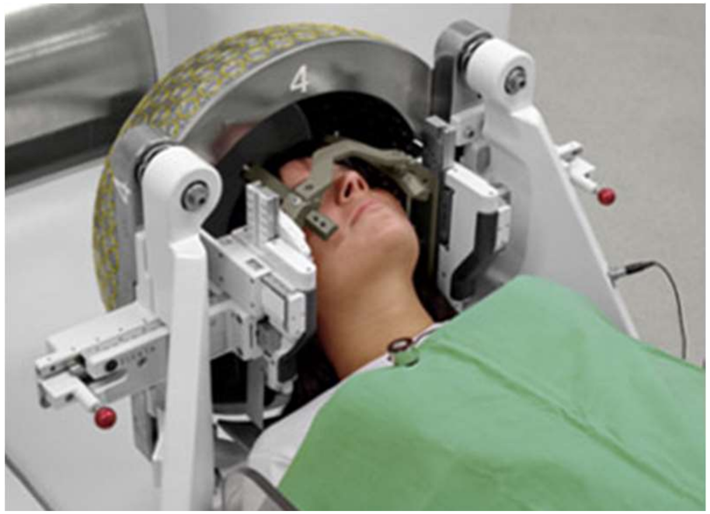
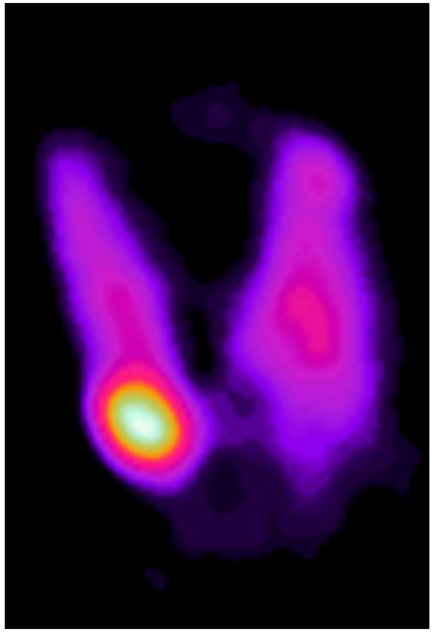
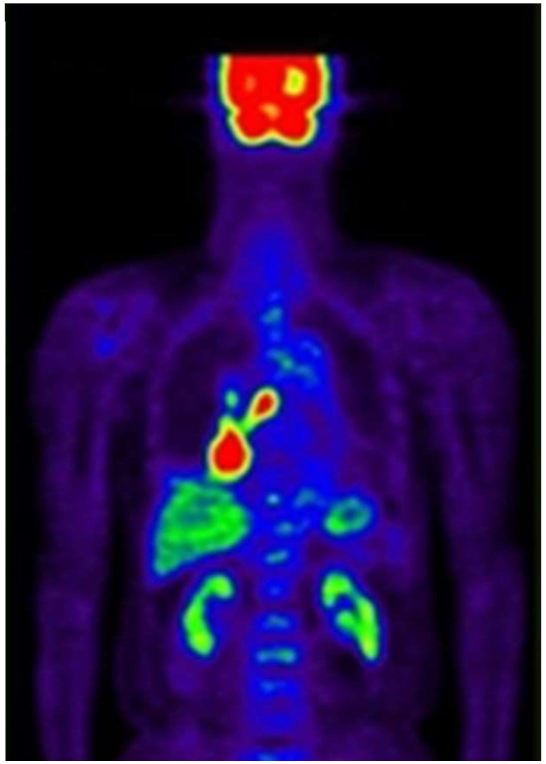
The atomic nucleus. Radioactivity. Nuclear radiations

László Smeller



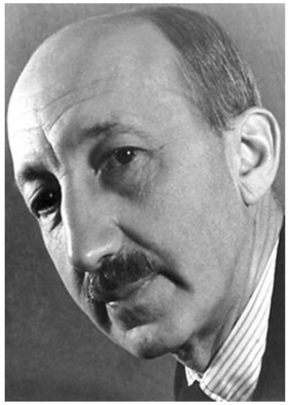




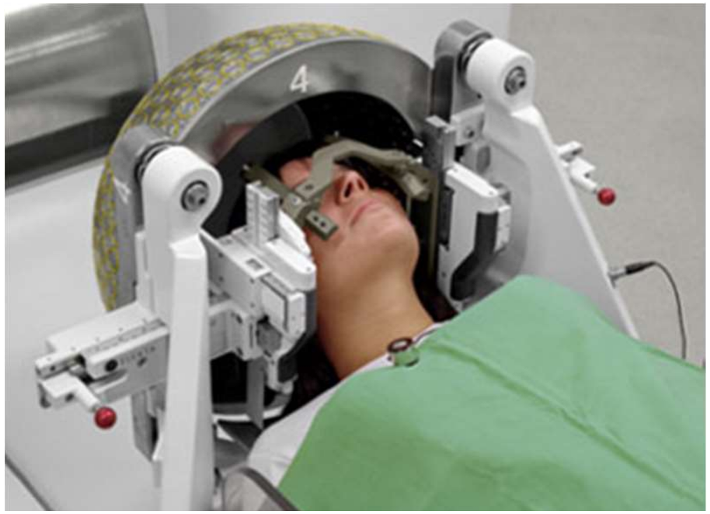
Why?

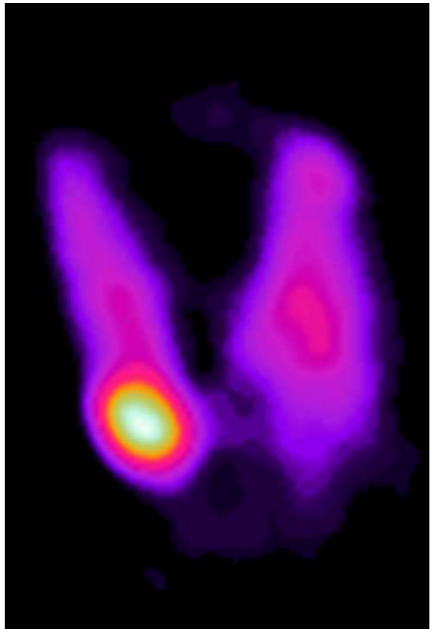
Medical applications:

