# Biophysics I

## 13. Nuclear radiations

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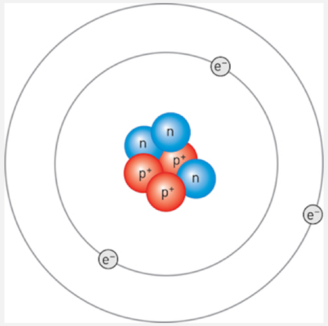


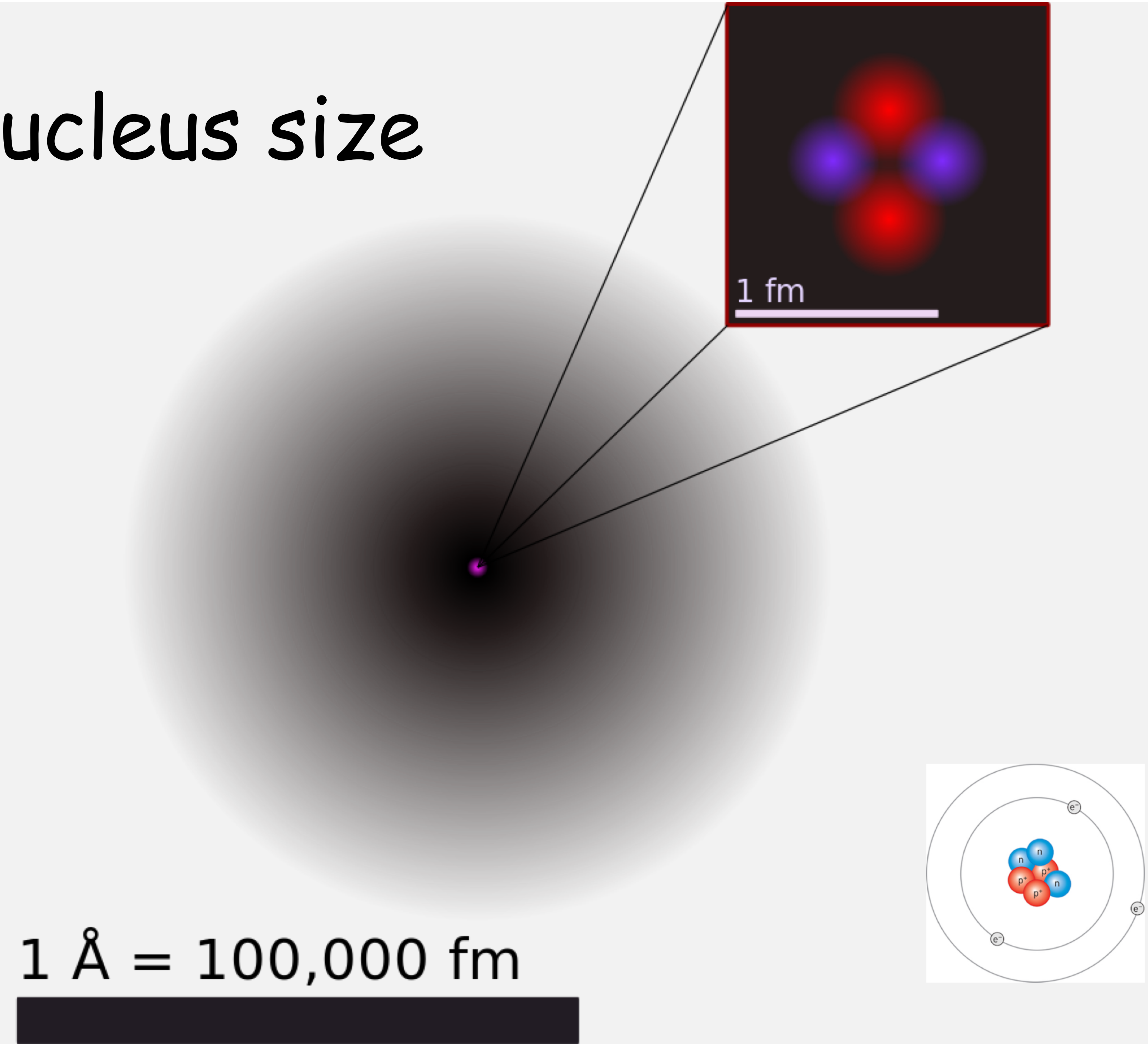

# Constituents of atoms

| Particle | Symbol | Resting Energy (MeV) | Relative Charge* | Mass (kg) | Relative Mass (AMU)** |
|---|---|---|---|---|---|
| electron | e | 0.51100 | 1- | $9.11 \times 10^{-31}$ | $5.4858X10^{-4}$ |
| proton | p | 938.272 | 1+ | $1.6726X10^{-27}$ | 1.0072765 |
| neutron | n | 939.566 | 0 | $1.6749X10^{-27}$ | 1.0086649 |

* electrons have an electric charge of $-1.602 \times 10^{-19}$ C

**The atomic mass unit is defined as 1/12 of the carbon ($^{12}$C) atom

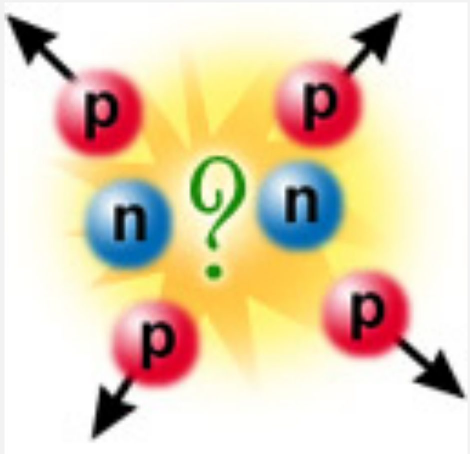
# Nucleus size



# Nuclear stability

There are very large *repulsive electrostatic forces* between protons

should cause the nucleus to fly apart




It must be an attractive force be present within the nucleus!

Rutherford, 1911 – nuclear force: an attractive force acting on short distances within the nucleus, independent of charges, and stronger than the Coulomb forces.

The hypothesis of neutron (discovered by Chadwick in 1932)

# Nuclear notation

***Mass number***
$A = Z + N$

$${}^{A}_{Z}X$$

***Chemical symbol for the element***

***Atomic number = Number of protons***

$${}^{27}_{13}Al$$

$N$ ***= number of neutrons***

***nucleon = proton or neutron***

# Nuclear stability

$$\Delta M = [Zm_p + (A\text{-}Z)m_n] - M(A,Z)$$

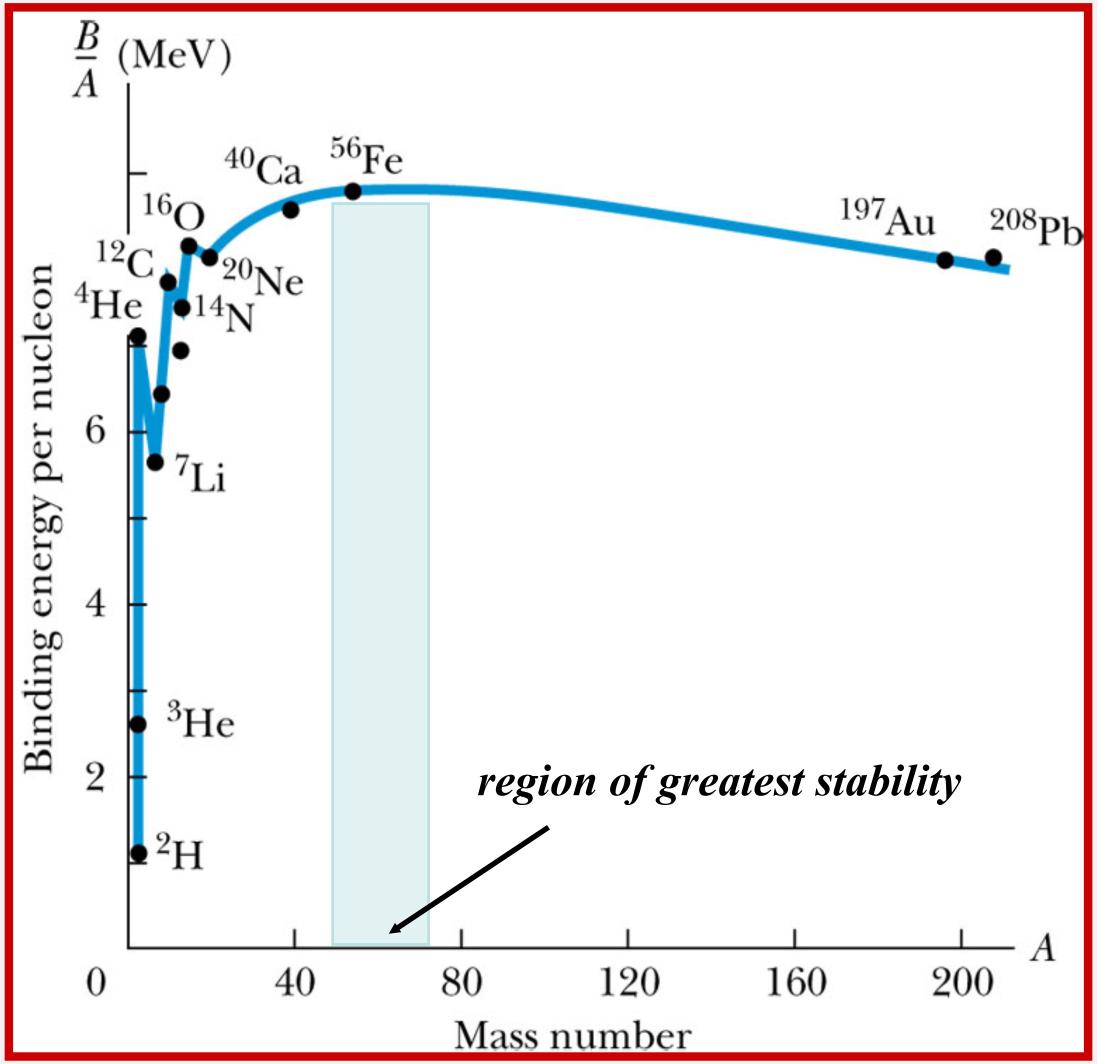
The mass defect (or mass deficit) problem: the mass of a nucleus is less than the mass of its constituent nucleons. The difference can be explained by Einstein's law of mass-energy equivalence:

$$\Delta E = \Delta Mc^2$$

The energy corresponding to the mass defect is the binding energy of the nucleons.

