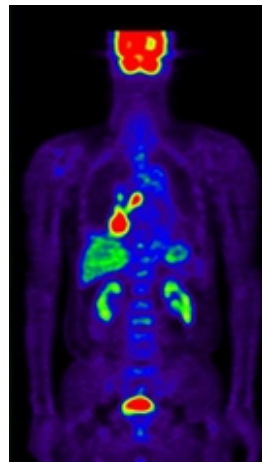
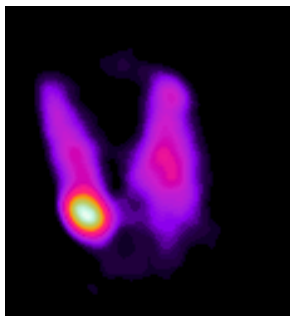


The atomic nucleus. Radioactivity. Nuclear radiations



László Smeller

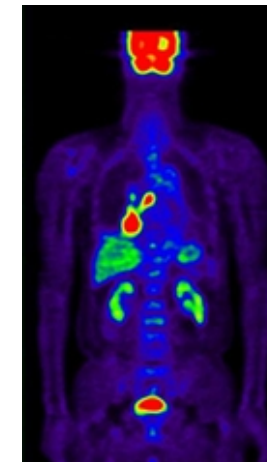
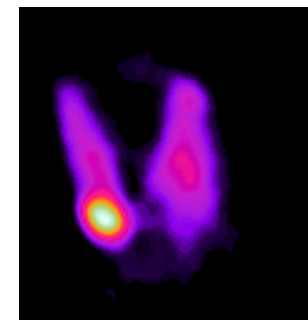


Why?







Medical application of nuclear radiation:



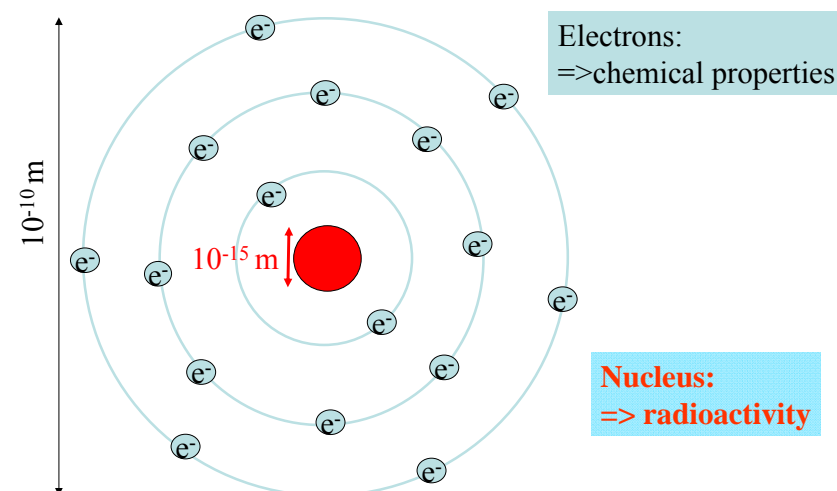
Nuclear imaging
Radiotherapy
Pharmacokinetics



Length scale of the nature

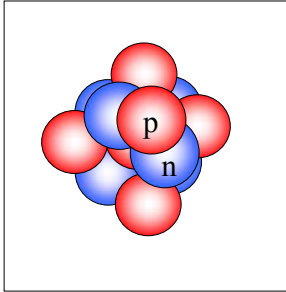
m		
10^0	meter	men 
10^{-3}	millimeter	letters you can read
10^{-6}	micrometer	size of a cell (e.g. erythrocyte)  $\varnothing 7\mu\text{m}$
10^{-9}	nanometer	protein 
10^{-10}	– angstrom	diameter of an atom, bond length H atom $\varnothing \approx 1$ angstrom (Å) 
10^{-12}	picometer	wavelength of the 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 43 Tc

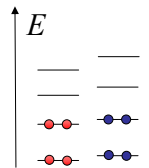
Stability of the nucleus

- 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
 $eV = 1,6 \cdot 10^{-19} \text{ J}$