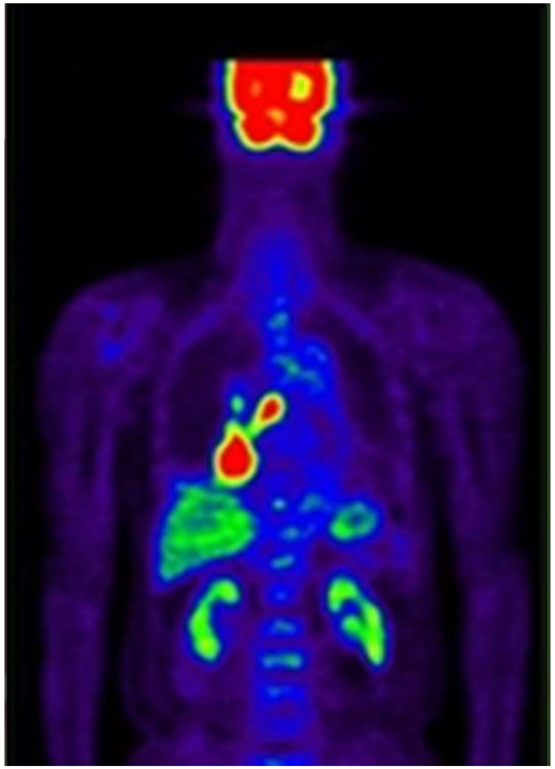
- Nuclear imaging
- Radiotherapy



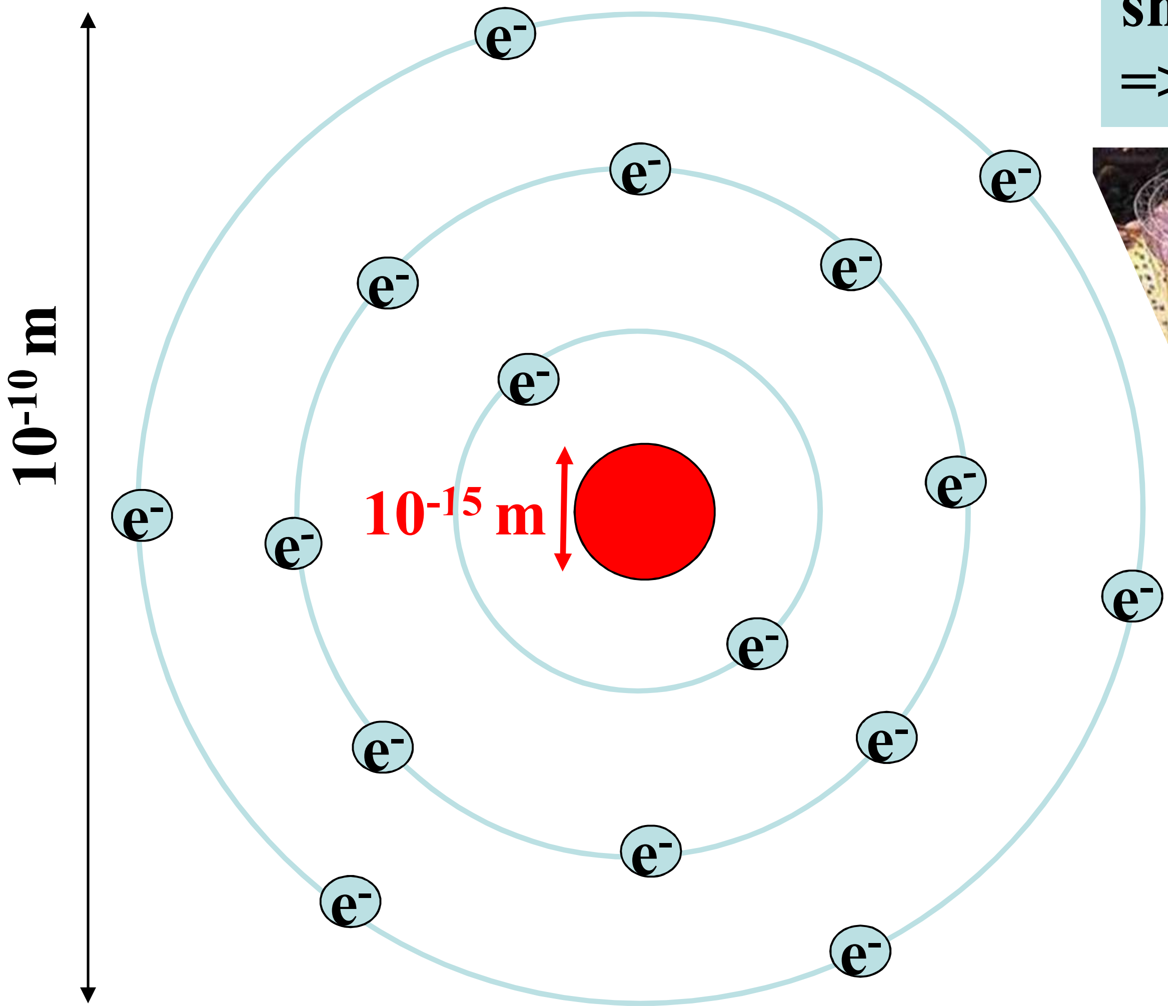
György Hevesy
Nobel prize 1943







Atom: electrons and nucleus

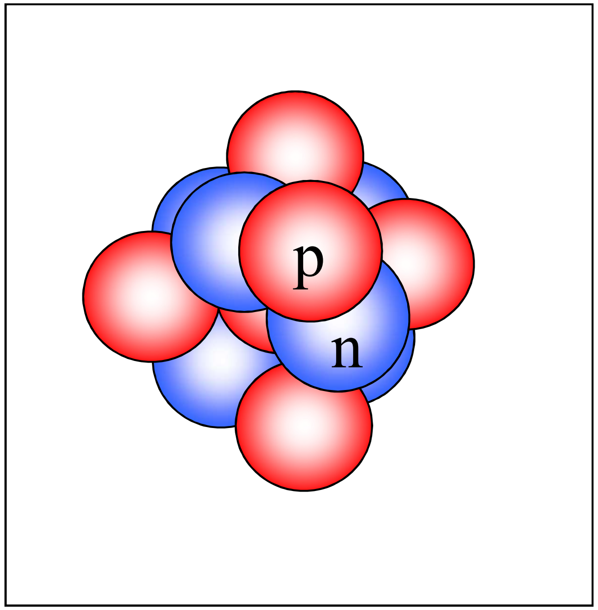


Changes in the electron shell:
=>chemical processes

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

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

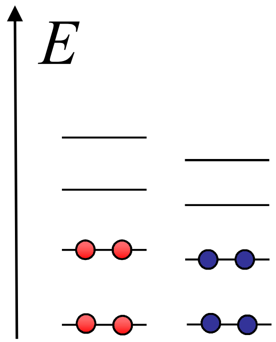
99 nucleon, 43 proton and 56 neutron

Stability of the nucleus

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

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

- Quantized energy levels for the nucleus.



- Typical binding energy is in the MeV range
  $eV = 1.6 \cdot 10^{-19}$ J

Isotopes

Variants of an element, wich differ in

- number of neutrons

=> mass number

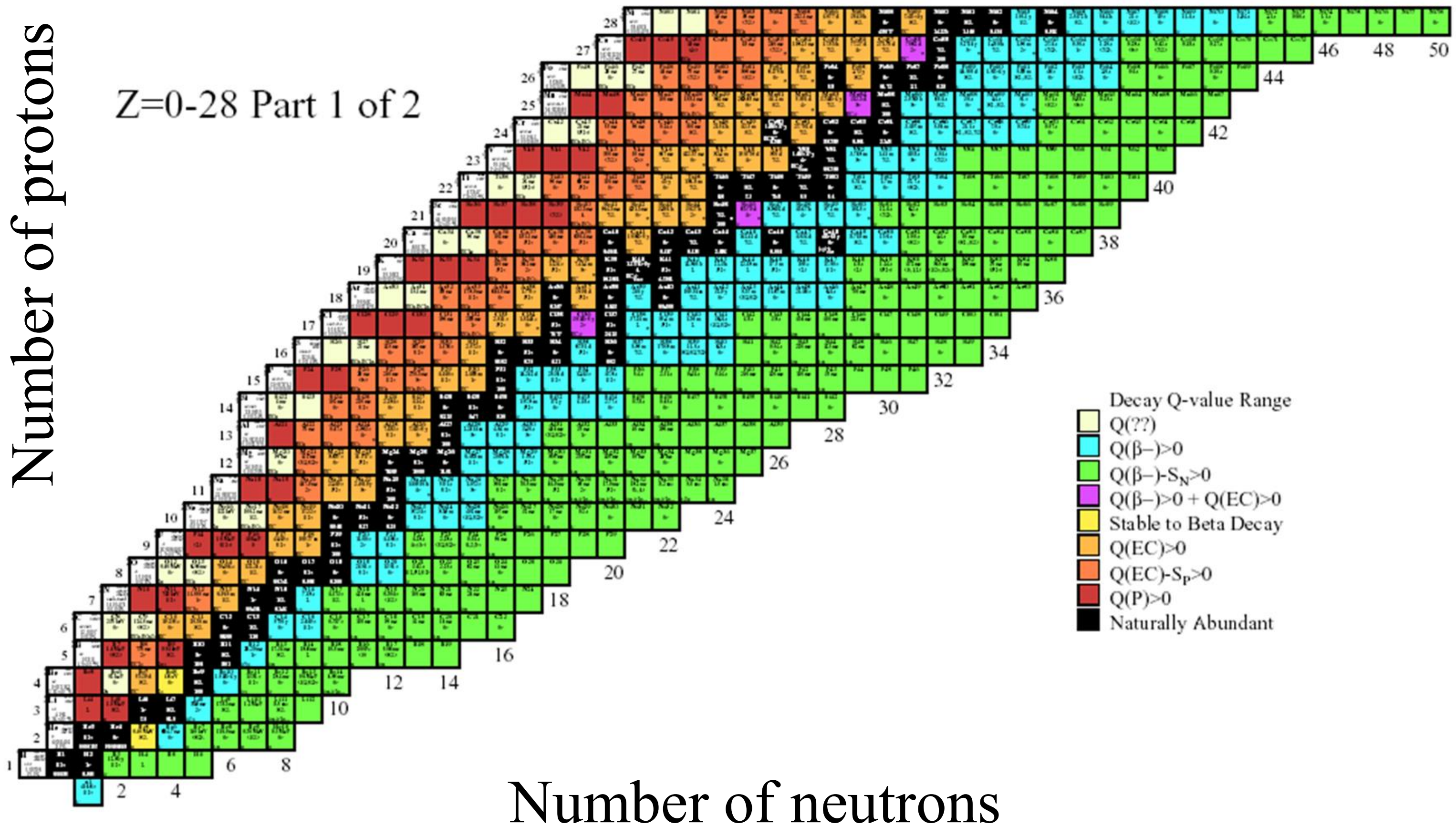
Remark:
The numbers of protons (=atomic numbers) are the same.

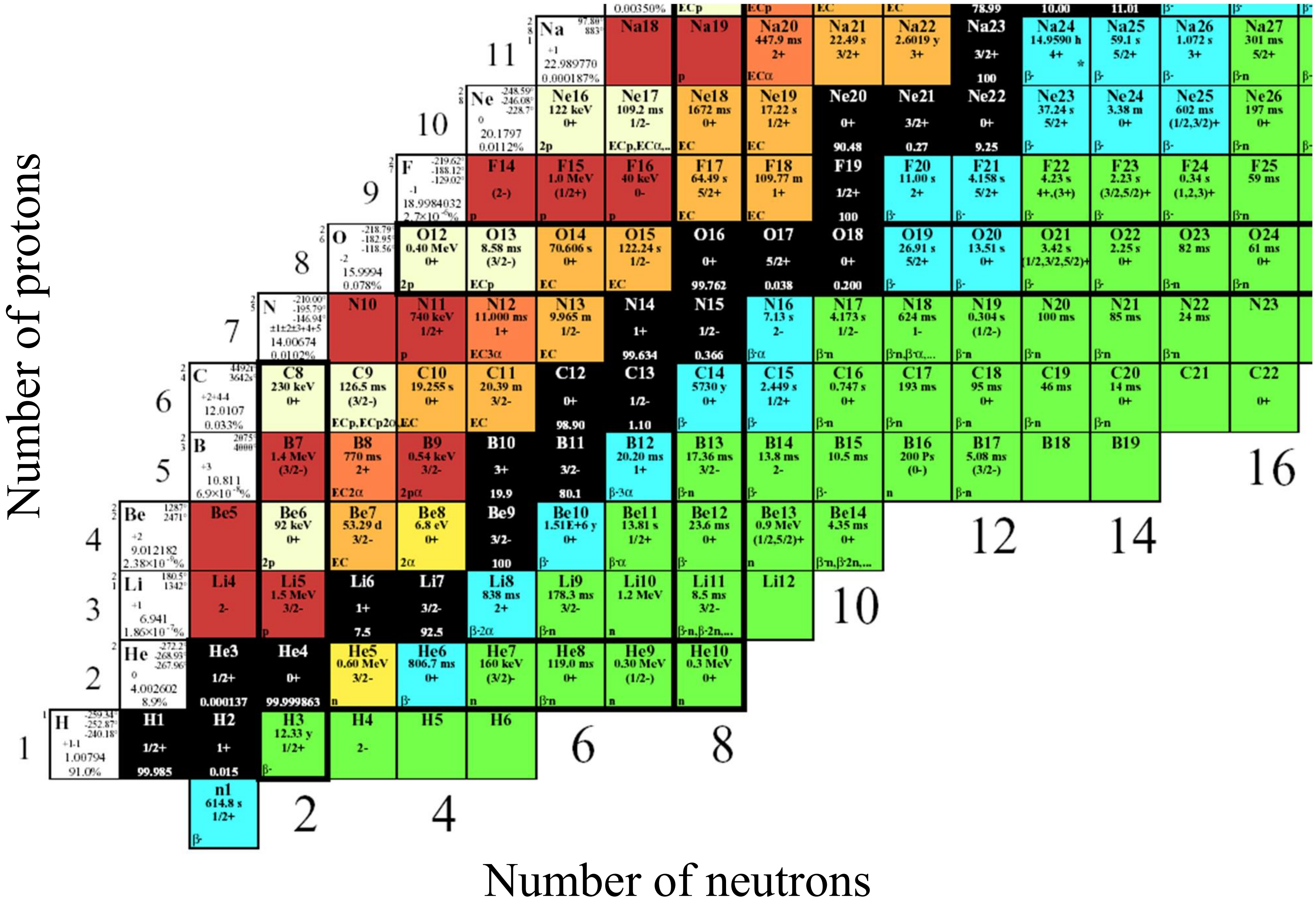
E.g.: $^{18}_{9}F$ $^{19}_{9}F$ $^{20}_{9}F$