# Binding energy per nucleon

- The curve increases rapidly
- Sharp peaks for the even-even nuclides ${}^{4}_{2}He$, ${}^{12}_{6}C$, and ${}^{16}_{8}O$
- Maximum is around A=56




*nucleon = proton or neutron*

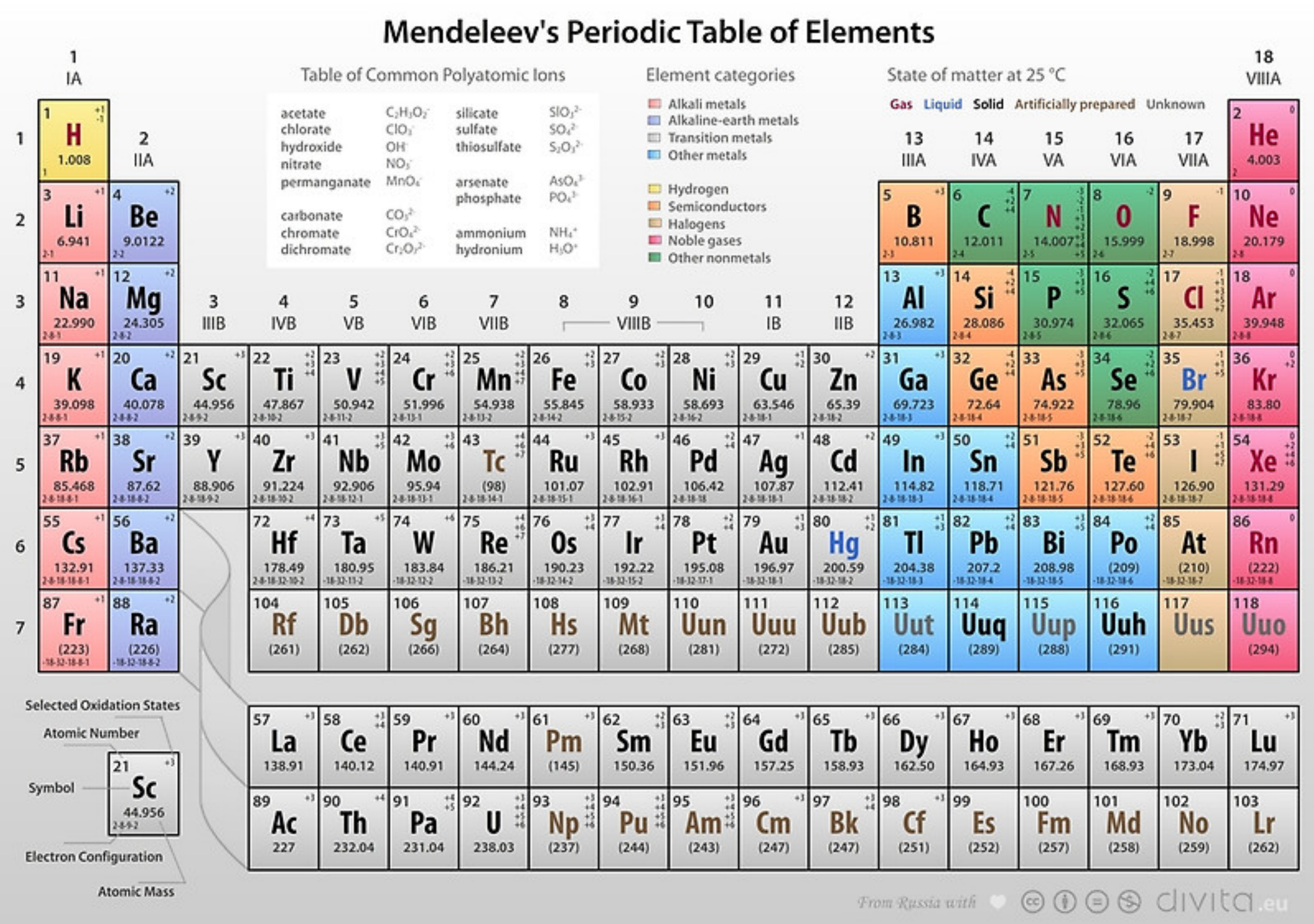
# Isotopes

Greek ***isos topos* = *equal place***

Isotopes of an element have nuclei with

- the same number of protons
- different numbers of neutrons
- different mass number

# isotope = equal place = equal atomic number



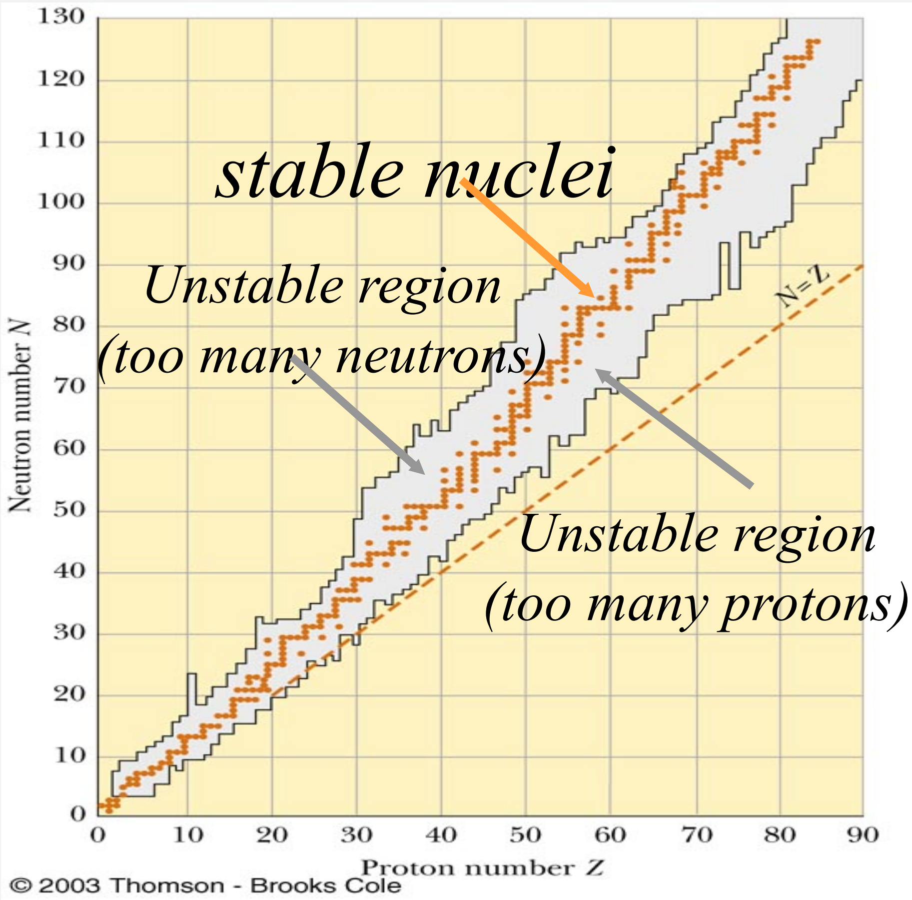
# Nuclear stability chart

- Light nuclei are most stable if
  N=Z

- Heavy nuclei are most stable when
  N > Z

  As the number of protons increases, the Coulomb force increases and so more neutrons are needed to keep the nucleus stable

- No nucleus is stable when Z > 83




*What does it mean „not stable"?*

# Radioactive decay

***Antoine Becquerel***

1903 Nobel Prize in Physics for discovering radioactivity

Image of Becquerel's photographic plate which has been fogged by exposure to radiation from a uranium salt. The shadow of a metal Maltese Cross placed between the plate and the uranium salt is clearly visible. (1896)

# Radioactive decay

- *Radioactivity* is the spontaneous release of energy in the form of particles or electromagnetic waves
- Experiments suggested that radioactivity was the result of the decay of unstable nuclei
- Three types of radiation can be emitted

Alpha ($\alpha$) particles

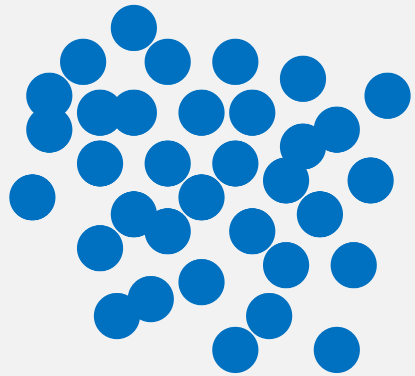
Beta ($\beta$) particles

Gamma ($\gamma$) rays

# Characteristics of radioactive decay

• it is a *statistical process* – individual disintegrations occur ***randomly***

• it results in a decrease over time of the initial number of unstable (radioactive) nuclei



