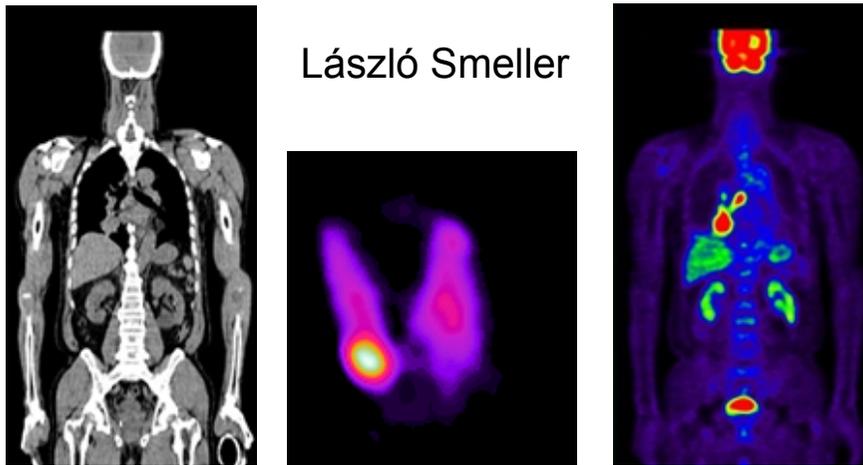


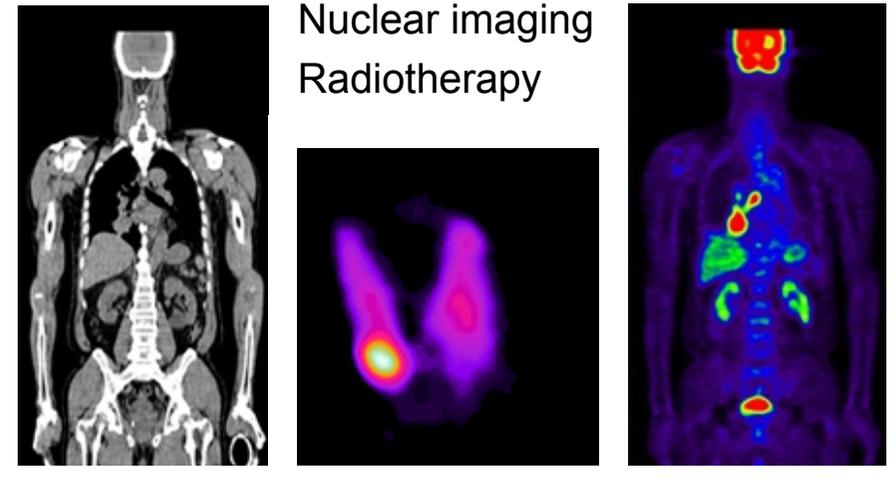
# The atomic nucleus. Radioactivity. Nuclear radiations



László Smeller

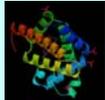
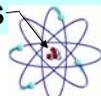
# Why?

Medical application of nuclear radiation:

