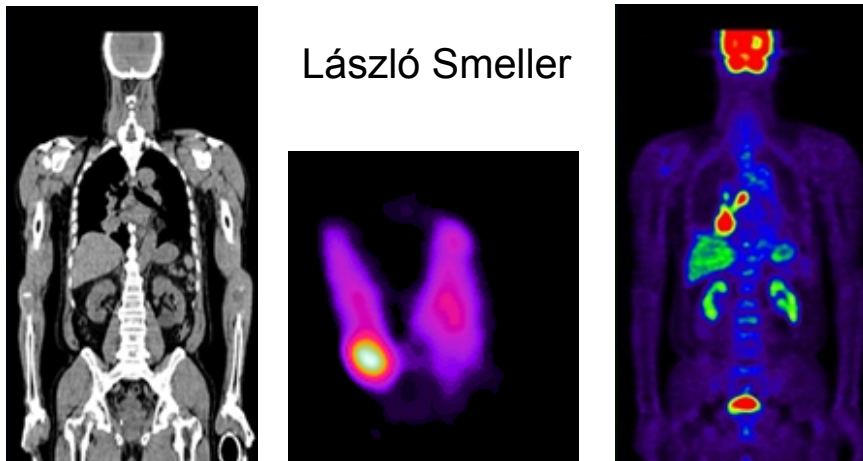
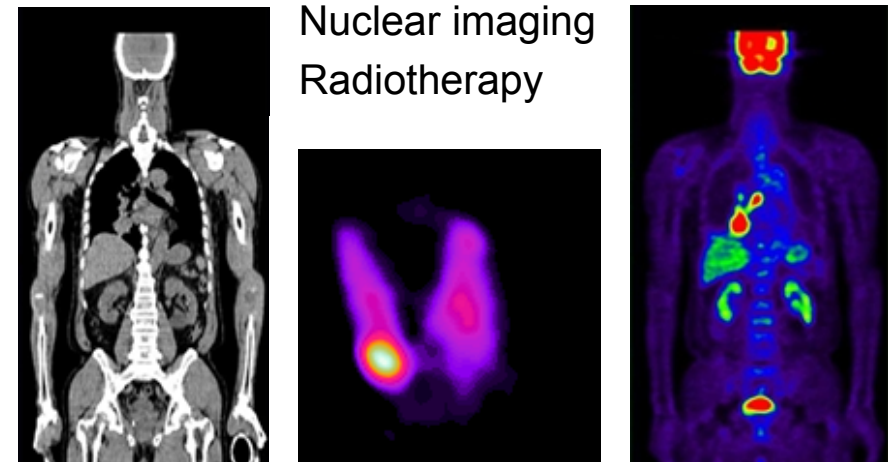


## The atomic nucleus. Radioactivity. Nuclear radiations









## Why?

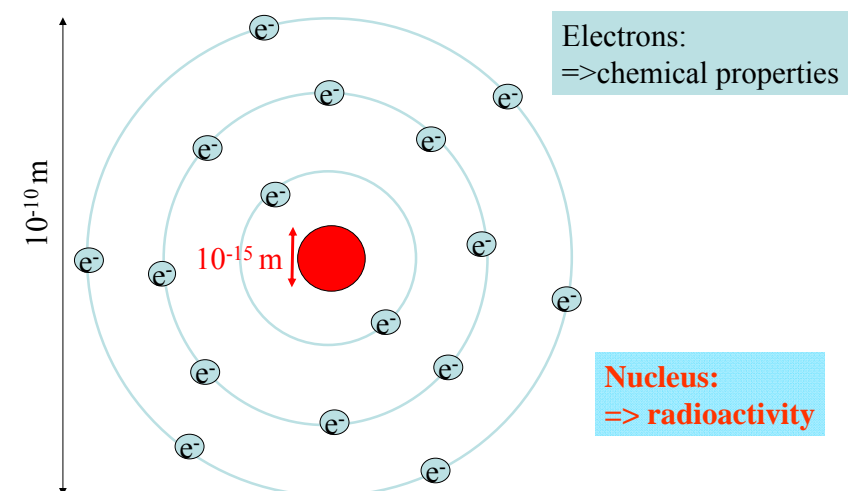
Medical application of nuclear radiation:



## Length scale of the nature

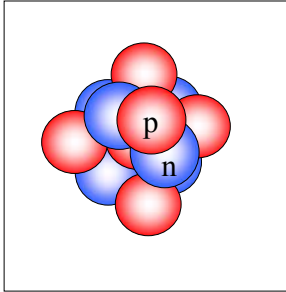
m		
$10^0$	meter	men 
$10^{-3}$	millimeter	letters you can read
$10^{-6}$	micrometer	size of a cell (e.g. erythrocyte)  $\varnothing 7\mu\text{m}$
$10^{-9}$	nanometer	protein 
$10^{-10}$	– angstrom	diameter of an atom, bond length H atom $\varnothing \approx 1$ angstrom (Å) 
$10^{-12}$	picometer	wavelength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

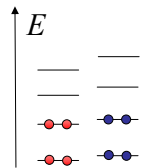
# Stability of the nucleus

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



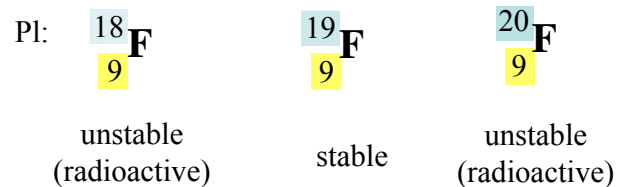
# Isotopes

Number of protons is the same

Number of neutrons is different

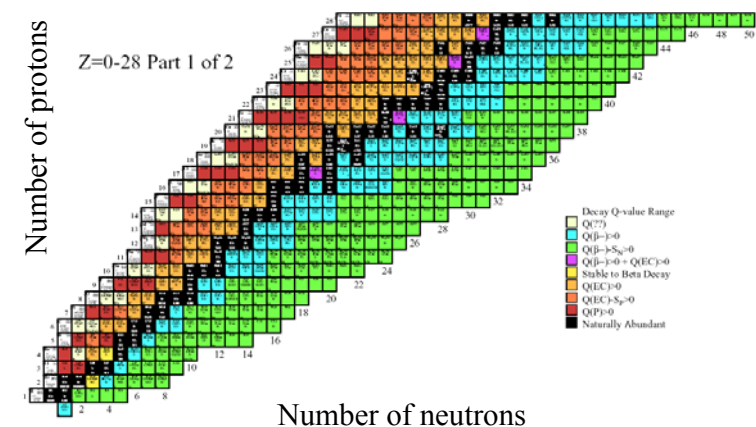
Variants of the same element

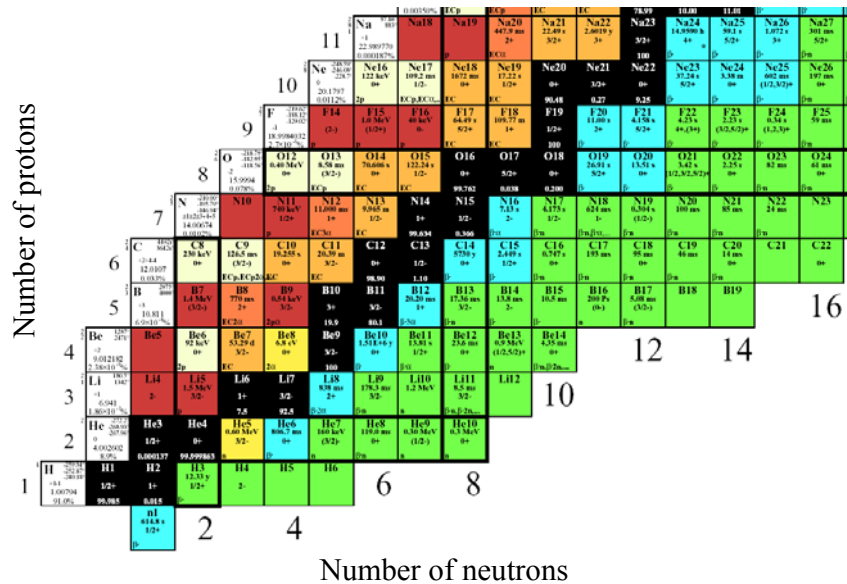
⇒ the chemical properties are identical.