# Characteristics of radioactive decay

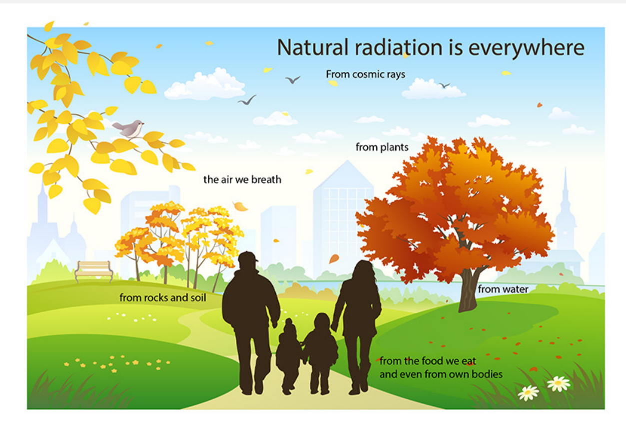
***Activity*:** $\Lambda = \left|\frac{\Delta N}{\Delta t}\right|$

***N: number of nuclei to be decayed***
***t: time***

***Activity = number of nuclei decayed in a unit time***

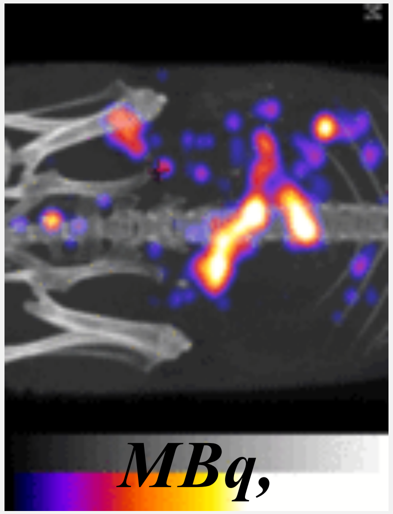
***unit: bequerel (Bq)   1Bq = 1 decay/sec***

*background*




***kBq,***

*diagnostics*

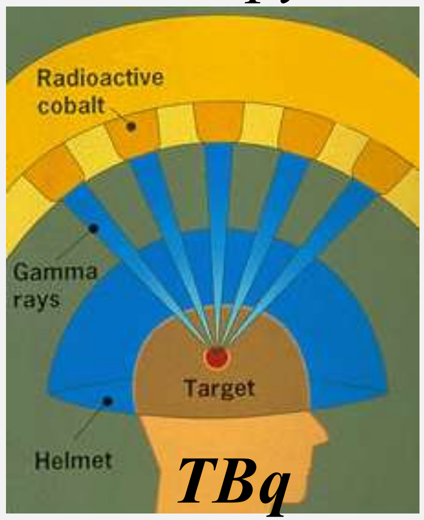


***MBq,***

*laboratory practice*

***GBq,***

*therapy*




***TBq***

# Radioactive decay law

**Differential form:** $$\frac{\Delta N}{\Delta t} = -\lambda N$$

solution

$\lambda$ : decay constant, characteristic for isotopes (1/s)

**Integral form:** $$N = N_0 e^{-\lambda t}$$

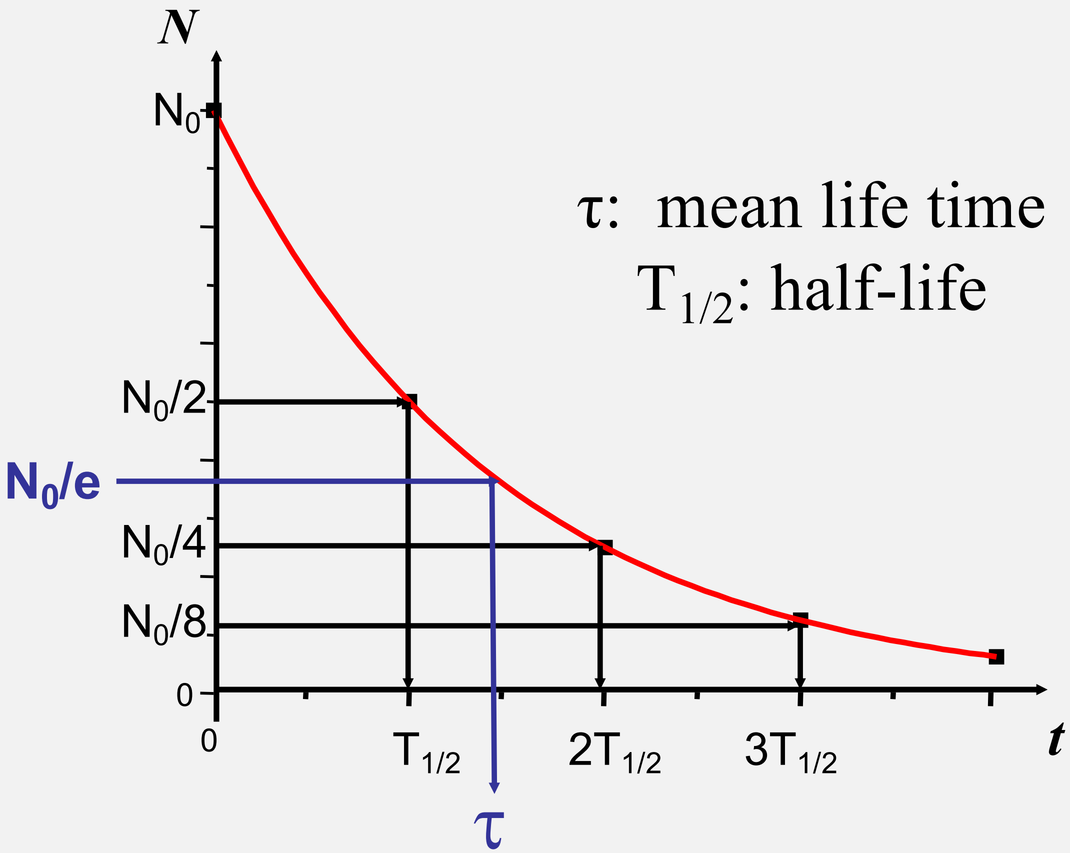
$N_0$: number of radioactive nuclei at t=0,
$N$: number of remaining radioactive nuclei at a later time $t$

Activity depends both on the type of isotope and on the size of the population of unstable (radioactive) nuclei

Specific activity: activity in a unit mass of isotope (Bq/kg)

# Graphical representation

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




τ: mean life time

$T_{1/2}$: half-life

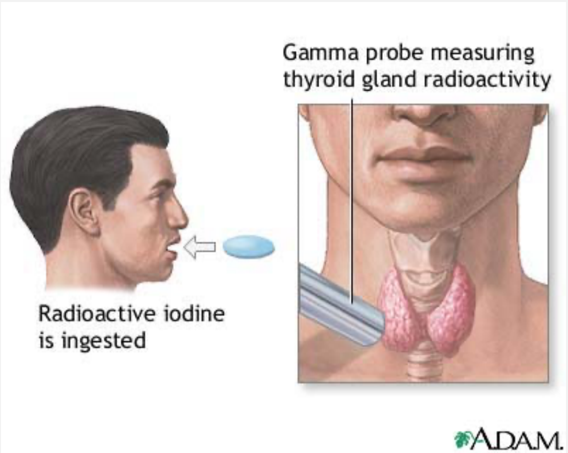
If t = τ

$$N_0 / e = N_0 e^{-\lambda\tau}$$

$$\lambda = \frac{1}{\tau}$$

If $t = T_{1/2}$ $\longrightarrow$ $N_0 / 2 = N_0 e^{-\lambda T_{1/2}}$ $\longrightarrow$ $\lambda = \frac{\ln 2}{T_{1/2}} = \frac{0.693}{T_{1/2}}$