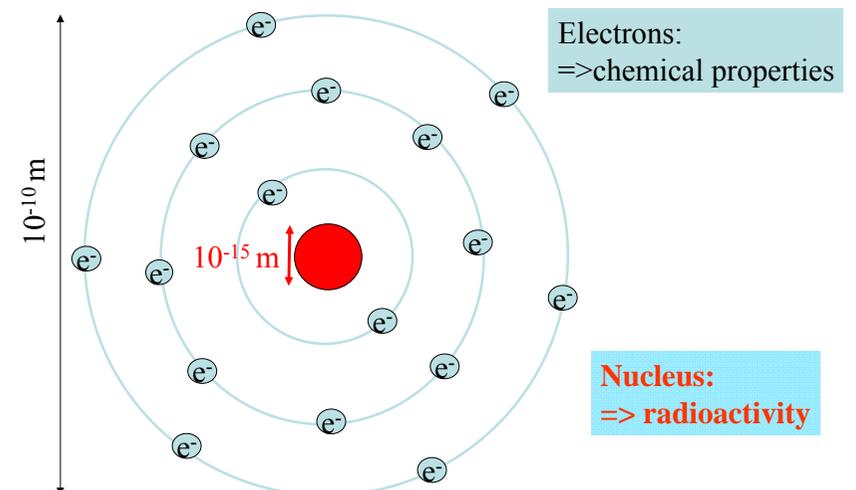


Nuclear imaging  
Radiotherapy

# 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 

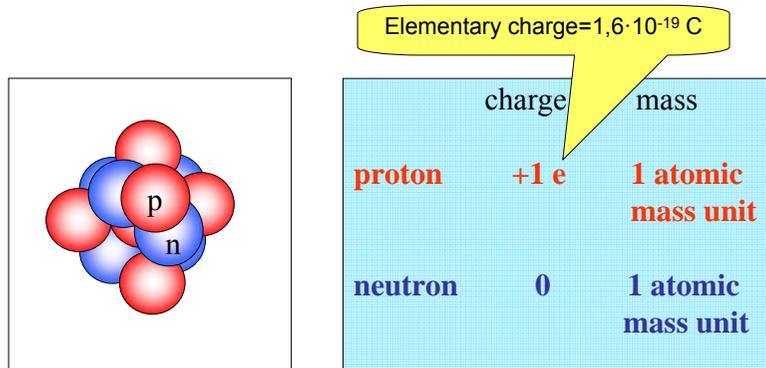
# The electrons and the nucleus



Electrons:  
=> chemical properties

Nucleus:  
=> radioactivity

# Structure of the nucleus



$A$  (mass number) = number of protons + number of neutrons  
 $Z$  (atomic number) = number of protons

$99$  **Tc**  
 $43$

99 nucleon, 43 proton and 56 neutron

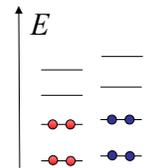
# Stability of the nucleus

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



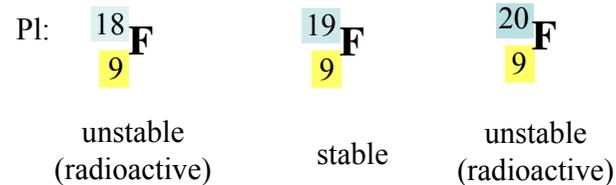
# Isotopes

Number of protons is the same

Number of neutrons is different

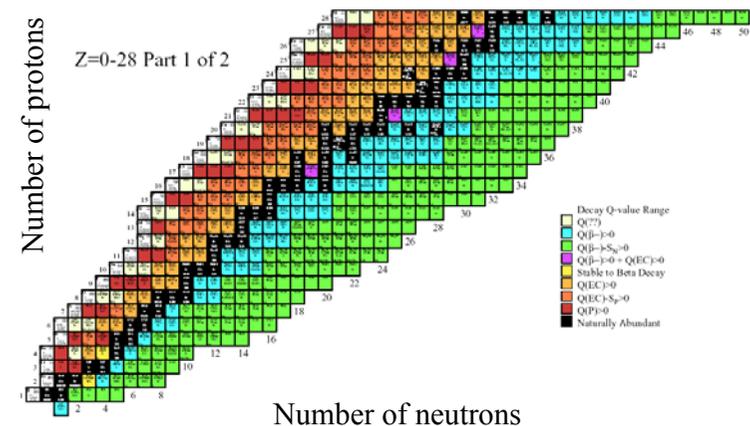
Variants of the same element

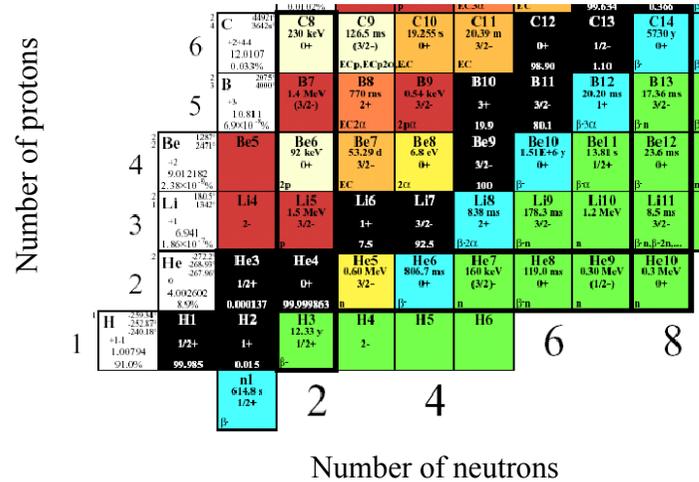
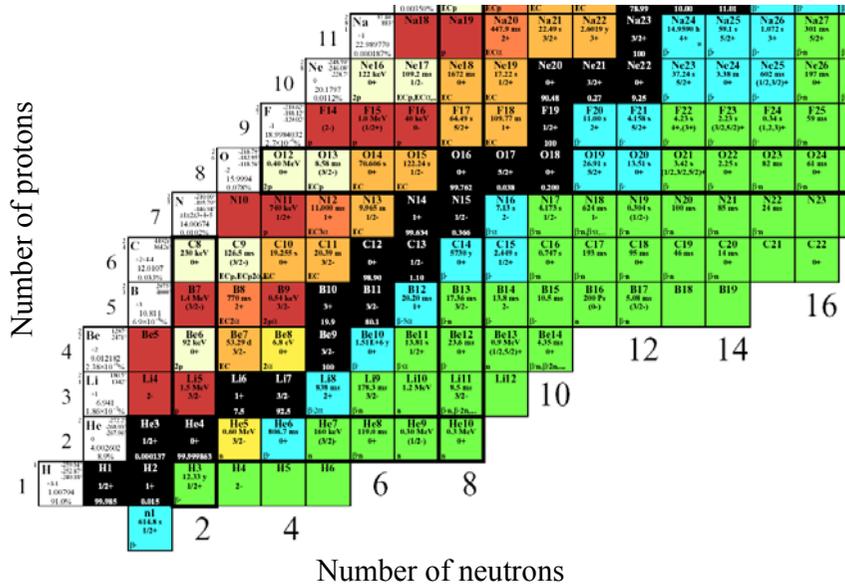
⇒ the chemical properties are identical.