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

isotope <-> radioactive isotope

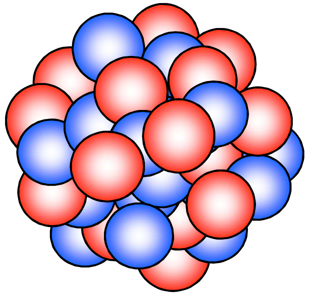
Table of isotopes




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
n1
H H1 H2 H3 H4 H5 H6
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 Na18 Na19 Na20 Na21 Na22 Na23 Na24 Na25 Na26 Na27

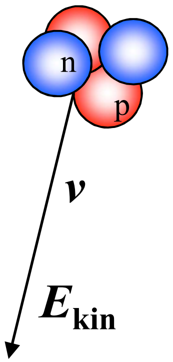
Radioactive decays and particles

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

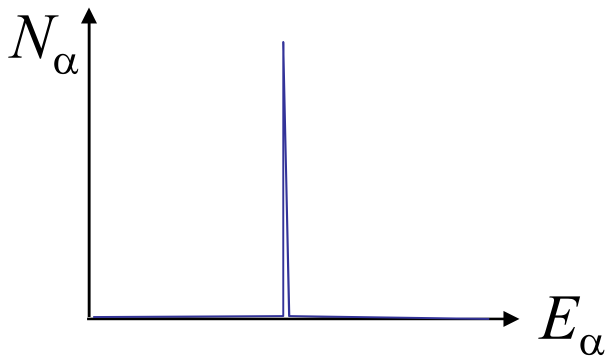
an α particle (^4He nucleus) will be emitted
typical for the heavy atoms



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

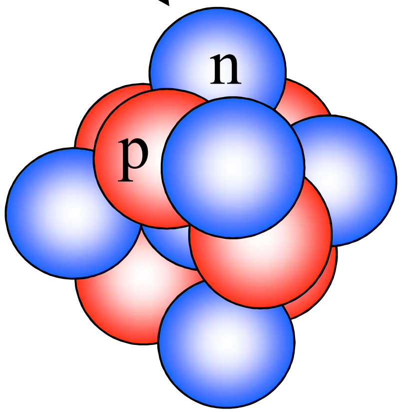
e.g. $$ {}_{88}^{226}\mathrm{Ra} \longrightarrow {}_{86}^{222}\mathrm{Rn} + {}_{2}^{4}\alpha $$

Energy distribution: line spectrum
$E_\alpha \sim$ MeV



β^- - decay

neutron surplus



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

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

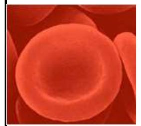
remains in the nucleus

leave the nucleus

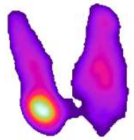
e.g.:

$^{20}_{9}F$

$^{32}_{15}P$

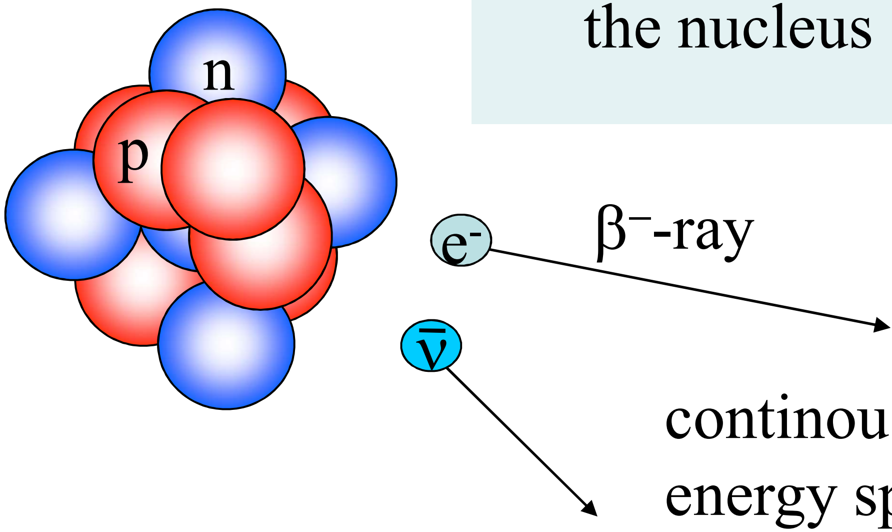


$^{59}_{26}Fe$

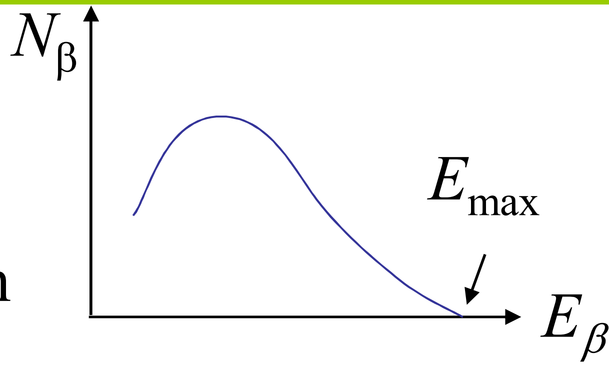


$^{131}_{53}I$

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



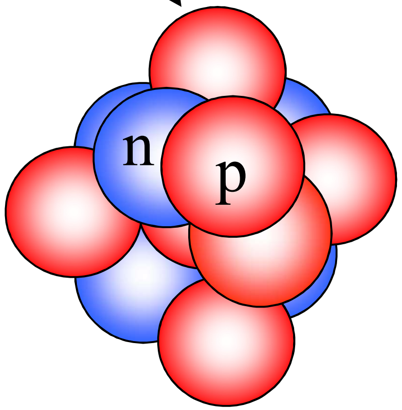
continous energy spectrum



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

β^+ - decay

proton surplus



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

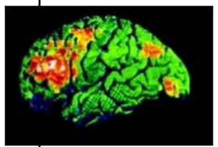
$$^{1}_{1}p \rightarrow {}^{1}_{0}n + {}_{+1}\beta + \nu$$

remains in the nucleus

leave the nucleus

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

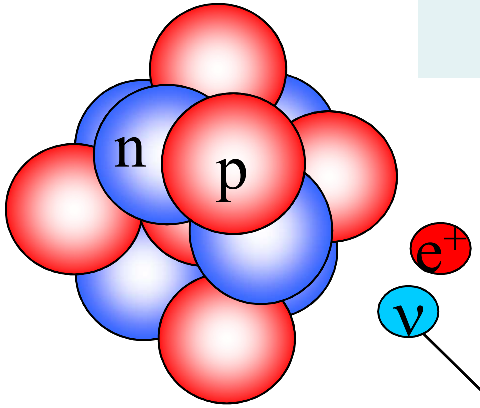
$^{15}_{8}O$



$^{18}_{9}F$

$^{52}_{26}Fe$

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



β^+-ray

continous energy spectrum

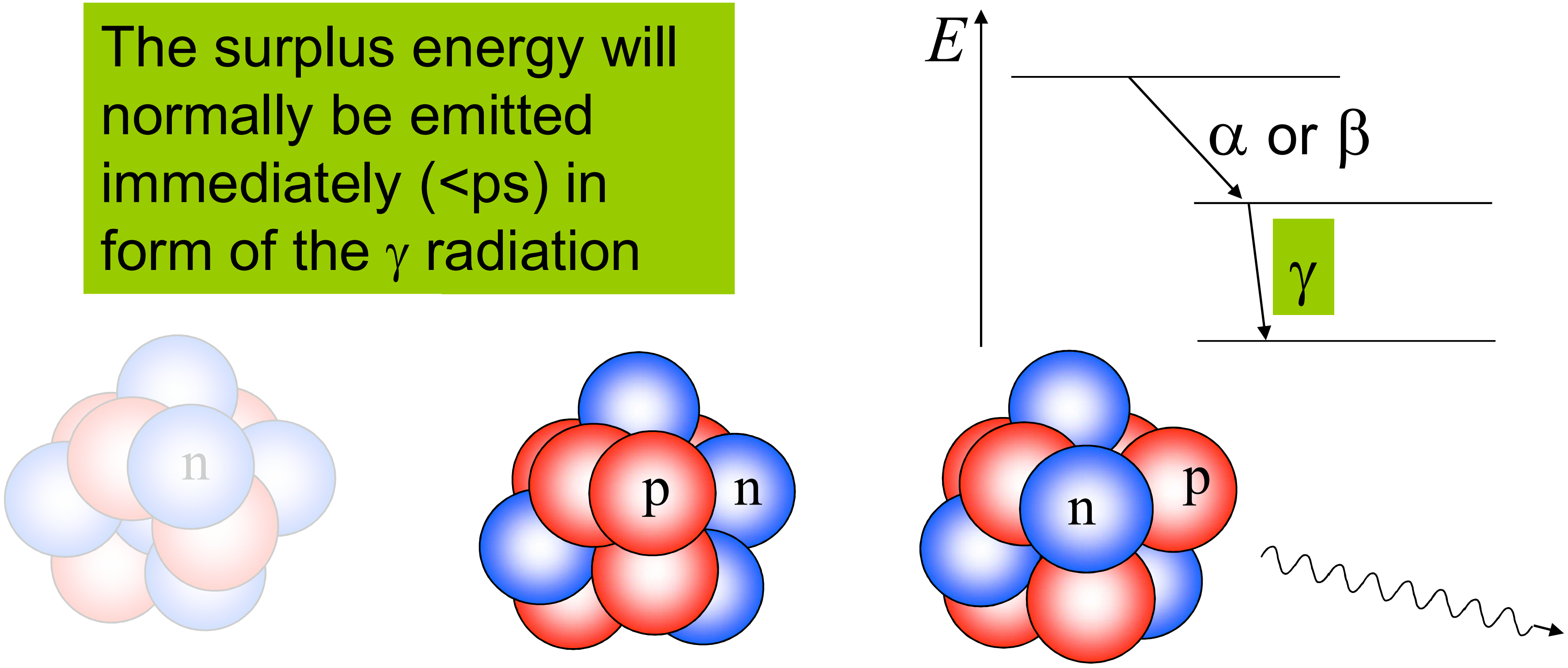
These isotopes must be produced artificially (e.g. in cyclotron)

Mecial application: PET

Prompt γ-radiation

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

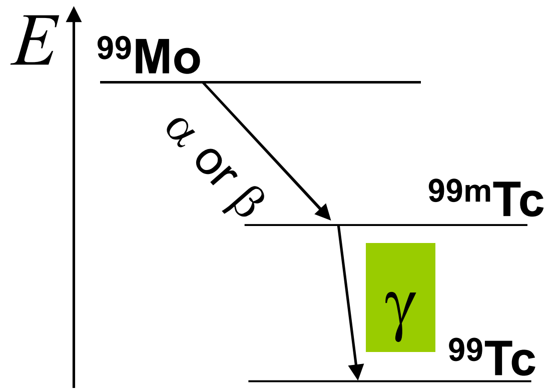
The surplus energy will normally be emitted immediately (<ps) in form of the γ radiation



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.