# Half-lives in Medical Practice

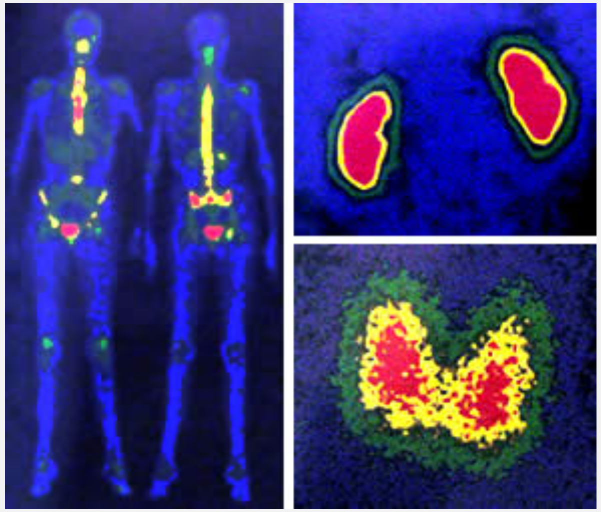


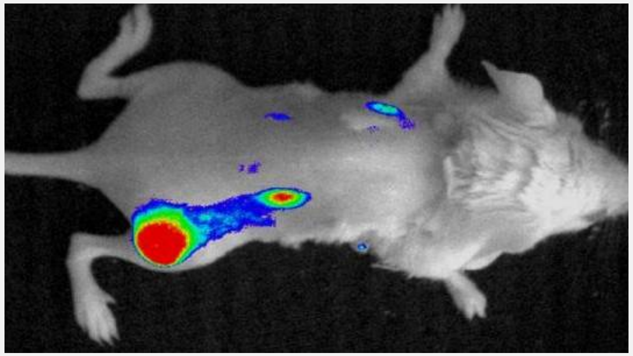

***Iodine - 131*** ($^{131}$I) ***-*** $T_{1/2}$ ***= 8 days***

***Thyroid treatment***

***Technetium-99m*** ($^{99m}$Tc) – $T_{1/2}$ ***= 6 hours***

***Isotope diagnostics***

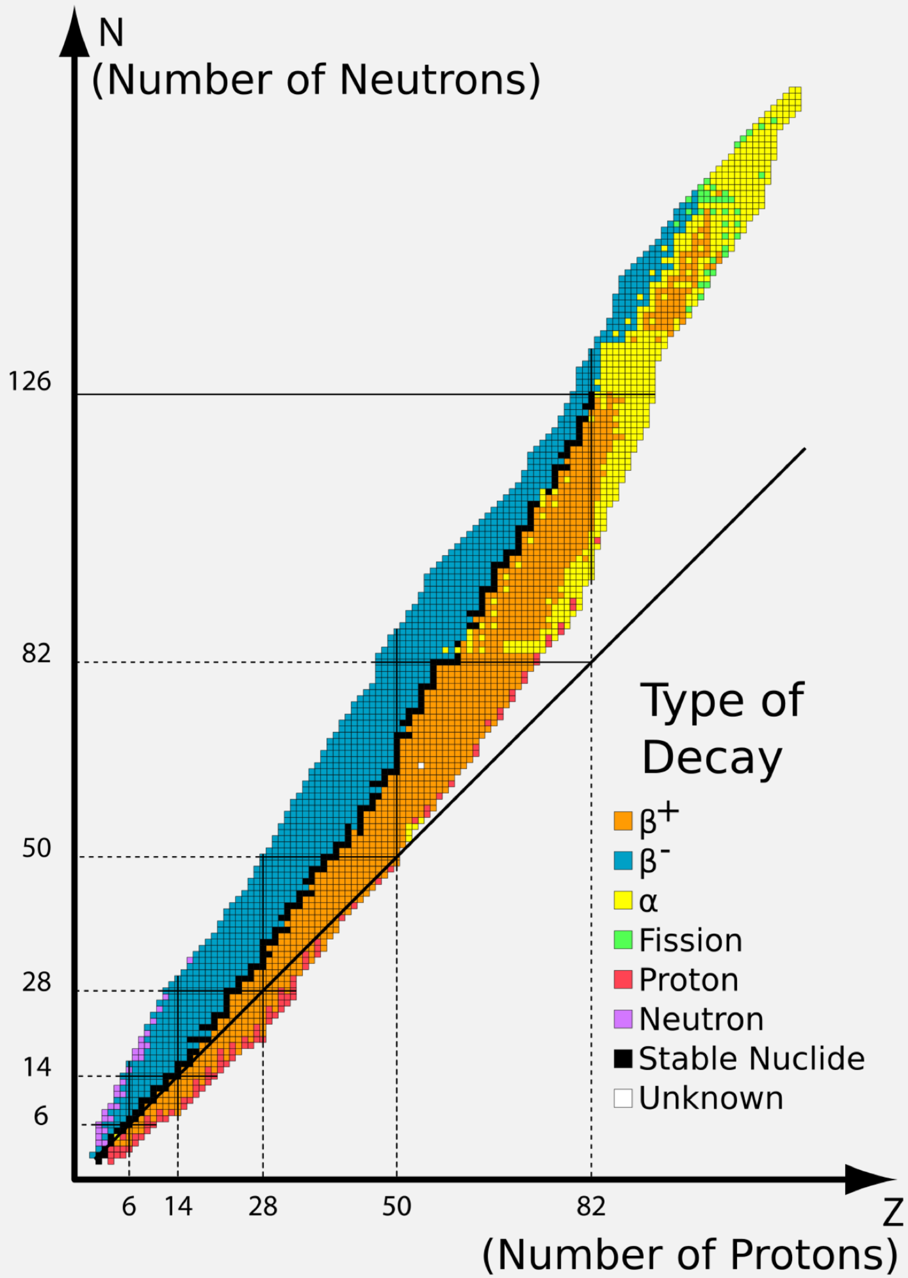


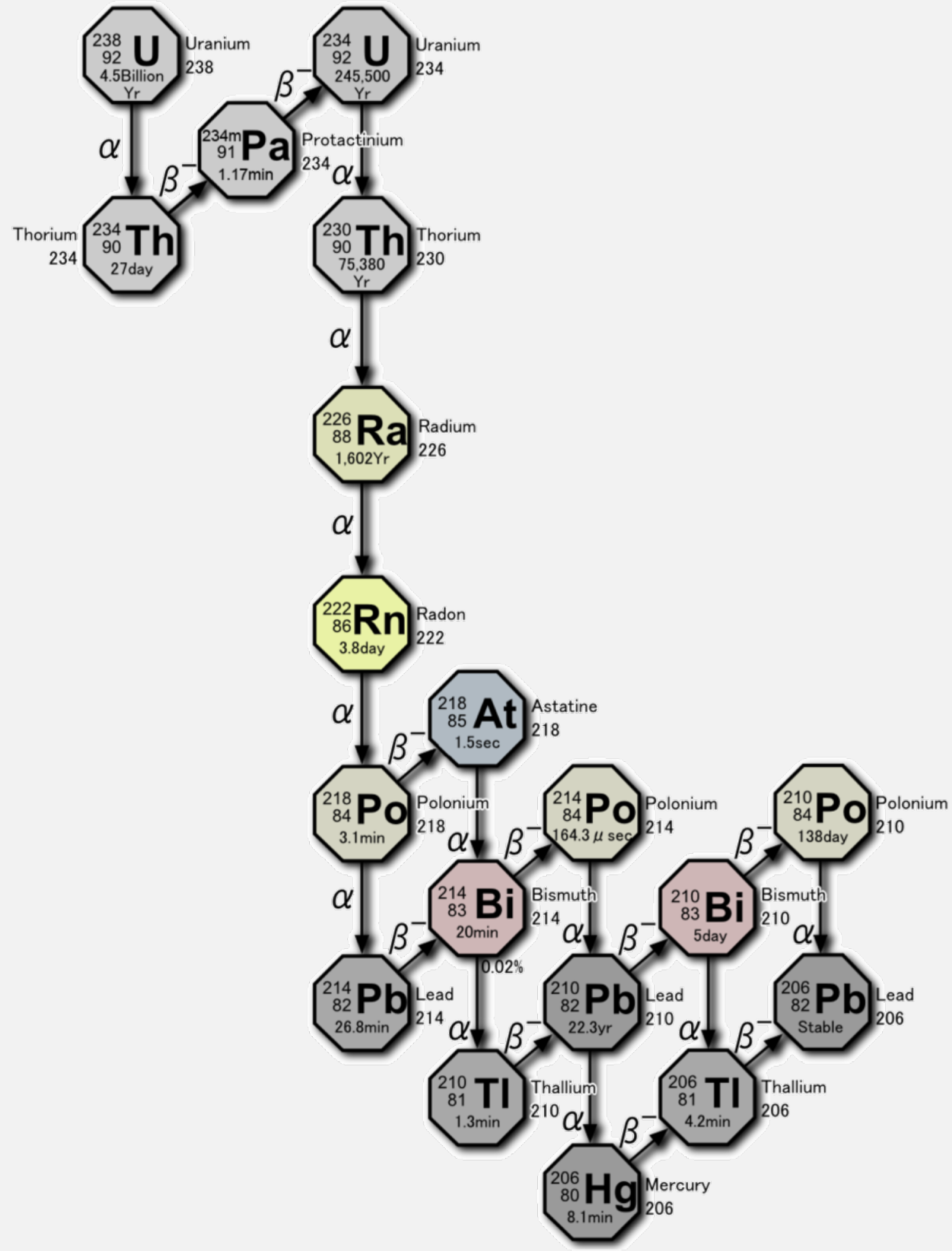


***Gold-198*** ($^{198}$Au) ***-*** $T_{1/2}$ ***= 2.7 days***

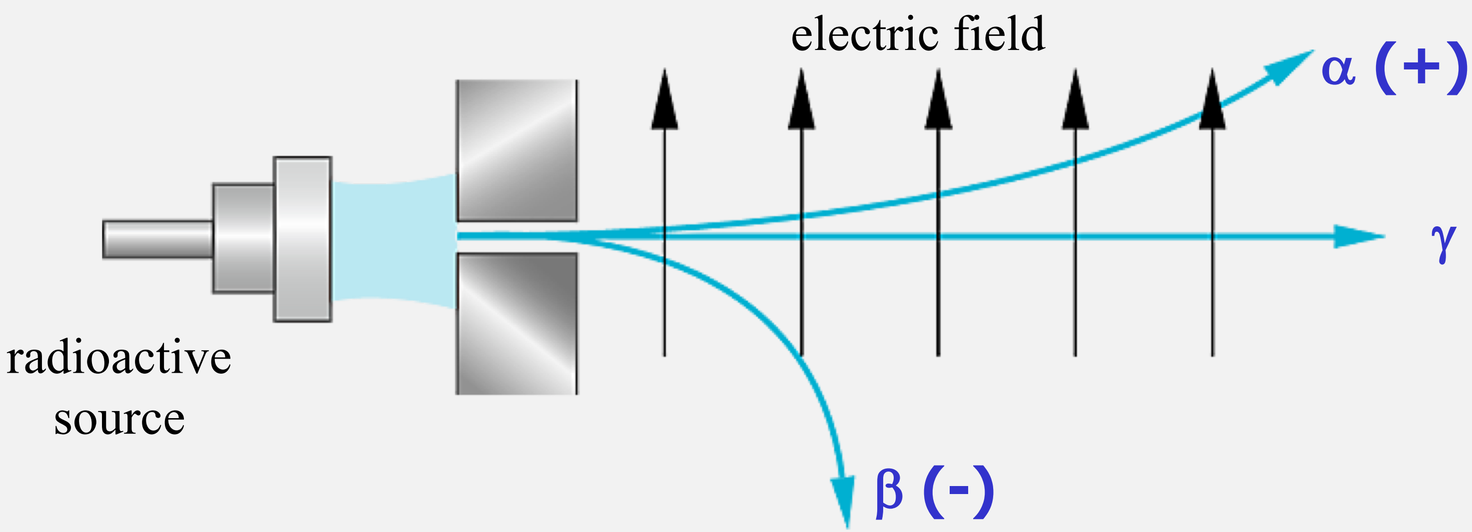