isotope <-> radioactive isotope

# Table of isotopes



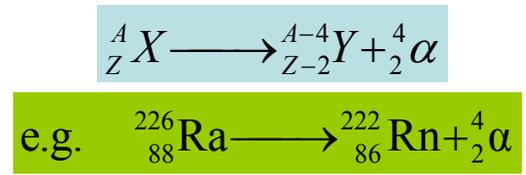


## Radioactive decays and particles

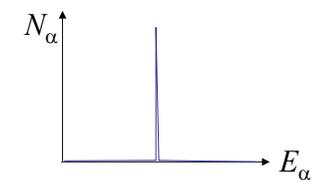
- $\alpha$  - decay       $\alpha$  - particle =  ${}^4_2\text{He}$  nucleus
- $\beta^-$  - decay :  $\beta^-$        $\beta^-$  particle = electron
- $\beta^+$        $\beta^+$  particle = positron
- Isomeric transition       $\gamma$ -ray
- K-electron capture      characteristic x-ray photon

## $\alpha$ - decay

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



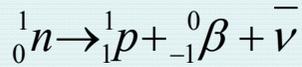
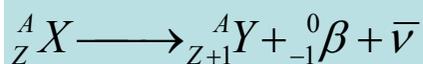
Line spectrum  
 $E_\alpha \sim \text{MeV}$



neutron surplus

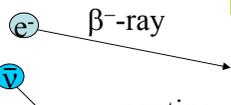
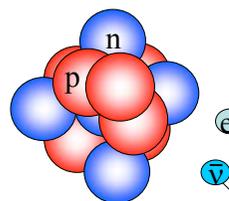
## $\beta^-$ - decay

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



remains in the nucleus

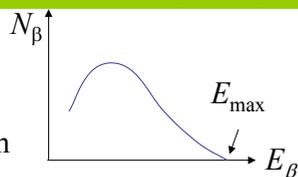
leave the nucleus



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

$\beta^-$ -ray

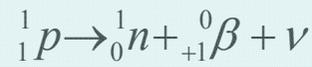
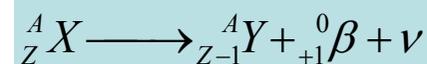
continuous energy spectrum



proton surplus

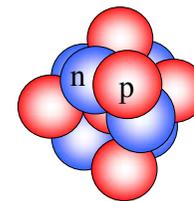
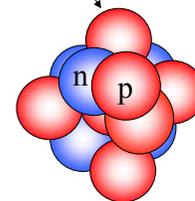
## $\beta^+$ - decay

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



remains in the nucleus

leave the nucleus



$\beta^+$ -ray

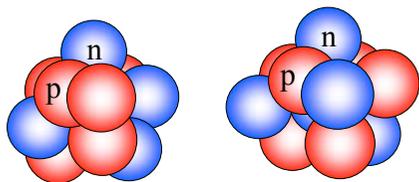
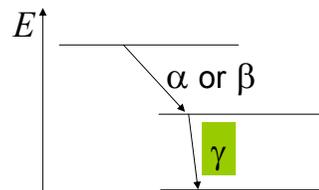
continuous energy spectrum

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.