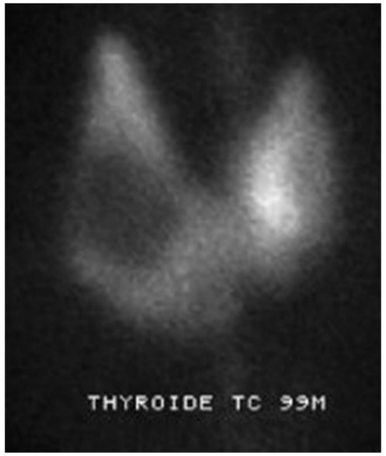
The parent and daughter atoms can be separated: the daughter atom emits **only γ-radiation!**

=> Isotope diagnostics (nuclear imaging)

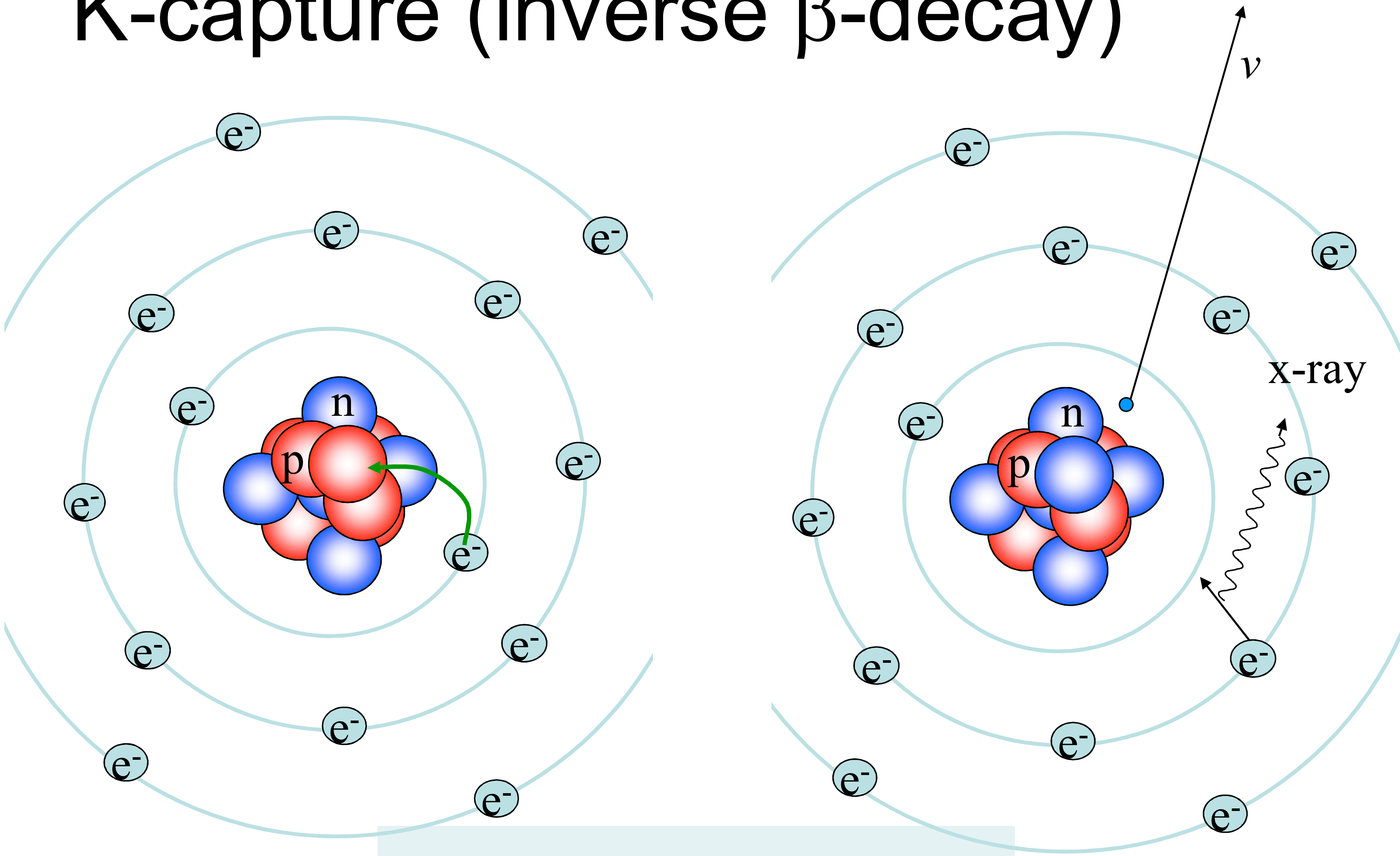
E.g.: ^{99m}Tc

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

66 h　　　6 h

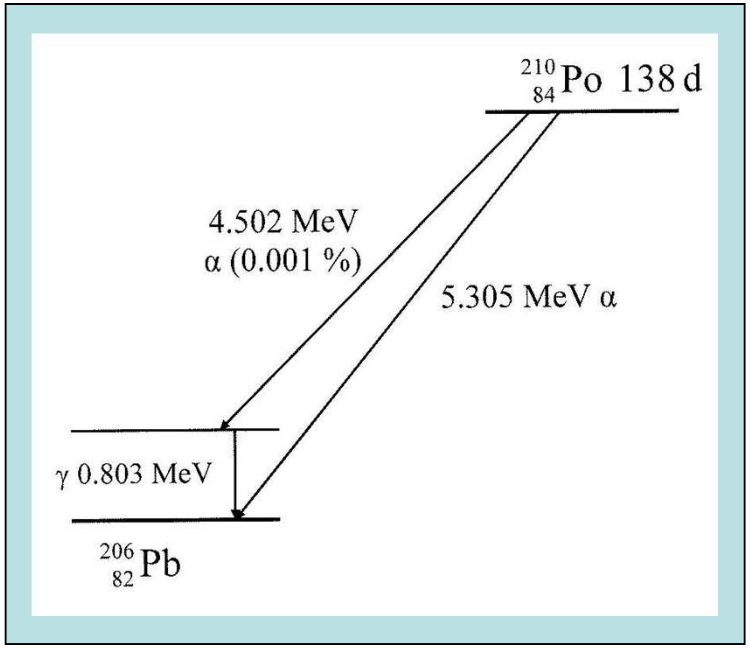


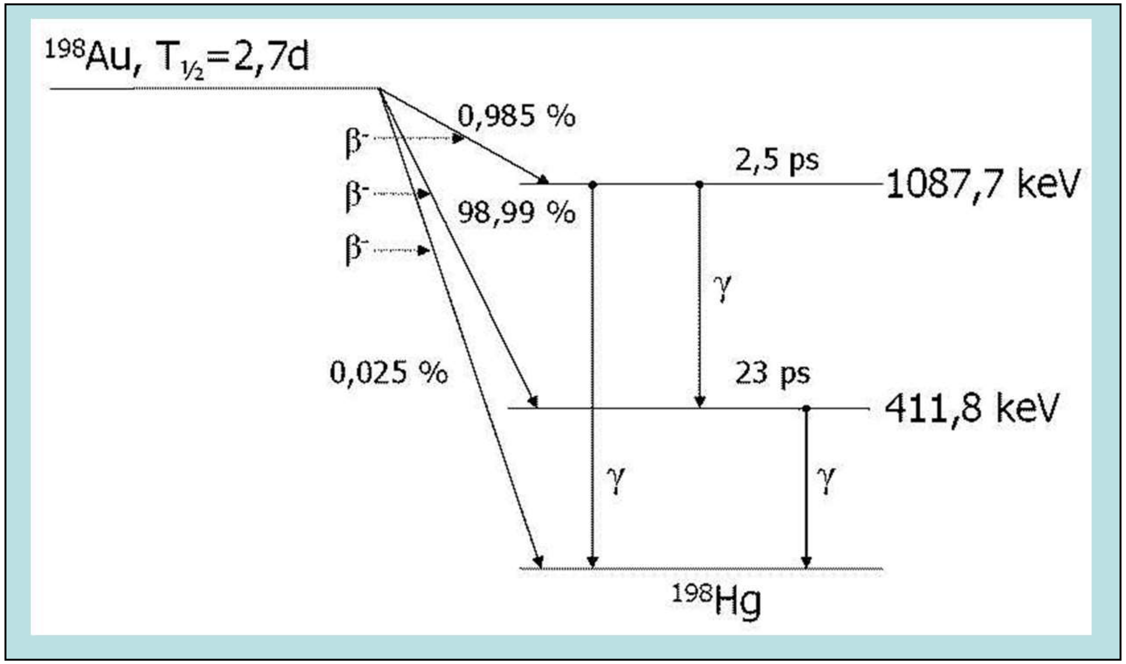
K-capture (inverse β-decay)