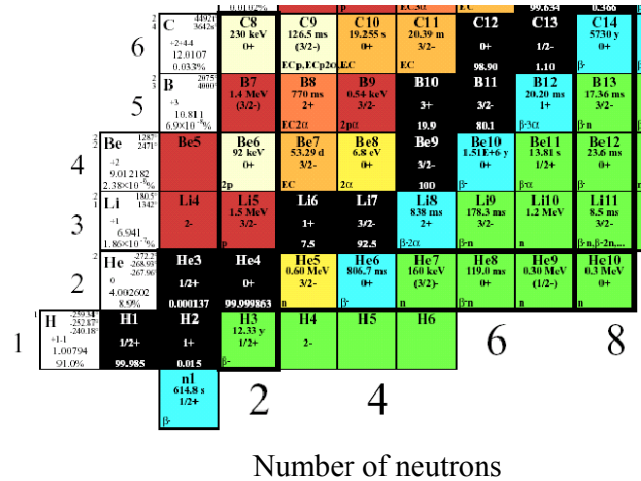
isotope  $\leftrightarrow$  radioactive isotope

# Table of isotopes





Number of protons



Number of neutrons

## Radioactive decays and particles

$\alpha$  - decay

$\alpha$  - particle =  ${}^4_2\text{He}$  nucleus

$\beta^-$  - decay :  $\beta^-$   
 $\beta^+$

$\beta^-$  particle = electron

$\beta^+$  particle = positron

Isomeric transition

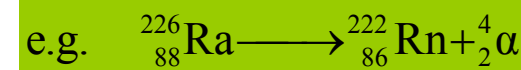
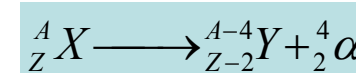
$\gamma$ -ray

K-electron capture

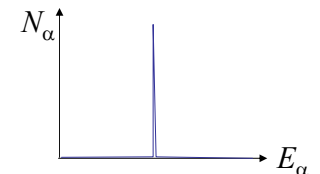
characteristic x-ray photon

## $\alpha$ - decay

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



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



neutron surplus

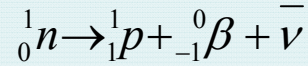
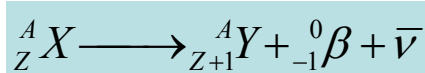
## $\beta^-$ - decay

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

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

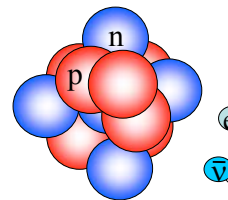
$^{59}_{26}\text{Fe}$

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



remains in  
the nucleus

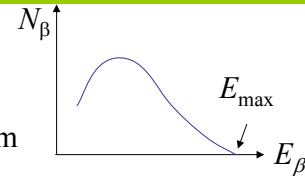
leave the  
nucleus



$\beta^-$ -ray

continuous  
energy spectrum

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



proton surplus

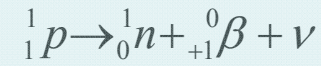
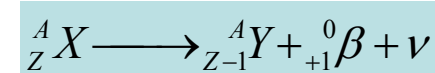
## $\beta^+$ - decay

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

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

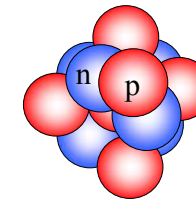
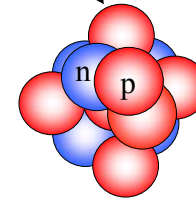
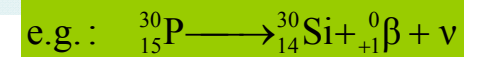
$^{18}_9\text{F}$

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



remains in  
the nucleus

leave the  
nucleus



$\beta^+$ -ray

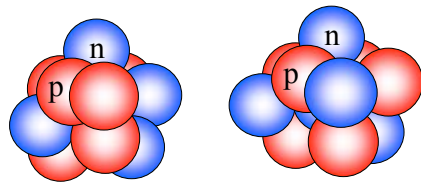
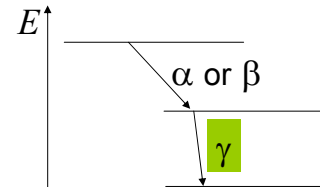
continuous energy spectrum

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

## Prompt $\gamma$ -radiation

The daughter nucleus has an **energetically unfavoured** arrangement of nucleons.

The surplus energy will be  
immediately (ns) emitted in  
form of the  $\gamma$  radiation



Atomic number, mass number are unchanged.