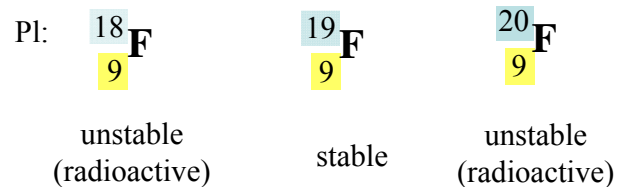
Isotopes

Number of protons is the same

Number of neutrons is different

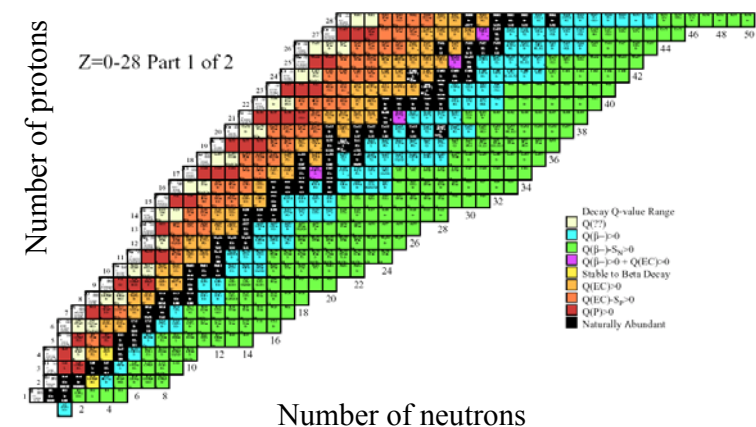
Variants of the same element

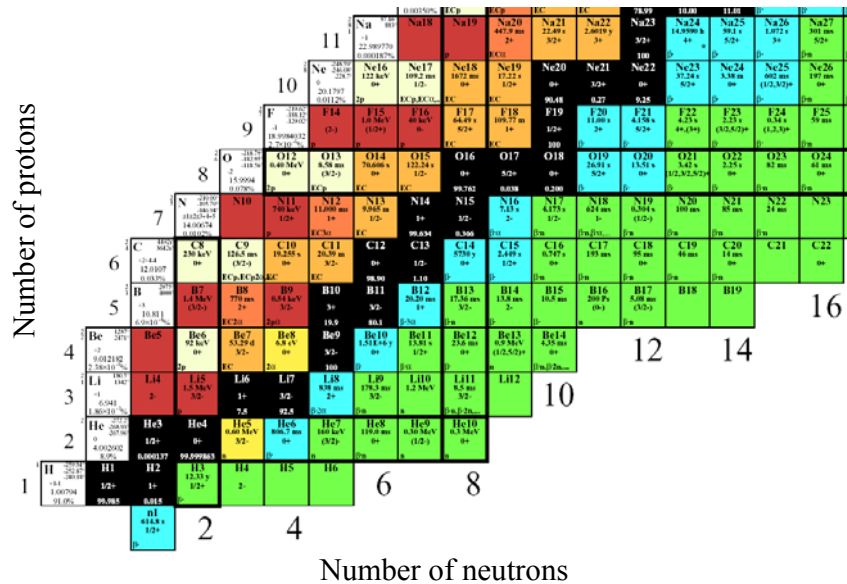
⇒ the chemical properties are identical.



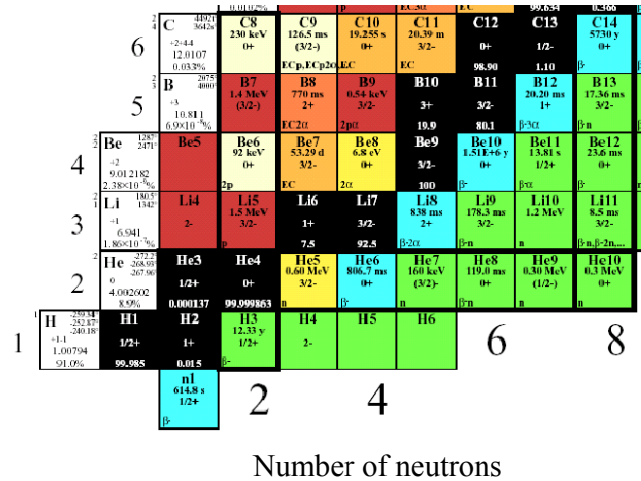
isotope \leftrightarrow radioactive isotope