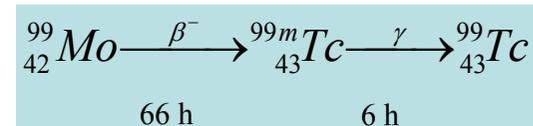
## Isomeric transition

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

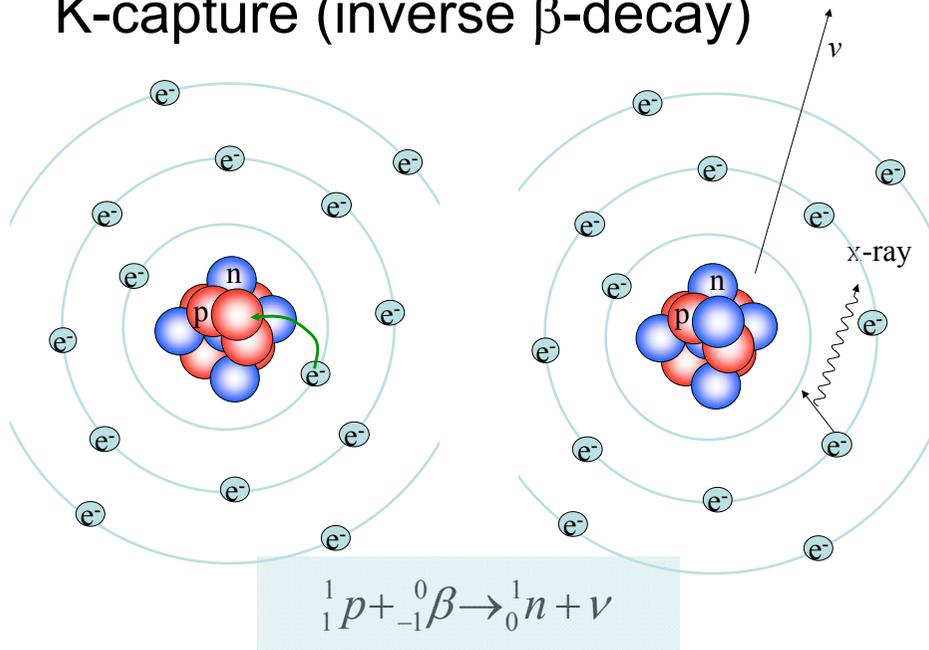
The parent and daughter atoms can be separated: the daughter atom emits **only  $\gamma$ -radiation!**

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

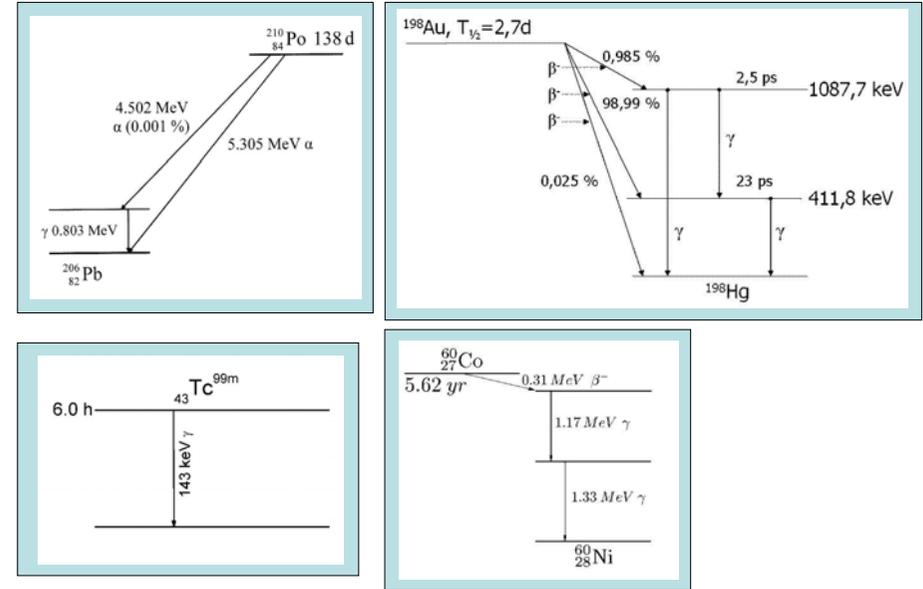
E.g.:  ${}^{99m}Tc$



# 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

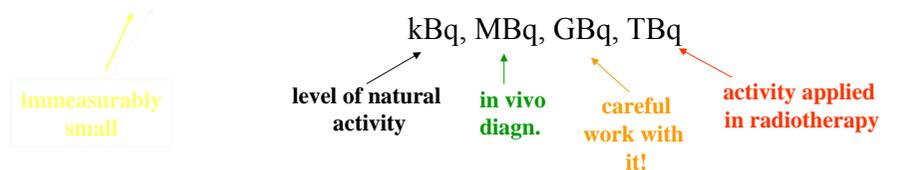
# Activity ( $\Lambda$ )