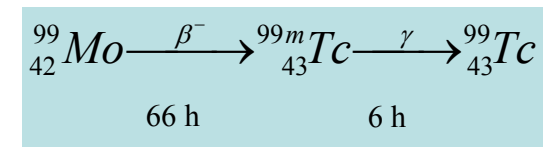
## Isomeric transition

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

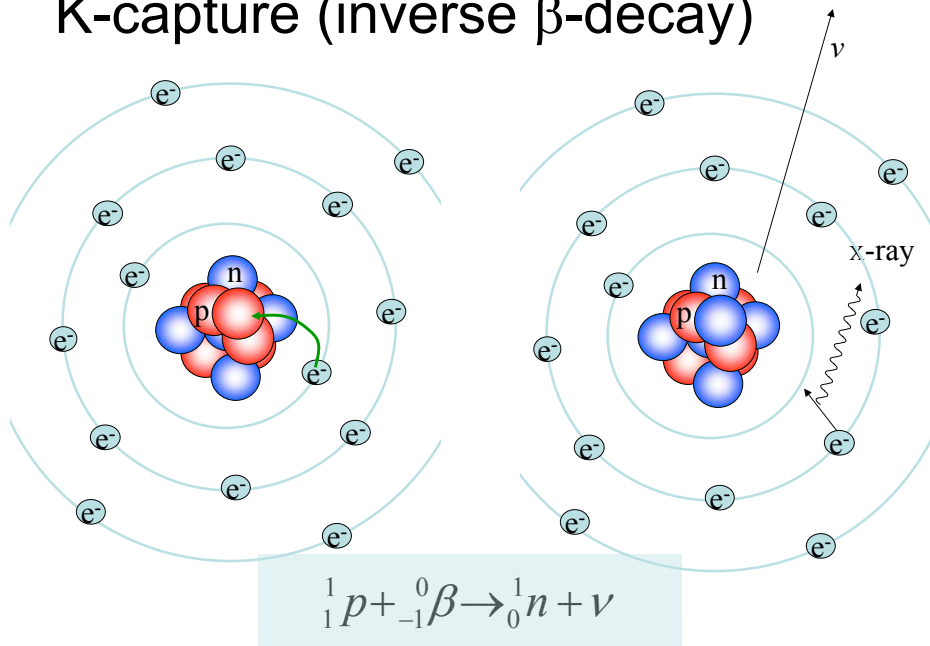
The parent and daughter atoms can be separated:  
the daughter atom emits **only  $\gamma$ -radiation!**

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

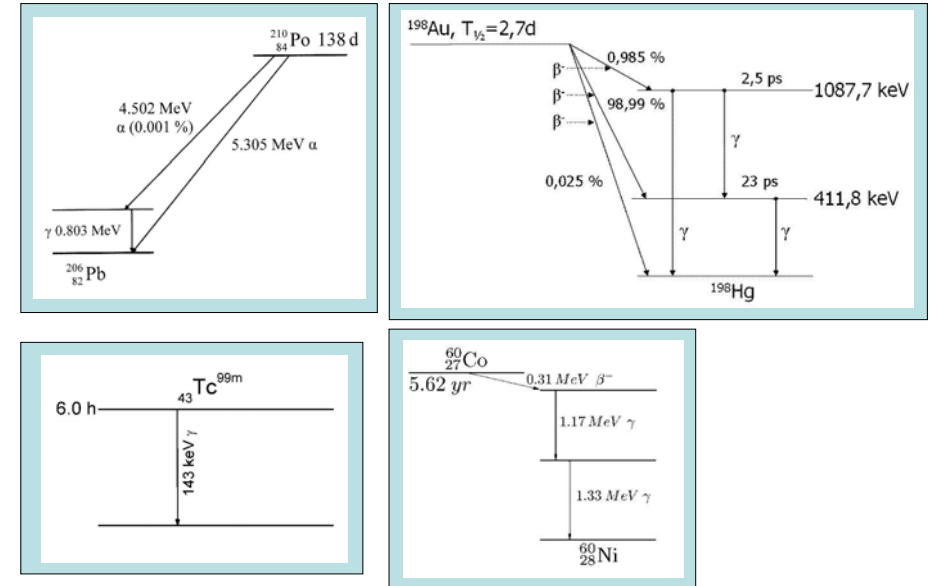
E.g.:  $^{99\text{m}}\text{Tc}$



## K-capture (inverse $\beta$ -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

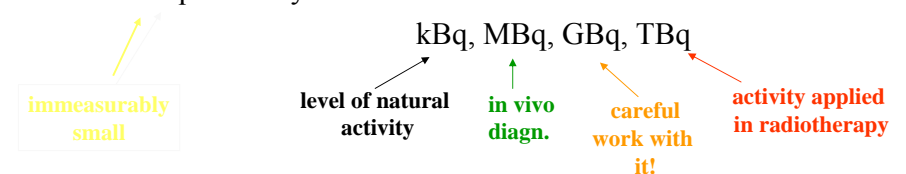
## Activity ( $\Lambda$ )