Table of isotopes





Number of protons



Number of neutrons

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

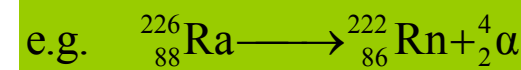
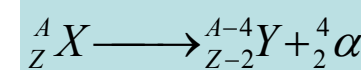
γ -ray

K-electron capture

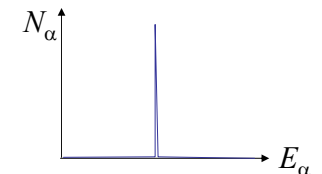
characteristic x-ray photon

α - decay

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



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



neutron surplus

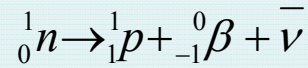
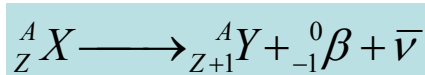
β^- - decay

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

${}^{32}_{15}\text{P}$

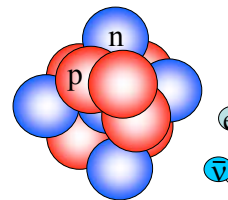
${}^{59}_{26}\text{Fe}$

${}^{131}_{53}\text{I}$



remains in
the nucleus

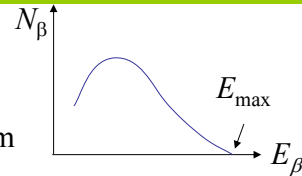
leave the
nucleus



β^- -ray
 $\bar{\nu}$

continuous
energy spectrum

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



proton surplus

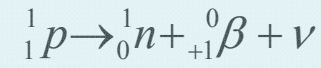
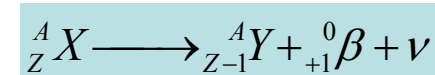
β^+ - decay

e.g.: ${}^{11}_6\text{C}$

${}^{15}_8\text{O}$

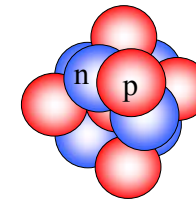
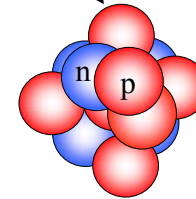
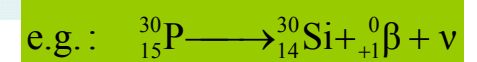
${}^{18}_9\text{F}$

${}^{52}_{26}\text{Fe}$



remains in
the nucleus

leave the
nucleus



β^+ -ray

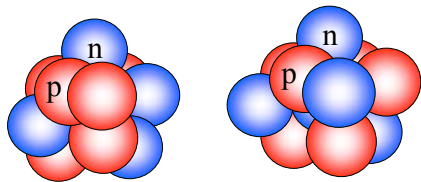
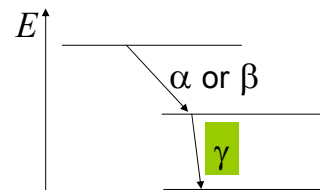
continuous energy spectrum

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.