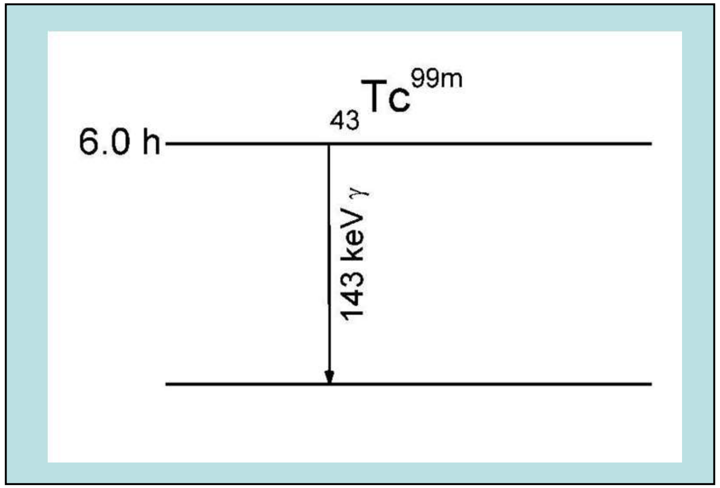


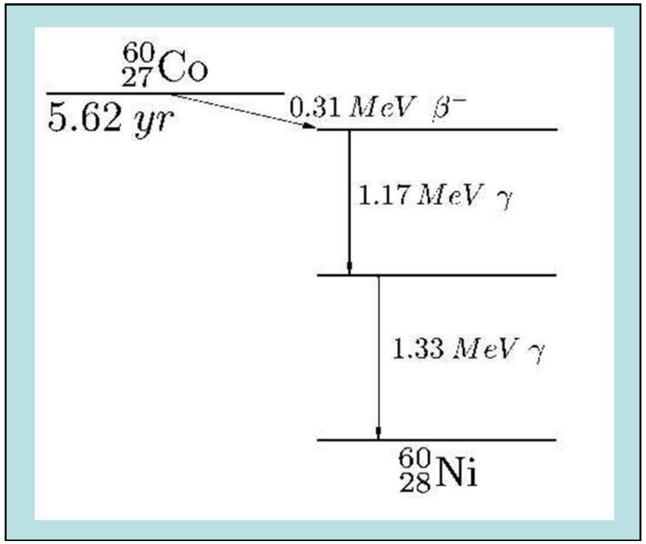
$$ {}_{1}^{1}p + {}_{-1}\beta \rightarrow {}_{0}^{1}n + \nu $$

Some examples of the decay paths









Characteristics of radioactive decays and of isotopes 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

level of natural activity

in vivo diagn.

work carefully with it!

activity used in radiotherapy

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)

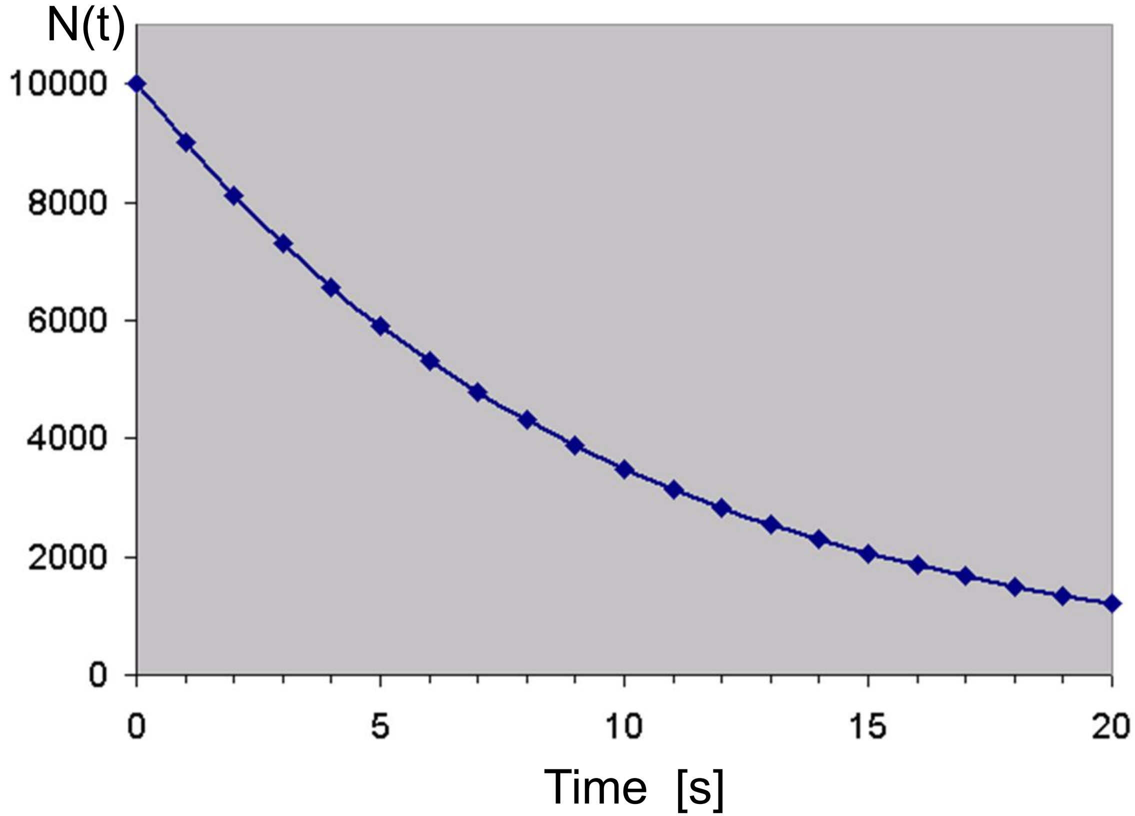
  $$\Delta N = -\lambda N \Delta t$$

- 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)

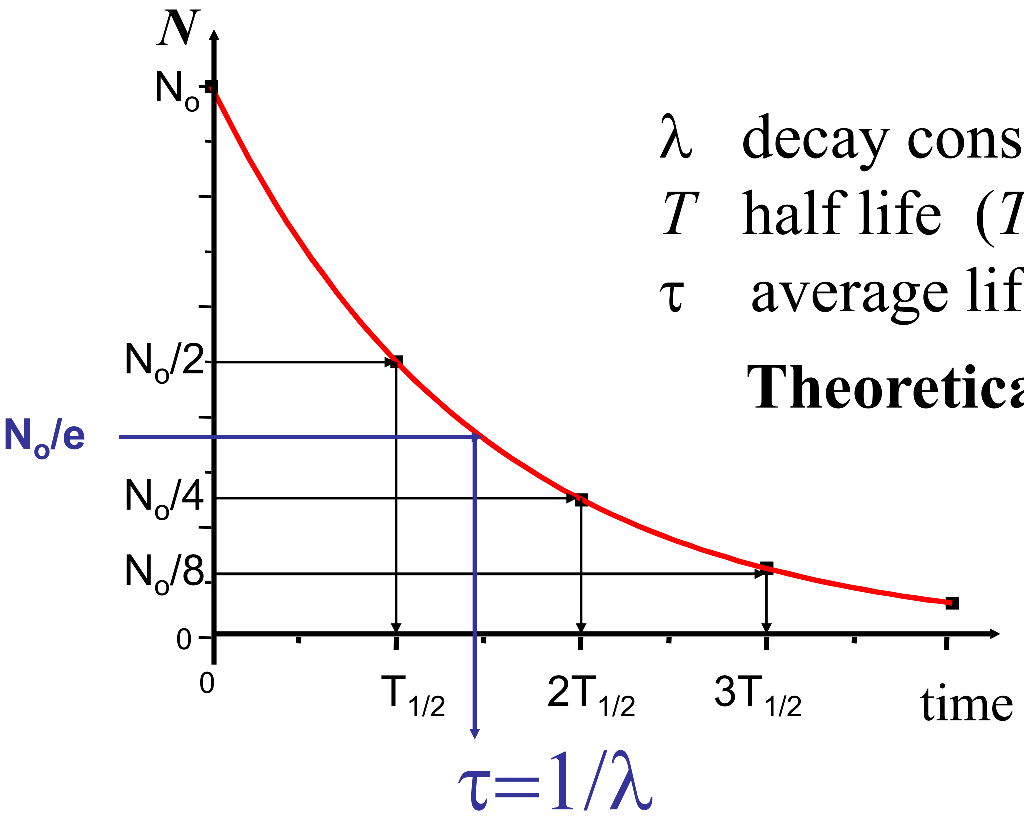
- after 1 s: 9000
- after 2 s: 8100
- after 3 s: 7290
- after 4 s: 6561
- ….



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 !

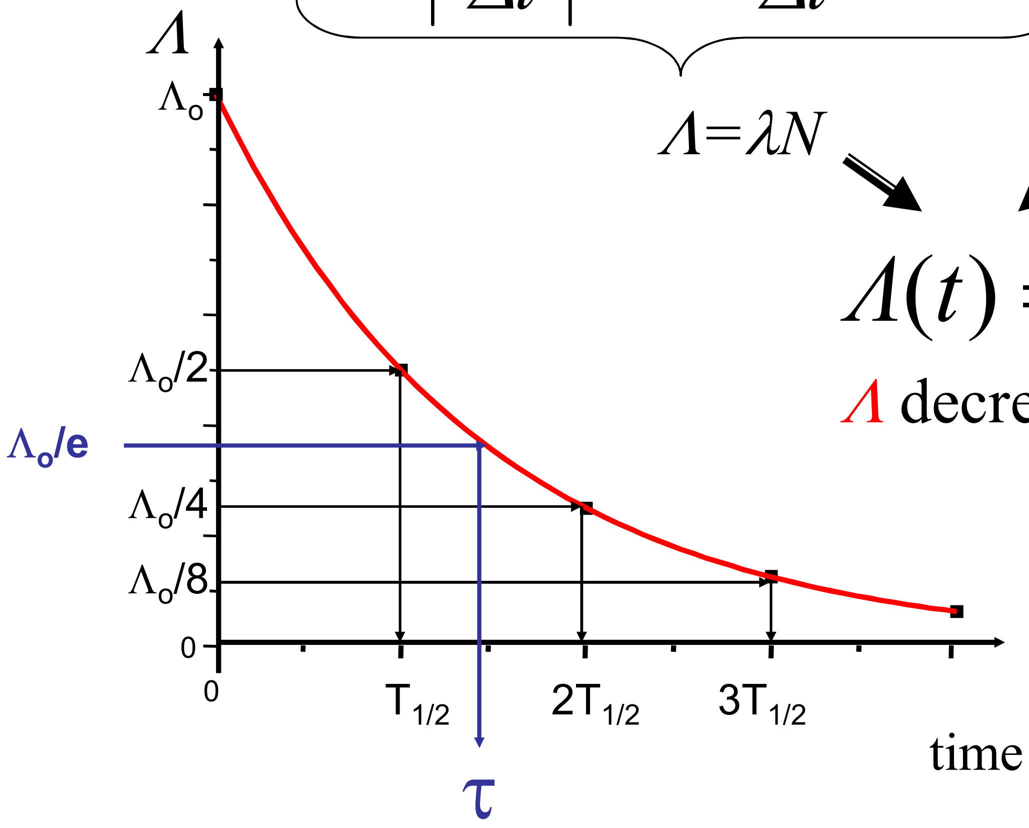
Decrease of the activity as a function of time