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

$N$  = 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

$$\Delta N = -\lambda N \Delta t \quad N: \text{Number of undecayed nuclei}$$

$$\frac{dN}{dt} = -\lambda N \quad \begin{array}{l} \lambda: \text{decay constant (probability of the decay [1/s])} \\ 1/\lambda = \tau \text{ average lifetime} \end{array}$$

Differential equation

solution:

$$N(t) = N_0 e^{-\lambda t} \quad \text{Exponential decrease}$$

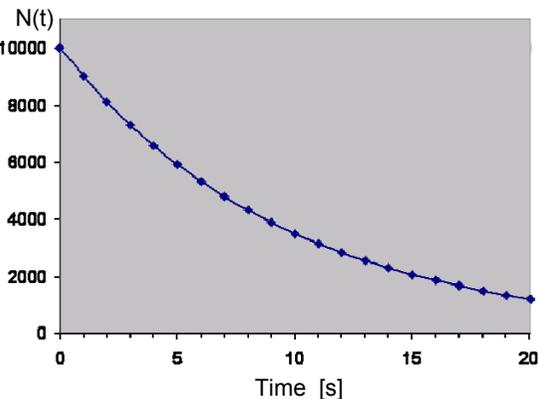
↑  
number of undecayed atoms at  $t=0$

## An example

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

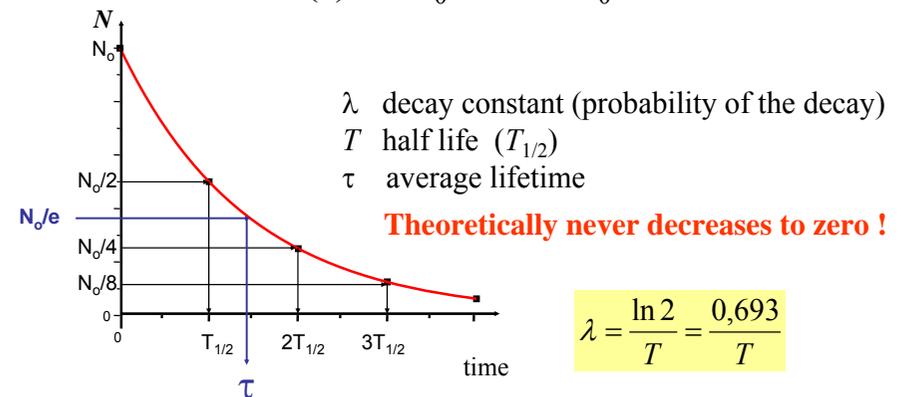
## An example

- At start:  $N_0=10000$  (number of atoms)  
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- after 2 s: 8100
- after 3 s: 7290
- after 4 s: 6561
- ....