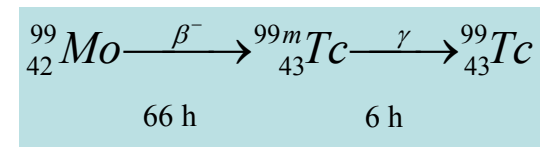
Isomeric transition

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

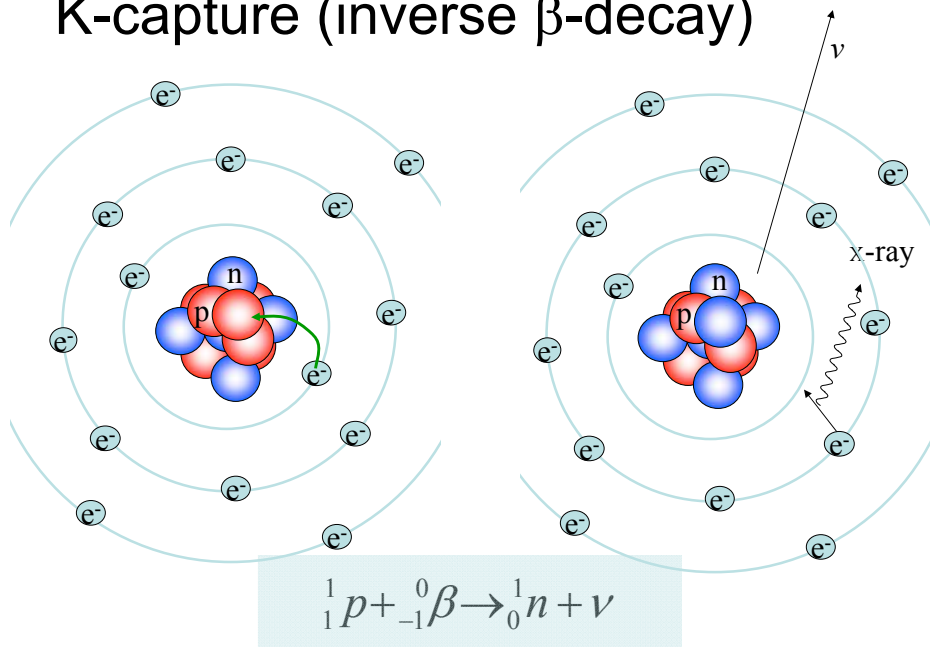
The parent and daughter atoms can be separated:
the daughter atom emits **only γ -radiation!**

=> **Isotope diagnostics (nuclear imaging)**

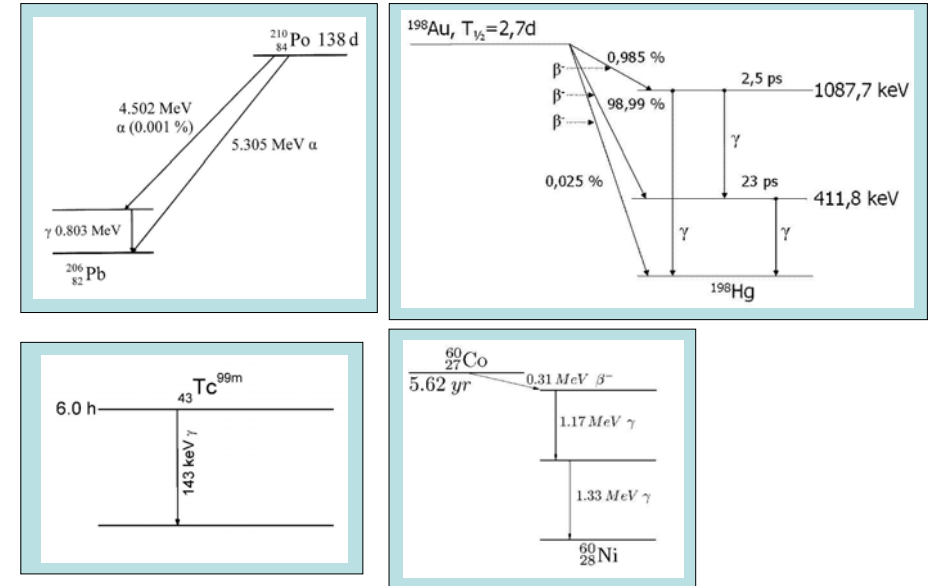
E.g.: ${}^{99m}_{42}\text{Tc}$



K-capture (inverse β -decay)



Some examples of the decay paths



Characteristics of radioactive decays in general

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

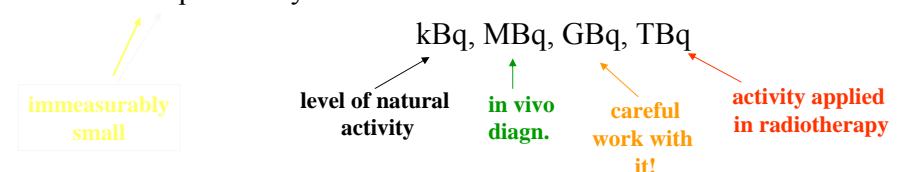
Activity (Λ)