***Tumor therapy***

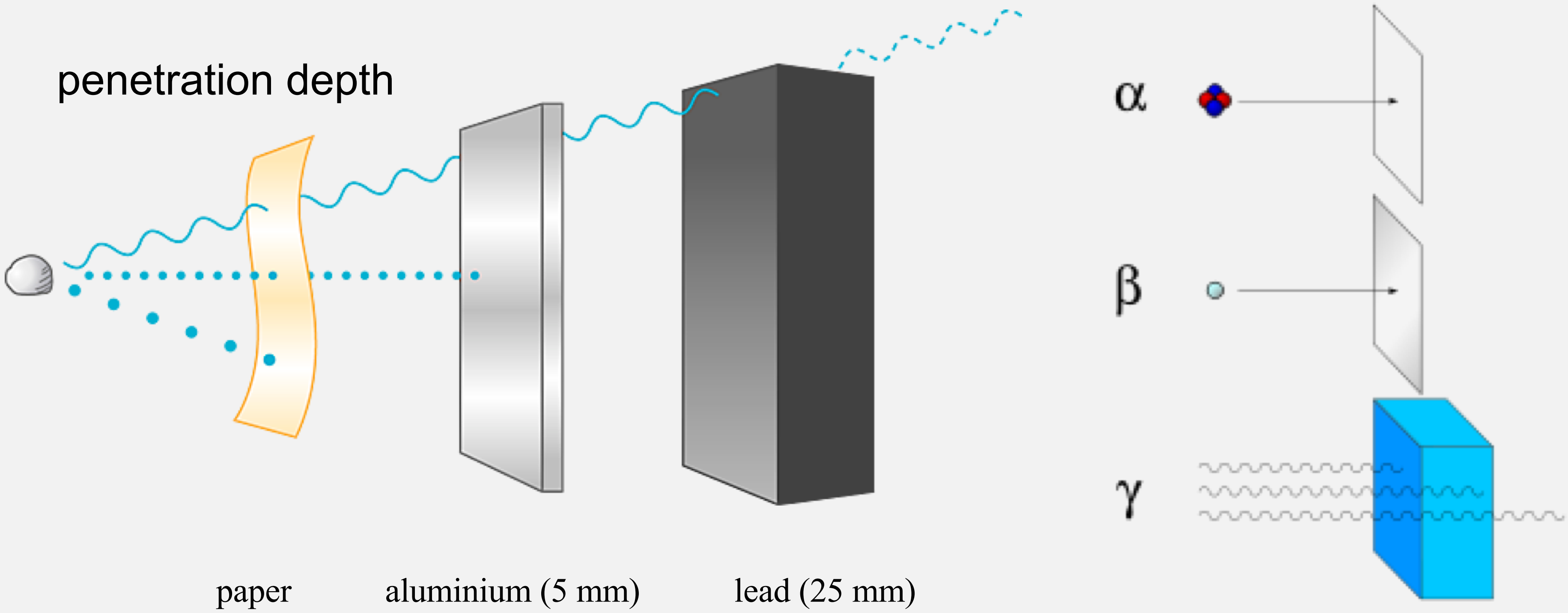
# Types of radioactive decay



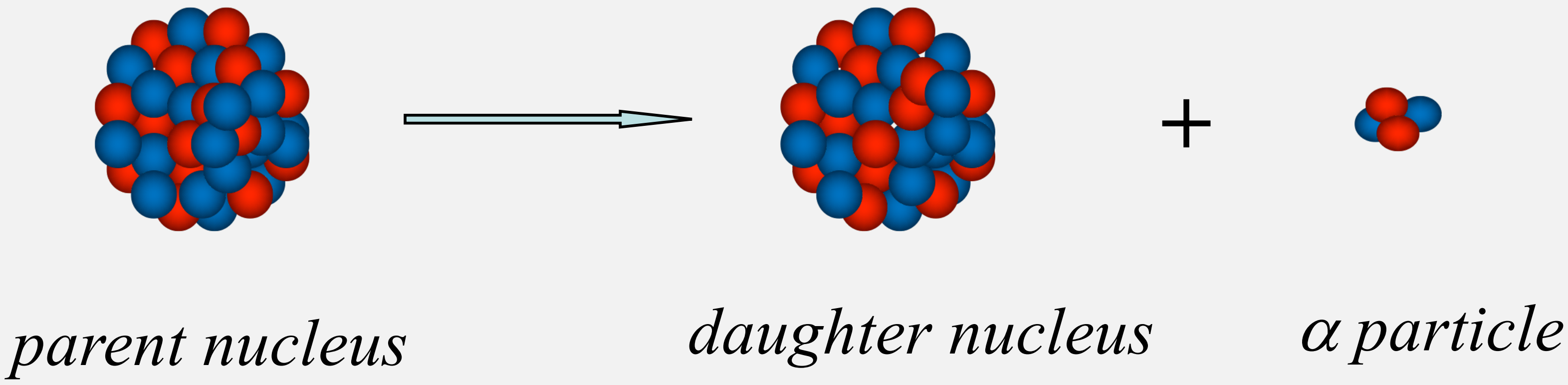



# Types of radioactive decay



# α decay




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

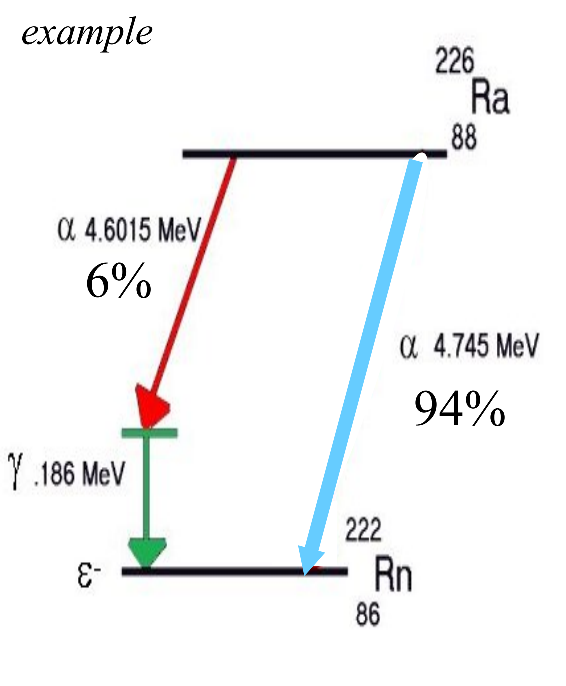
**α particle** is a nucleus of helium containing two neutrons and two protons

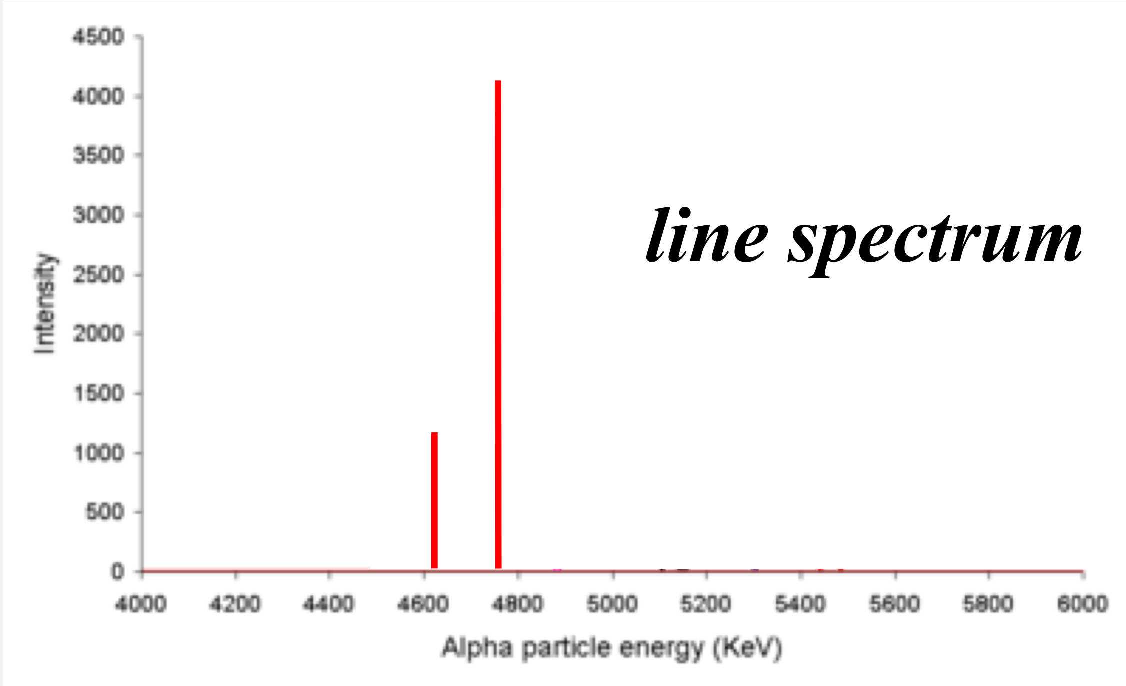
Heavy nuclei (A > 150) can disintegrate by emission of an α particle