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

$N$  = Number of undecayed atoms  
 $t$  = time  
 $\Delta N$  = Number of decays during  $\Delta t$  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

$$\frac{dN}{dt} = -\lambda N$$

$\lambda$ : 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

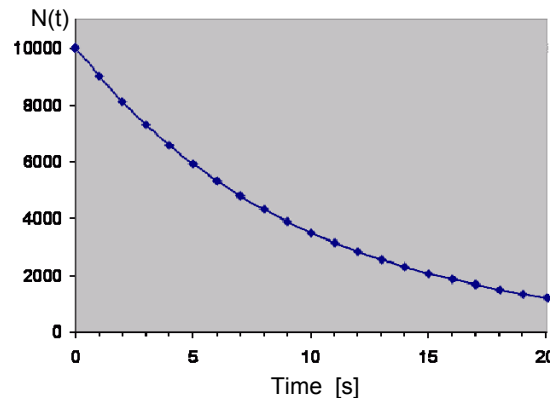
number of undecayed atoms at  $t=0$

## An example

- At start:  $N_0 = 10000$  (number of atoms)  
 $\lambda = 0,1 \text{ } 1/\text{s}$  (decay probability)
- 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)
- ....

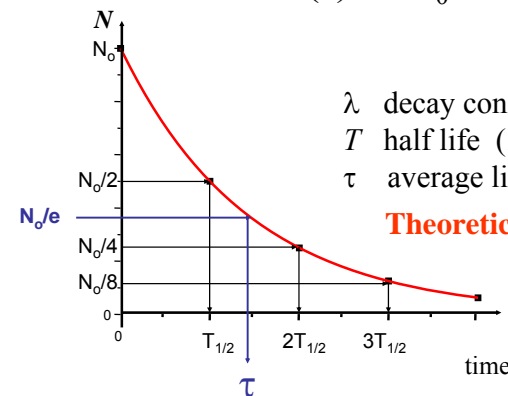
## An example

- At start:  $N_0 = 10000$  (number of atoms)  
 $\lambda = 0,1 \text{ } 1/\text{s}$  (decay probability)
- after 1 s: 9000
- after 2 s: 8100
- after 3 s: 7290
- after 4 s: 6561
- ....



## Law of radioactive decay

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



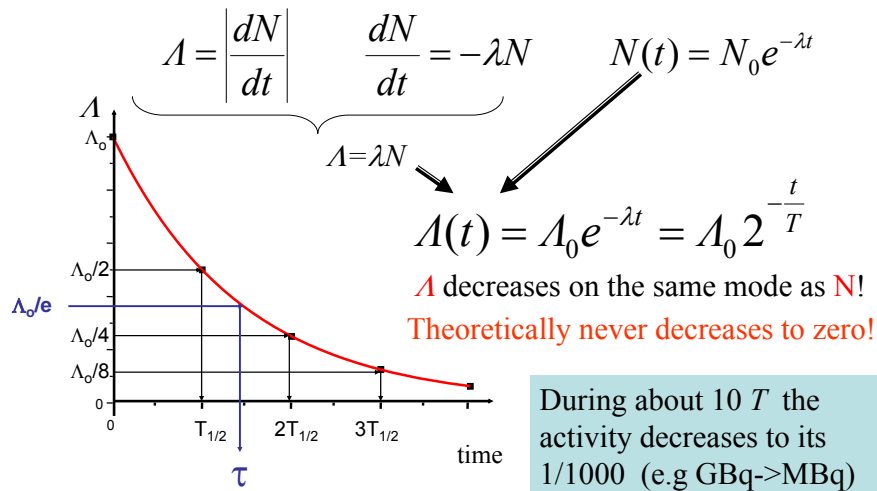
$\lambda$  decay constant (probability of the decay)  
 $T$  half life ( $T_{1/2}$ )  
 $\tau$  average lifetime