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

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:

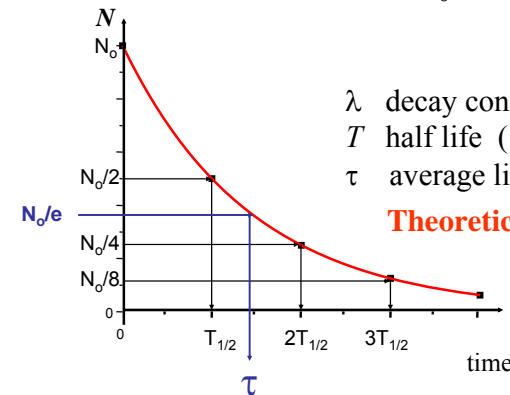
$$N(t) = N_0 e^{-\lambda t}$$

Exponential decrease

number of undecayed atoms at $t=0$

Law of radioactive decay

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

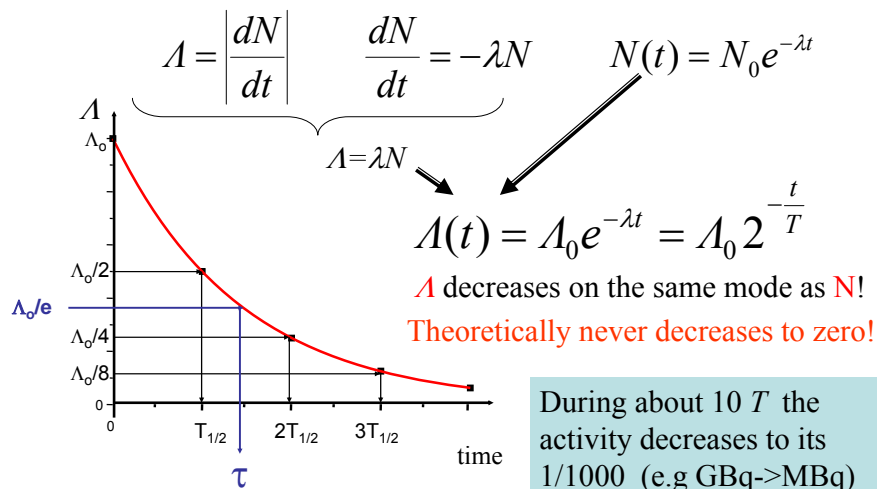


λ decay constant (probability of the decay)
 T half life ($T_{1/2}$)
 τ average lifetime

Theoretically never decreases to zero !

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

Decrease of the activity as a function of time



Few examples for half life

^{232}Th	$1,4 \cdot 10^{10} \text{ y}$
^{238}U	$4,5 \cdot 10^9 \text{ y}$
^{40}K	$1,3 \cdot 10^9 \text{ y}$
^{14}C	5736 y
^{137}Cs	30 y
^3H	12,3 y

^{60}Co	5,3 y
^{59}Fe	1,5 m
^{56}Cr	1 m (28 d)
^{131}I	8 d
$^{99\text{m}}\text{Tc}$	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



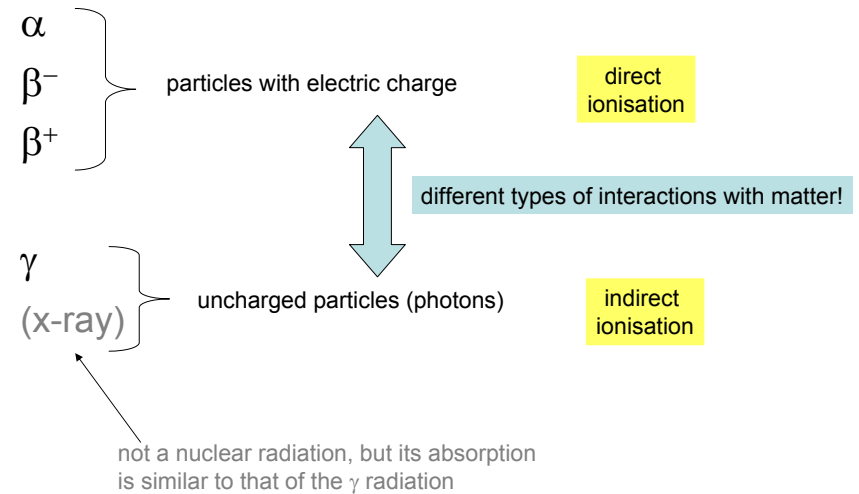
Transformation of the nucleus (decay)