*example:*

$$^{226}_{88}Ra \longrightarrow \, ^{222}_{86}Rn + \, ^{4}_{2}\alpha$$

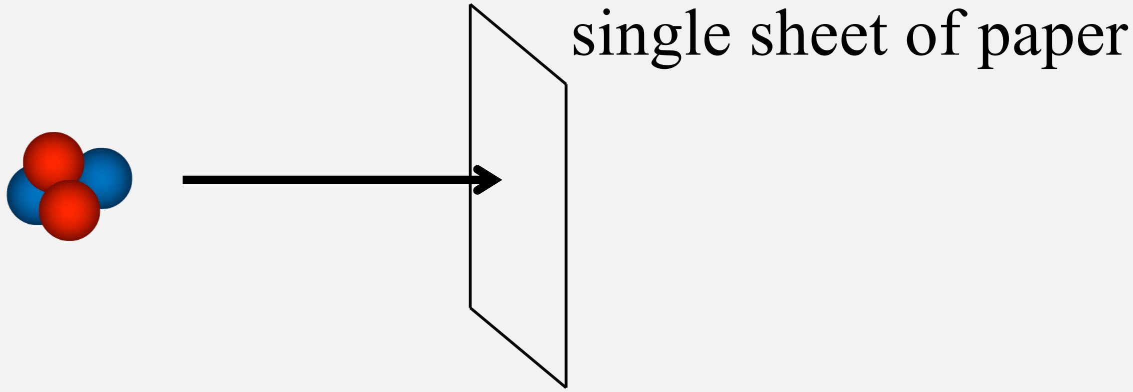
# Energy spectrum of α radiation




***Energy is characteristic for the nucleus***

# Penetration depth of $\alpha$ particles

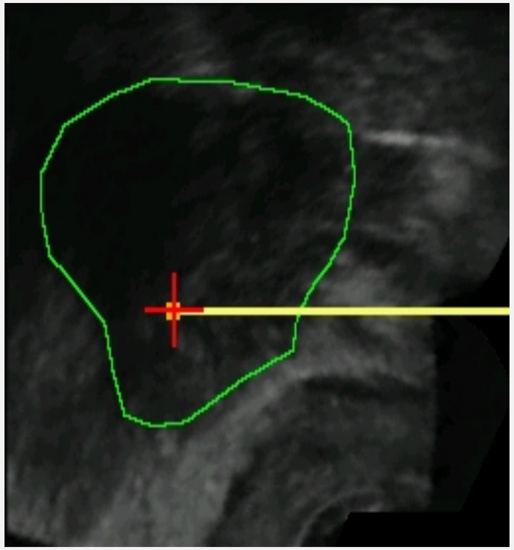



| **absorber** | **density** | **alpha range** |
|---|---|---|
| air (STP) | 1.2 mg/cm$^3$ | 3.7 cm |
| paper (20lb) | 0.89 g/cm$^3$ | 53 µm |
| water (soft tissue) | 1.0 g/cm$^3$ | 45 µm |

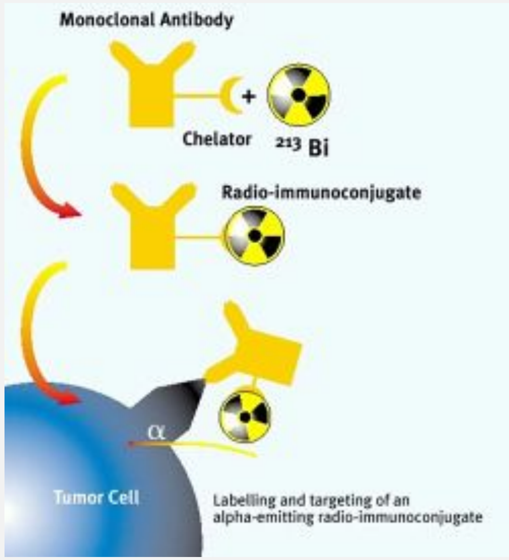
# Medical application of α radiation

Diagnostics: none

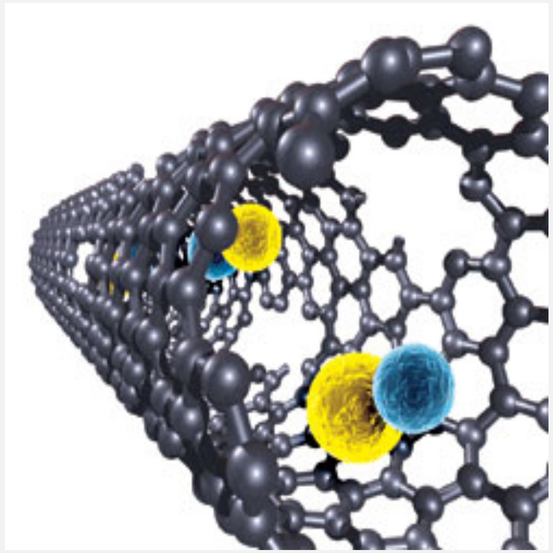
Targeted alpha **therapy** of cancer



Seed implantation by needle



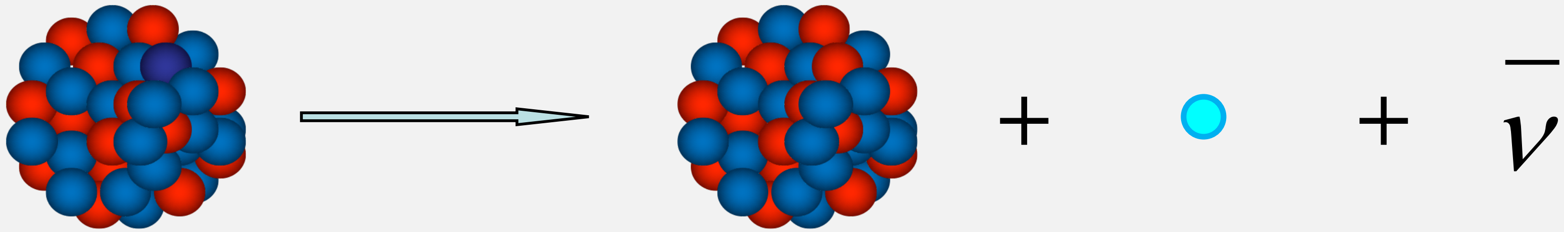

Monoclonal antibody



Carbon nano-tube

# β decay

## 1. Neutron excess: β⁻ decay



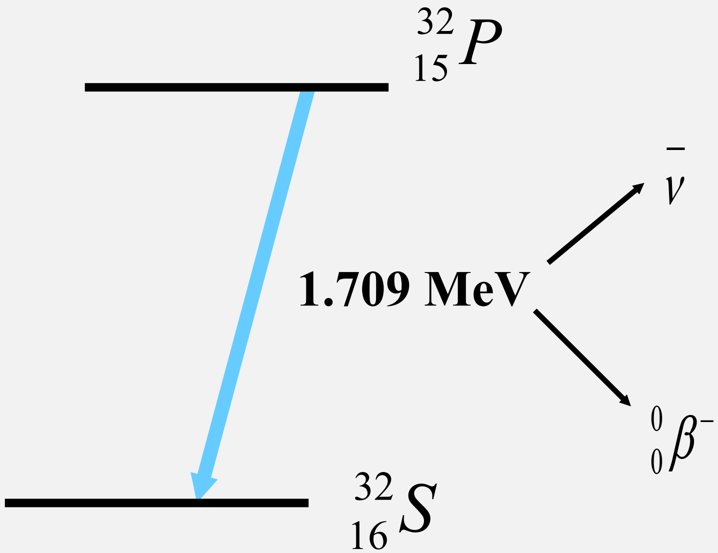

$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + e^{-} + \bar{\nu} $$

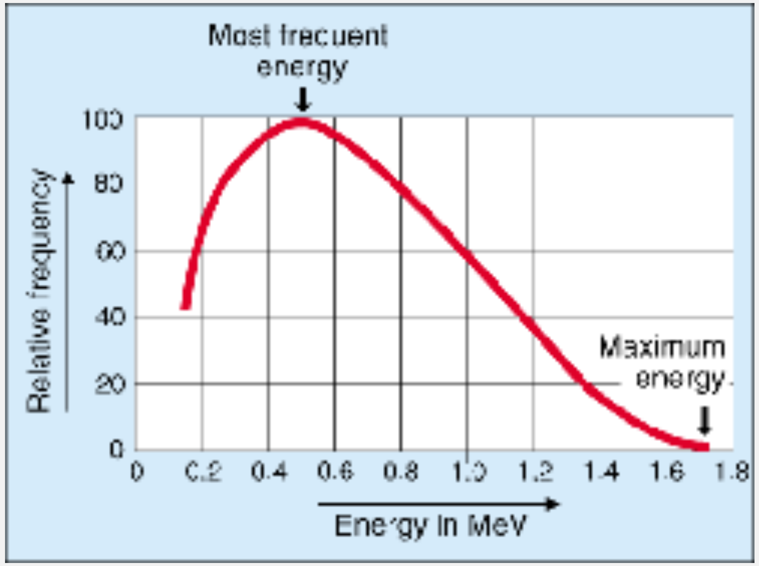
$$ {}^{1}_{0}n \longrightarrow {}^{1}_{1}p^{+} + {}^{0}_{0}\beta^{-} + \bar{\nu} $$

*example:*

$$ {}^{131}_{53}I \longrightarrow {}^{131}_{54}Xe + {}^{0}_{0}\beta^{-} + \bar{\nu} $$