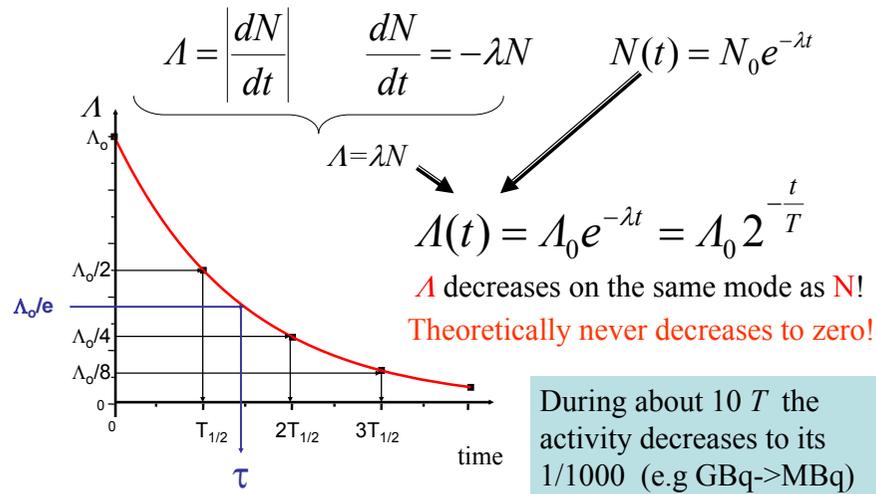
## Law of radioactive decay

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



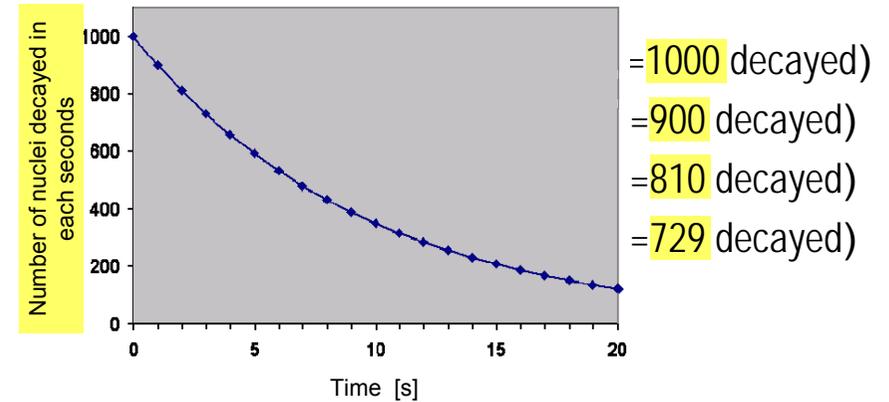
$$\lambda = \frac{\ln 2}{T} = \frac{0,693}{T}$$

## Decrease of the activity as a function of time



## An example

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



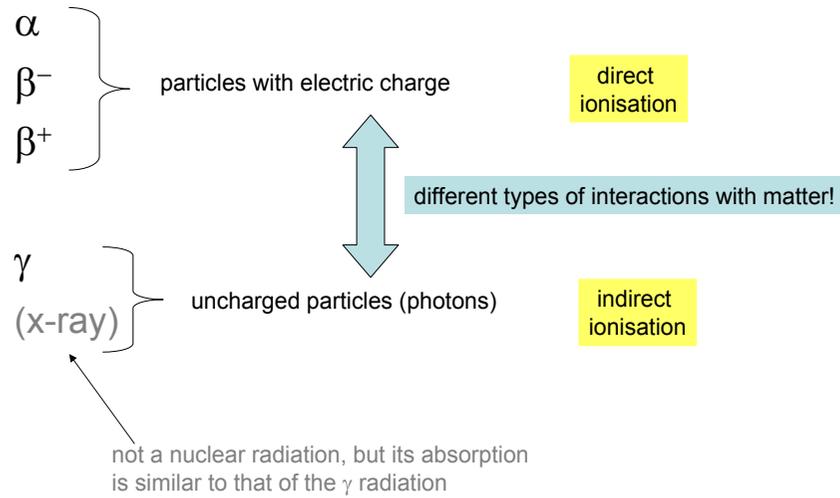
Transformation of the nucleus (decay)

MeV (pJ)

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



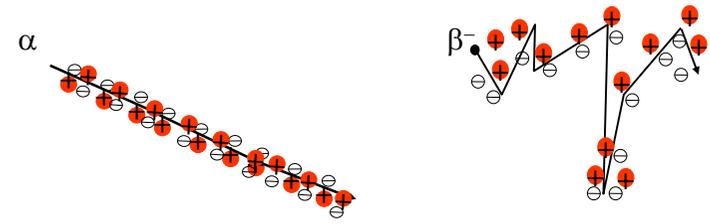
# Absorption of the nuclear radiation



# Absorption of the charged particles

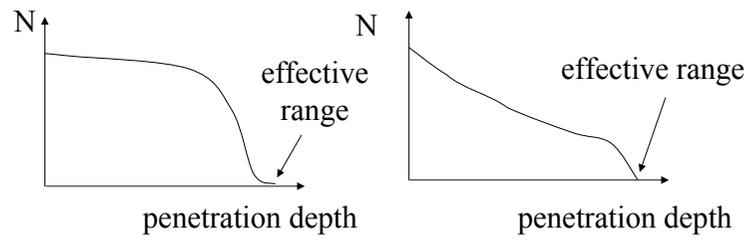
Ionizing during the path => continuous decrease of the particle energy  
 The energy after a given path length decreases to the thermal value

effective range



# Effective range

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



# Applications