**Theoretically never decreases to zero !**

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

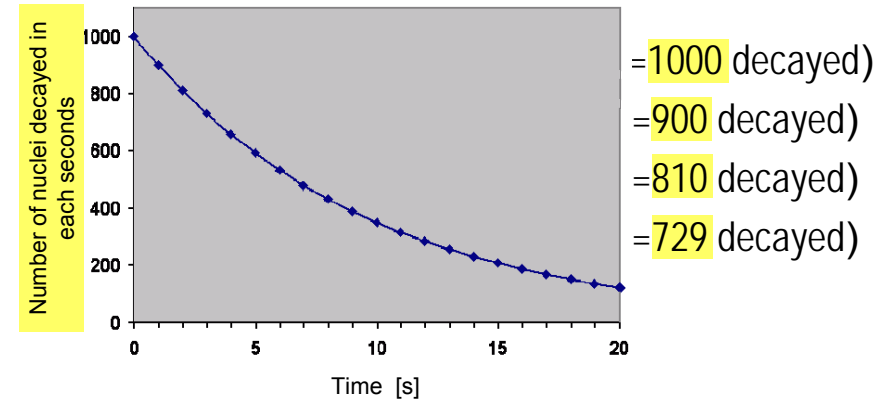


## Decrease of the activity as a function of time



## An example

- At start:  $N_0 = 10000$  (number of atoms)  
 $\lambda = 0,1 \text{ } 1/\text{s}$  (decay probability)



## Few examples for half life

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

**Don't learn these numbers!**

## Typical energy levels in the microworld

Excitation of the outer electrons

eV (aJ)

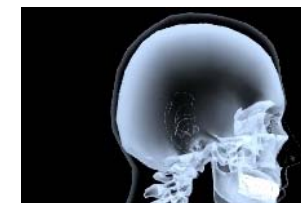
light



Electron transition between inner electrons

keV (fJ)

X-ray



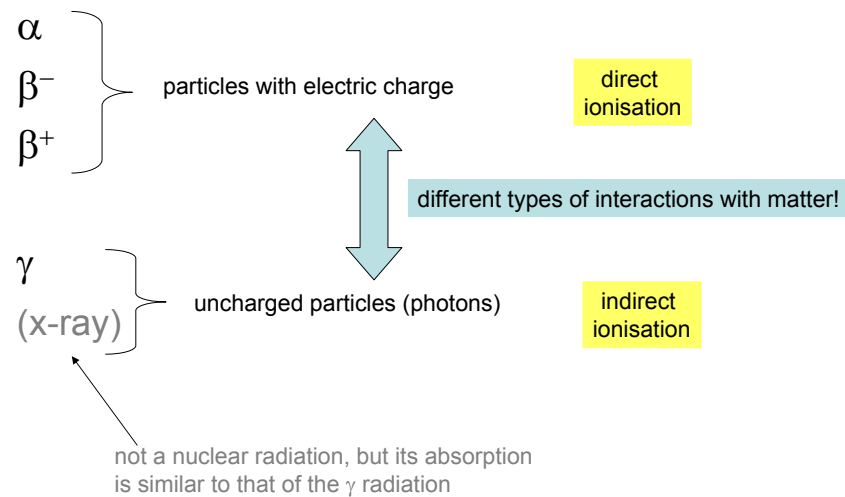
Transformation of the nucleus (decay)

MeV (pJ)

**Nuclear radiation**  
 $\alpha, \beta, \gamma$



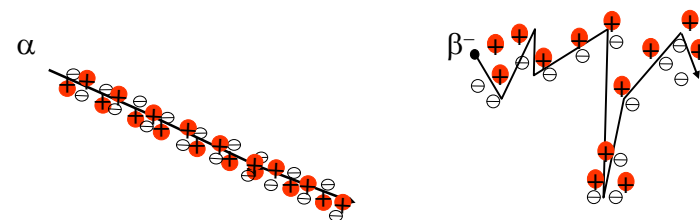
## Absorption of the nuclear radiation



## Absorption of the charged particles

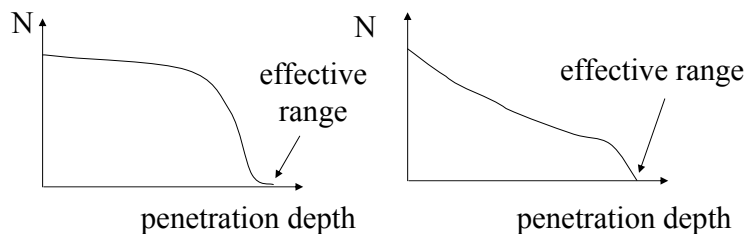
Ionizing during the path => continuous decrease of the particle energy  
The energy after a given path length decreases to the thermal value

effective range



## Effective range

	$\alpha$ -particle	$\beta^-$ -particle
in air	<b>few cm</b>	<b>~ m</b>
in tissue	<b>0,01-0,1 mm</b>	<b>~ cm</b>



## Applications