# Energy spectrum of β radiation



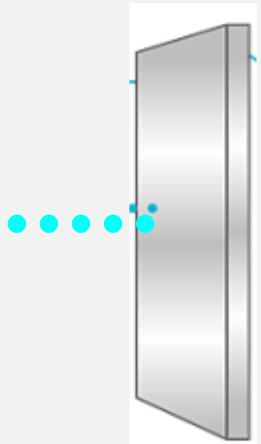




*Energy distribution of the β- particles emitted during the β- decay of $^{32}P$.*

***continuous spectrum***

with a maximum kinetic energy for the β particle

# Penetration depth of $\beta^-$ particles



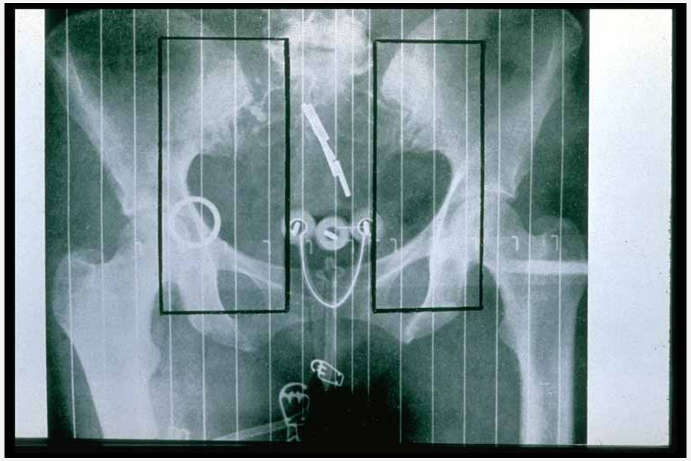
5 mm aluminum

| ***absorber*** | ***density*** | ***maximum beta range*** ***(2.3 MeV)*** | ***(1.1 MeV)*** |
|---|---|---|---|
| air | 1.2 mg/cm$^3$ | 8.8 m | 3.8 m |
| water (soft tissue) | 1.0 g/cm$^3$ | 11 mm | 4.6 mm |
| aluminum | 2.7 g/cm$^3$ | 4.2 mm | 2.0 mm |
| lead | 11.3 g/cm$^3$ | 1.0 mm | 0.4 mm |

# Medical application of $\beta^-$ radiation

Diagnostics: none

Targeted therapy: hyperthyroidism, thyroid, prostate, and several other types of cancer

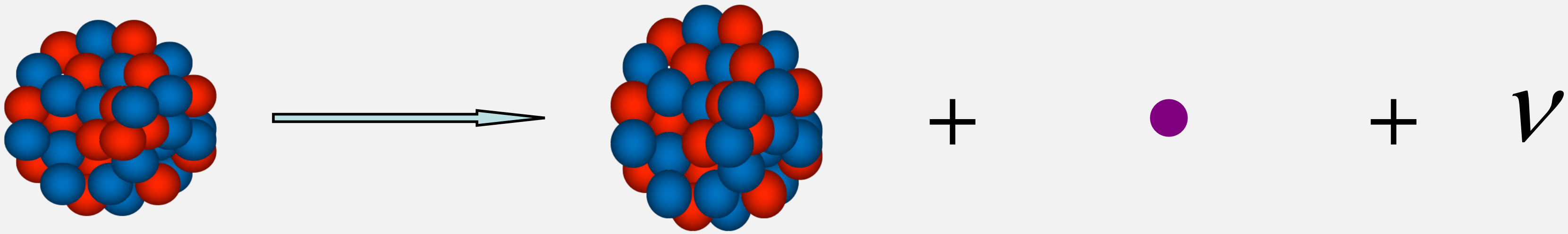


Brachytherapy*:* implants into the tumours

Endovascular irradiation

# β decay

## 2. Proton excess: $\beta^+$ decay



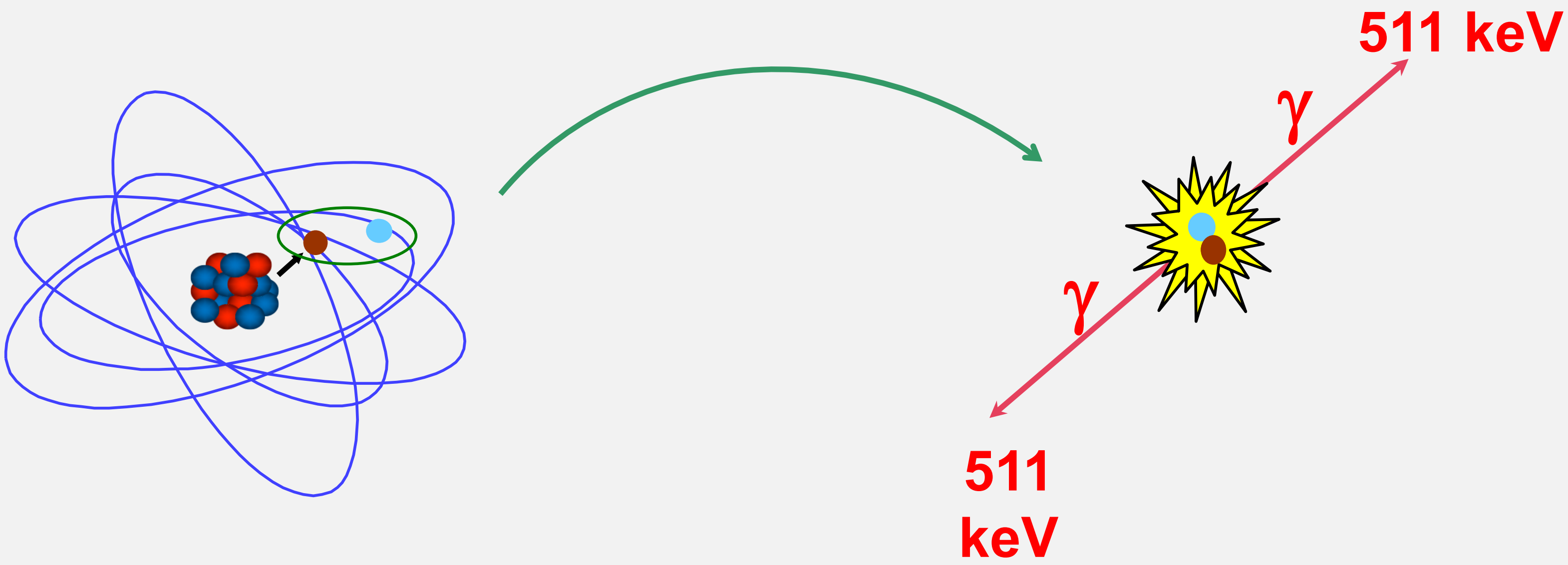

$$^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y + e^{+} + \nu$$

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

*example:*

$$^{11}_{6}C \longrightarrow {}^{11}_{5}B + e^{+} + \nu$$

# Annihilation - particle-antiparticle pairs annihilate each other



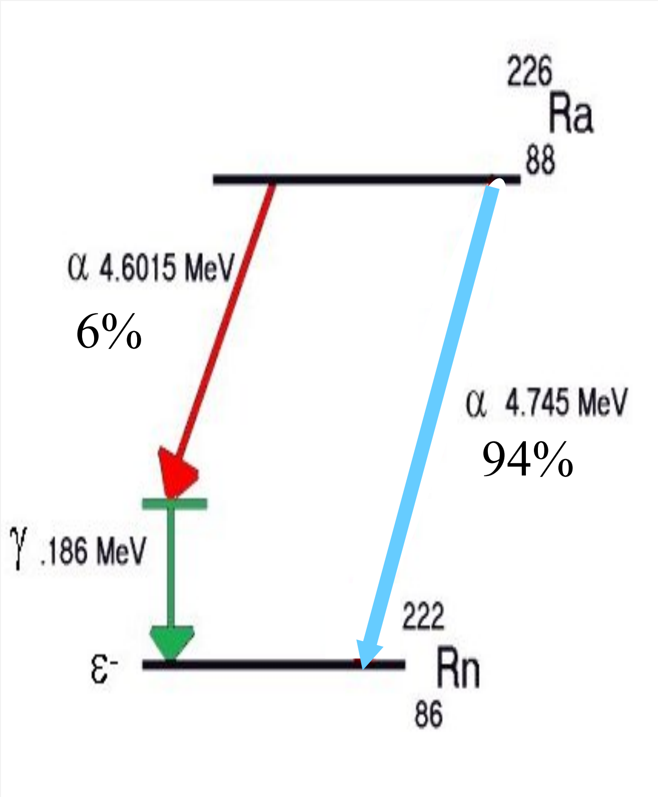

1. Conservation of momentum: two photons with opposite direction are produced

2. Energy balance:

$$m_e c^2 + m_p c^2 = 2\ hf$$

*mass–energy equivalence*

# γ decay – Isomeric transition



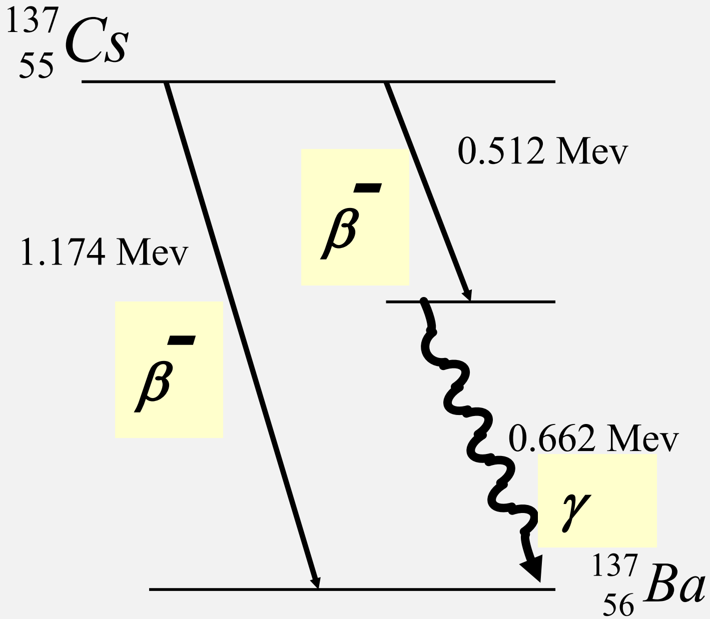

Sometimes the newly formed isotopes (after $\alpha$ or $\beta$ decay) appear in the excited state.