MeV (pJ)

Nuclear radiation
 α , β , γ



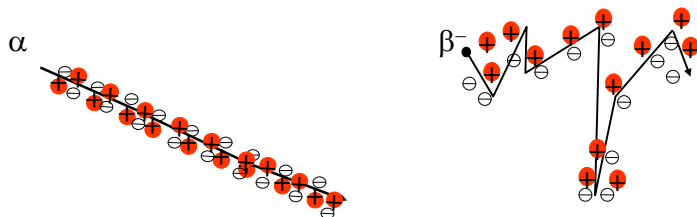
Absorption of the nuclear radiation



Absorption of the charged particles

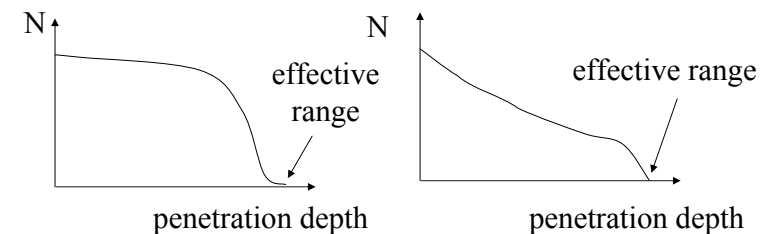
Ionizing during the path \Rightarrow continuous decrease of the particle energy
The energy after a given path length decreases to the thermal value

effective range



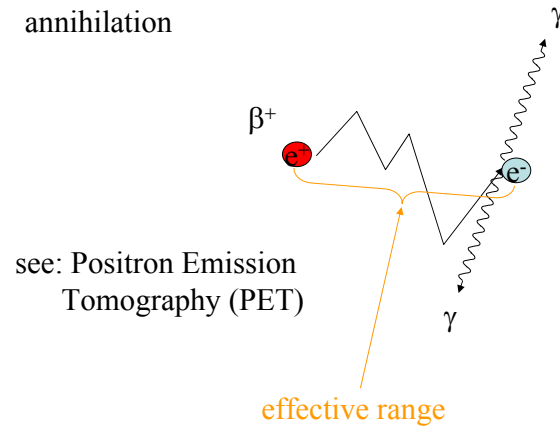
Effective range

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



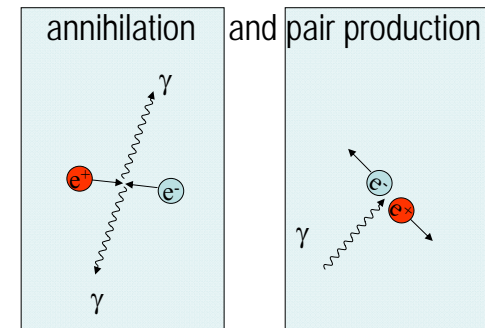
β^+ -radiation

annihilation



Electron and positron

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

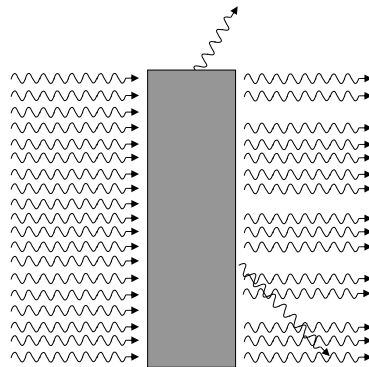


Einstein:
mass-energy
equivalence

$$E=mc^2$$

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

Absorption of the γ -radiation



Similar to the absorption of the x-ray. See the details next week!

Applications