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

$$\Lambda = \lambda N$$

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

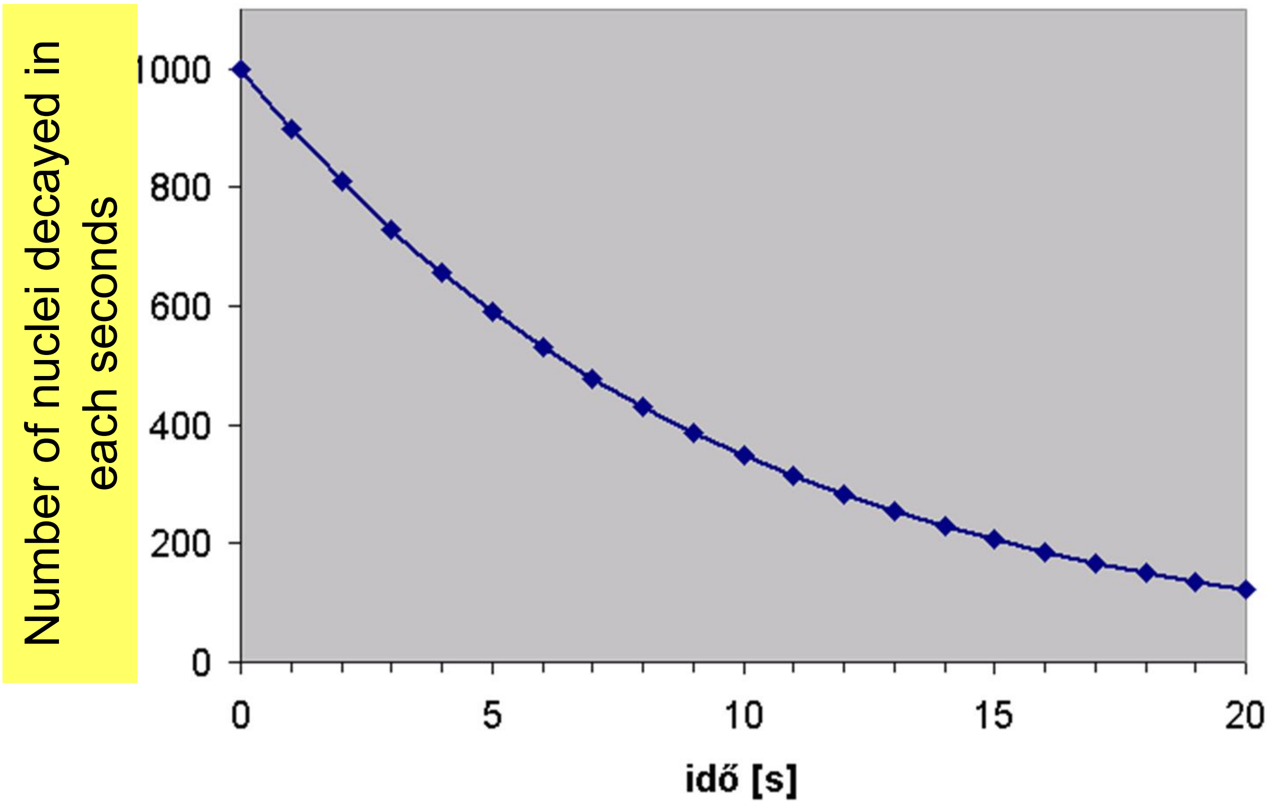
Λ decreases on the same way as N!



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

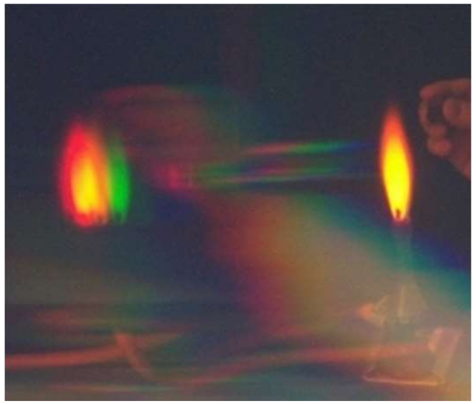
^{232}Th	$1.4 \cdot 10^{10}$ y
^{238}U	$4.5 \cdot 10^{9}$ y
^{40}K	$1.3 \cdot 10^{9}$ y
^{14}C	5736 y
^{137}Cs	30 y
^{3}H	12.3 y

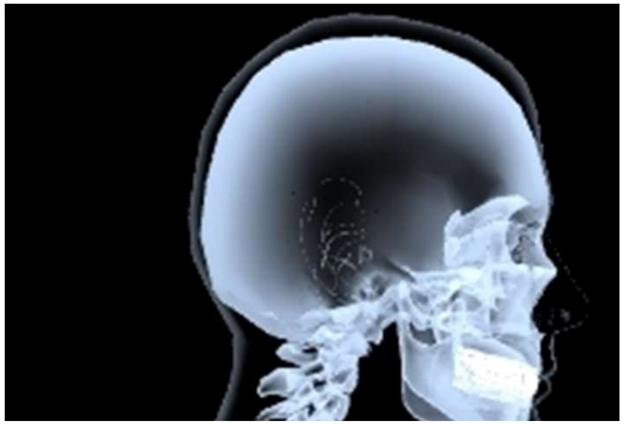
^{60}Co	5.3 y
^{59}Fe	1.5 m
^{56}Cr	1 m (28 d)
^{131}I	8 d
^{99m}Tc	6 h
^{18}F	110 min
^{11}C	20 min
^{15}O	2 min
^{222}Th	2.8 ms

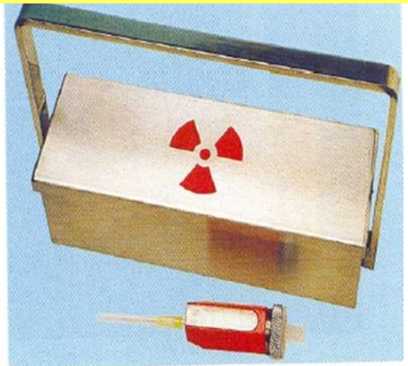
Don't learn these numbers!

Typical energy levels in the microworld

Excitation of the outer electrons	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)

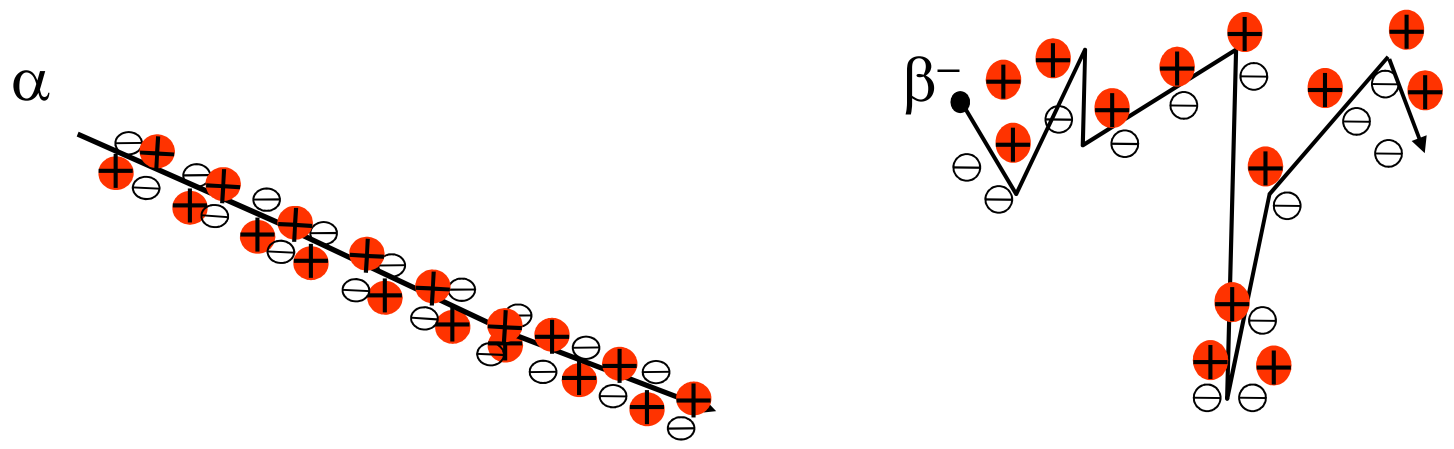
indirect ionisation

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

Absorption of the charged particles

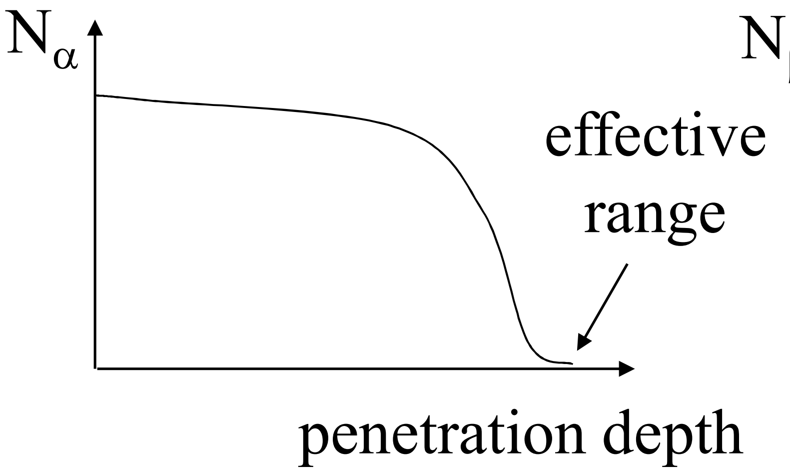
Ionizing during the path => continuous decrease of the particle energy
The energy after a given path length decreases to the thermal value

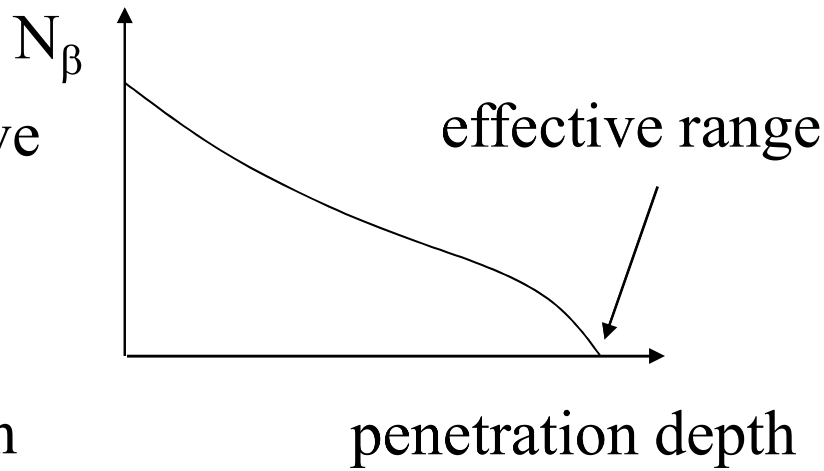
effective range



Effective range

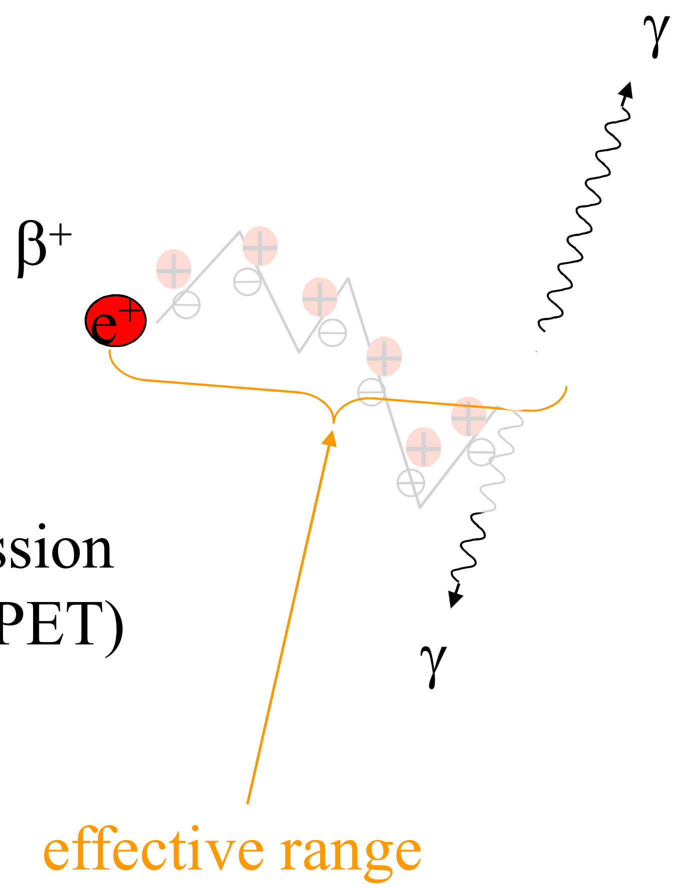
	α-particle	β^--particle
in air	**few cm**	**~ m**
in tissue	**0,01-0,1 mm**	**~ cm**





β^+-radiation

ionization and annihilation

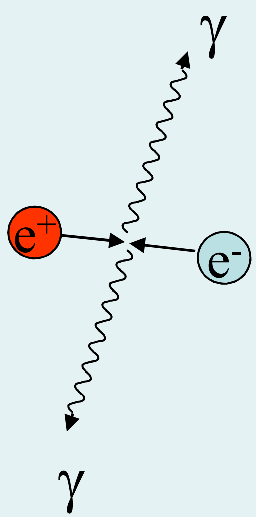


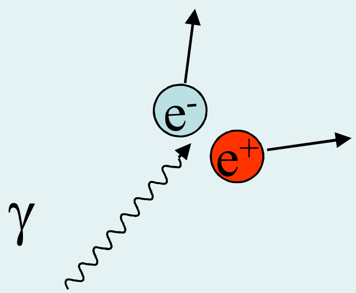
see: Positron Emission Tomography (PET)

Electron and positron

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

annihilation and pair production





Einstein:

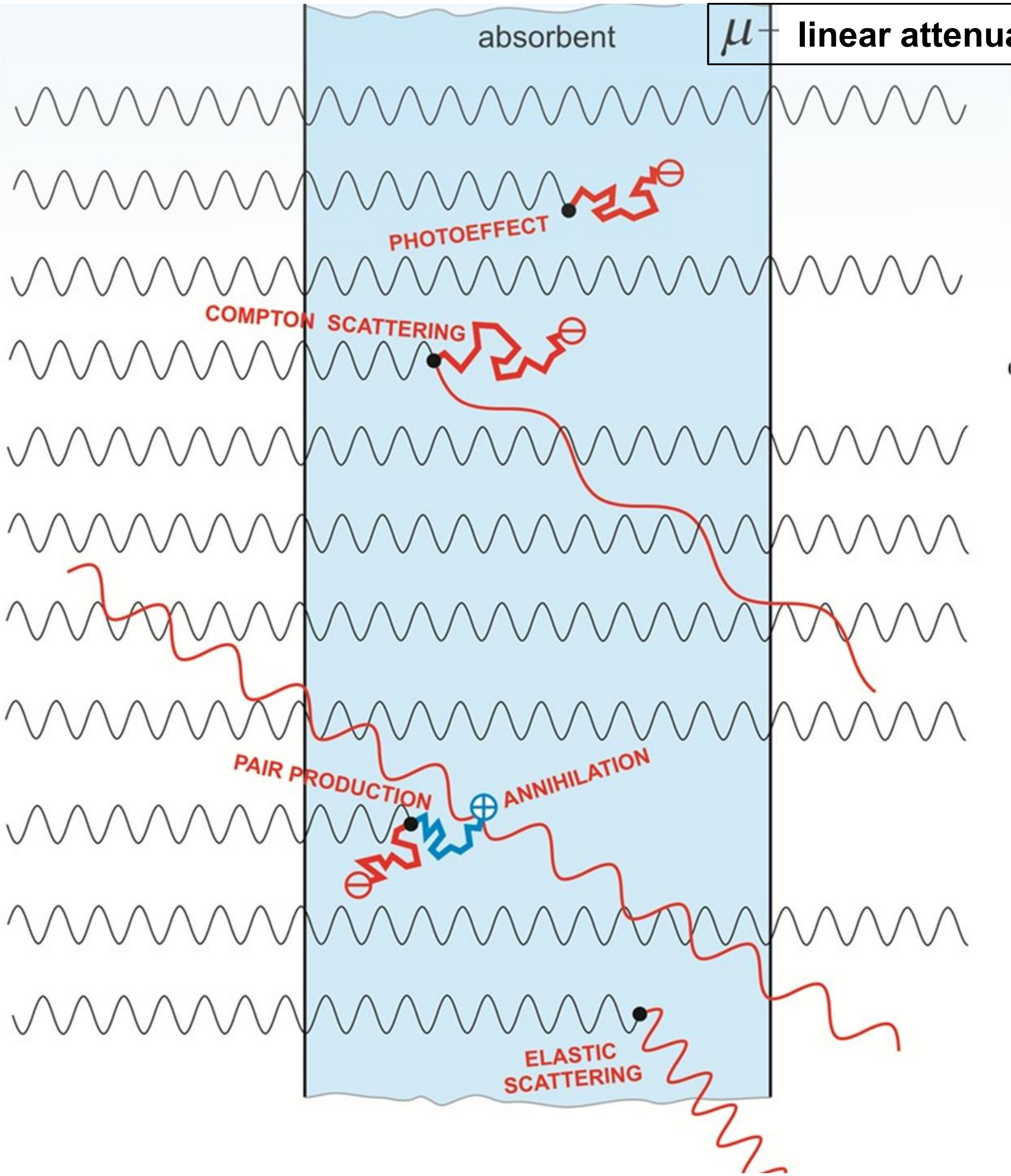
mass-energy ekvivalence

$$E=mc^2$$

$m_e c^2$=511 keV≈0.5 MeV

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

μ – **linear attenuation coefficient**



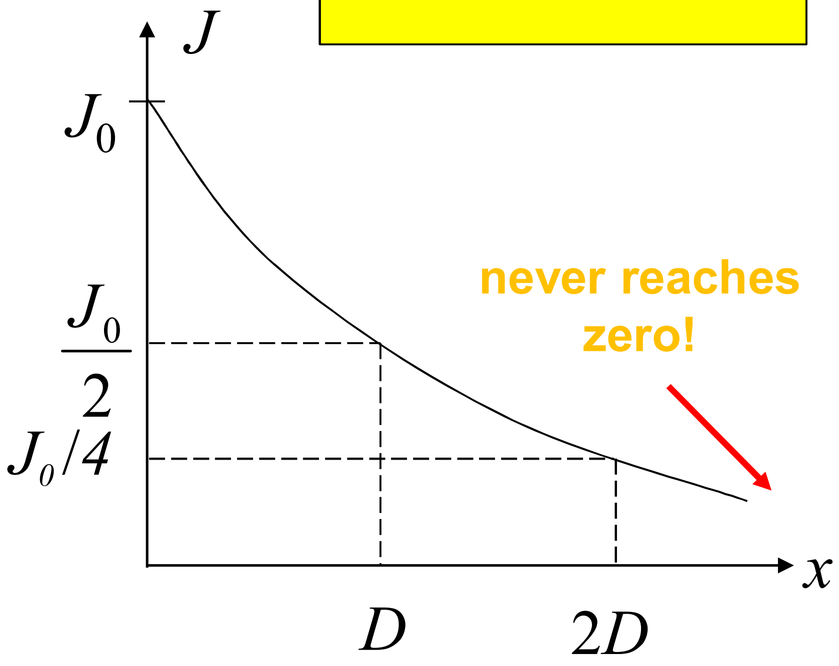
Attenuation:
absorption + scattering

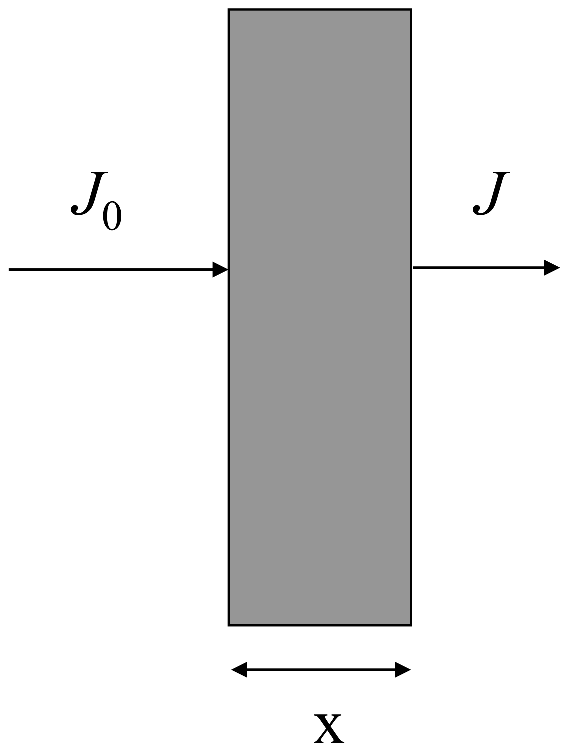
Random processes contributing:

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

Attenuation
of the γ–radiation and x-ray

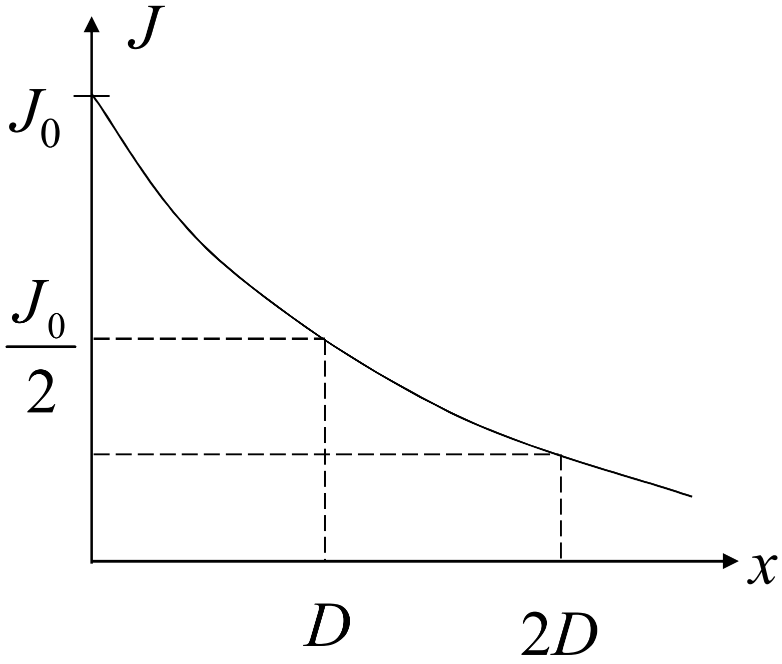
$$J = J_0 e^{-\mu x}$$





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)

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

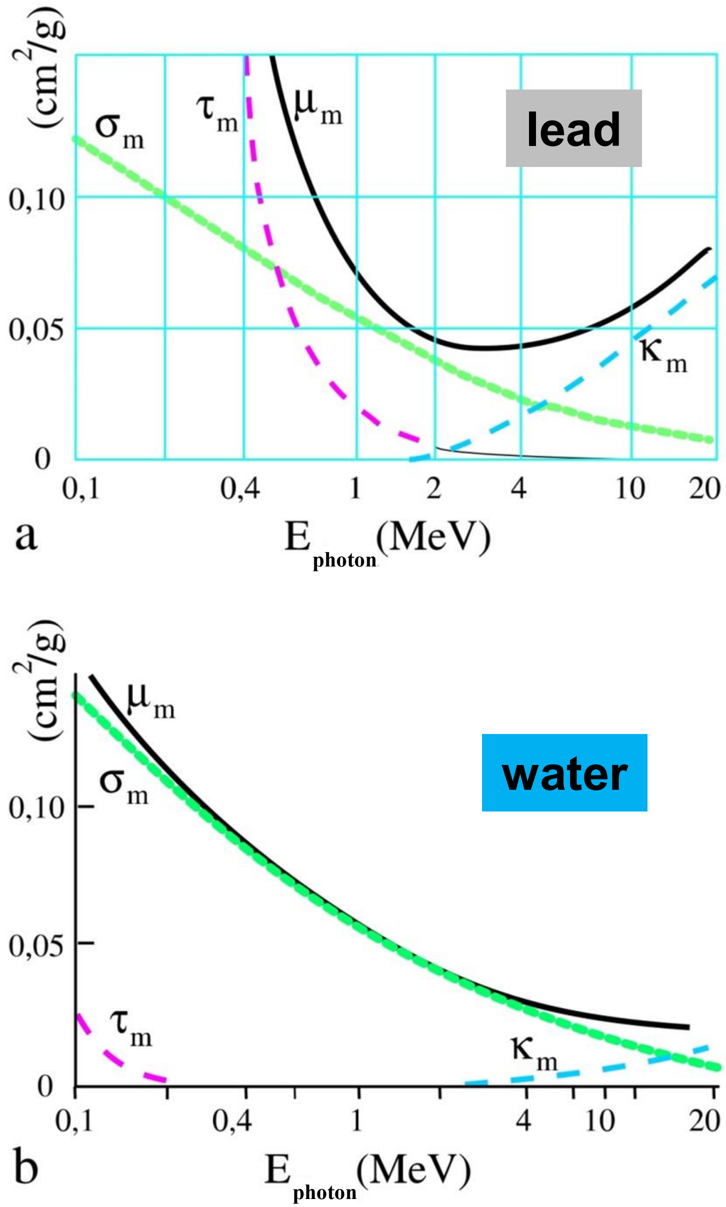
$$\mu_m = \frac{\mu}{\rho}$$ mass attenuation coefficient

mass attenuation coeff.

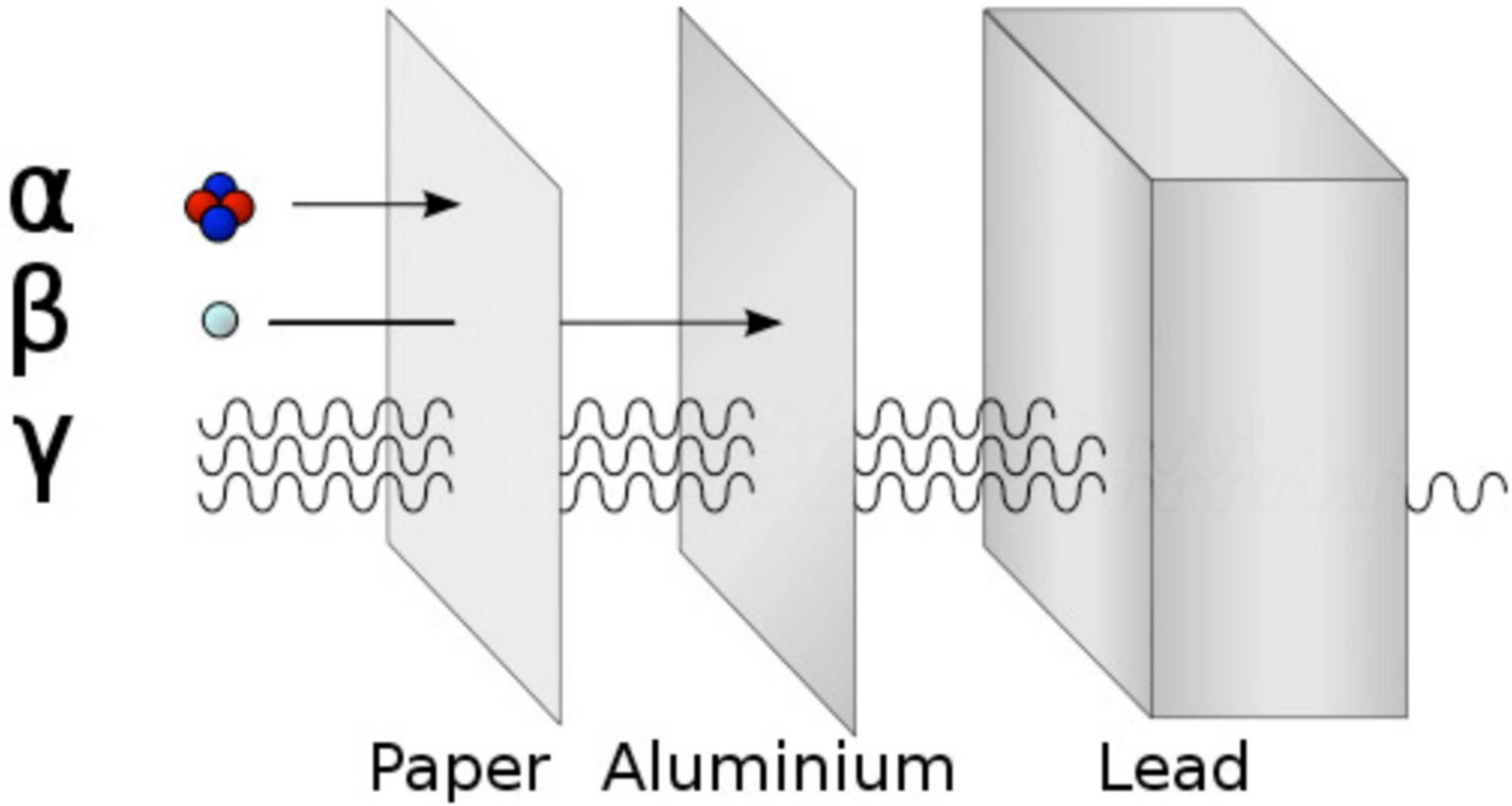
$$\mu_m = \frac{\mu}{\rho}$$

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

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



Summary of the absorption of α, β and γ radiation



Applications (attenuation)

lead glass

protective apron

Applications: isotopes and nuclear radiation