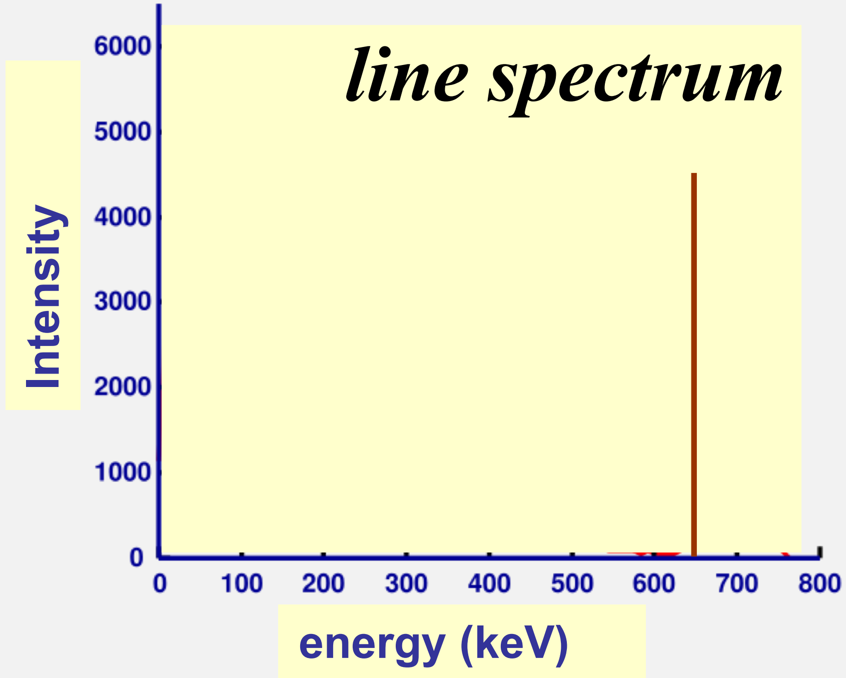
Excited nuclides release the excess of energy by emission of gamma rays.

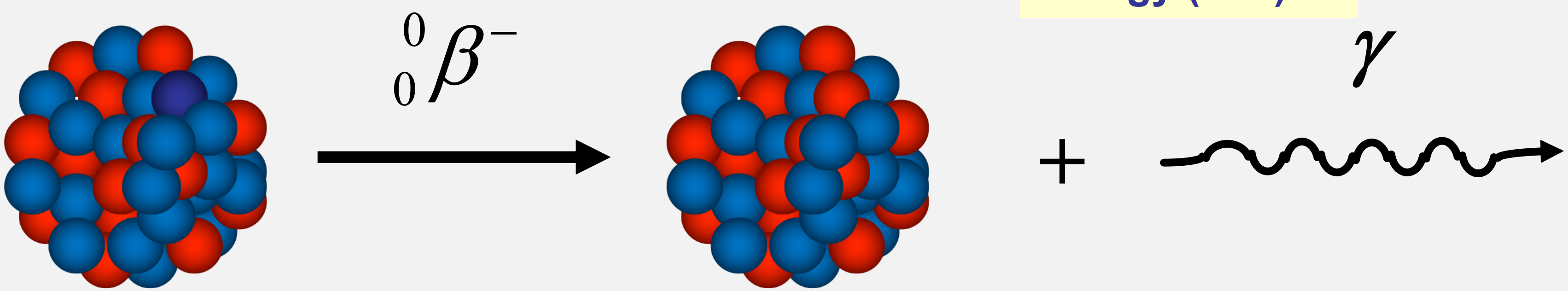
half-life ranging from hours up to more than 600 years

$$^{Am}_{Z}X \rightarrow {}^{A}_{Z}X + \gamma$$

# Energy spectrum of γ radiation



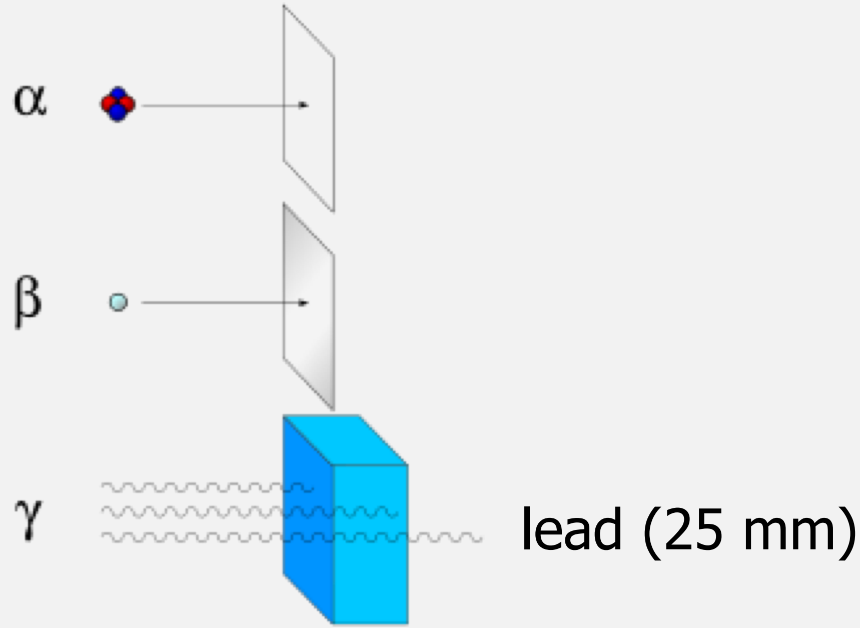




*parent nucleus* *daughter nucleus* *gamma Ray*

***Energy is characteristic for the nucleus***

# Penetration depth of $\gamma$ radiation

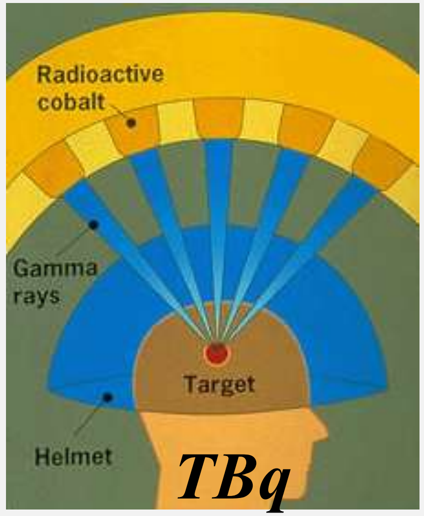


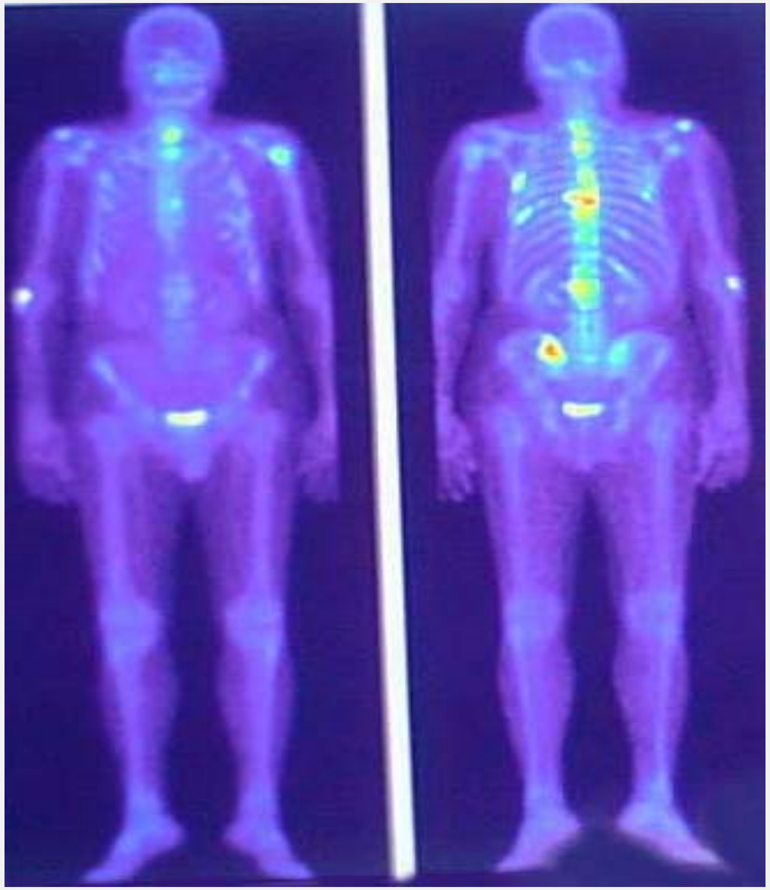

Penetration depth is higher than that of α or β particles, but it is highly energy dependent.

Gamma rays can travel from hundreds of meters in the air and can easily go right through people (~dm).

# Medical application of $\gamma$ rays

*therapy: $\gamma$-knife*

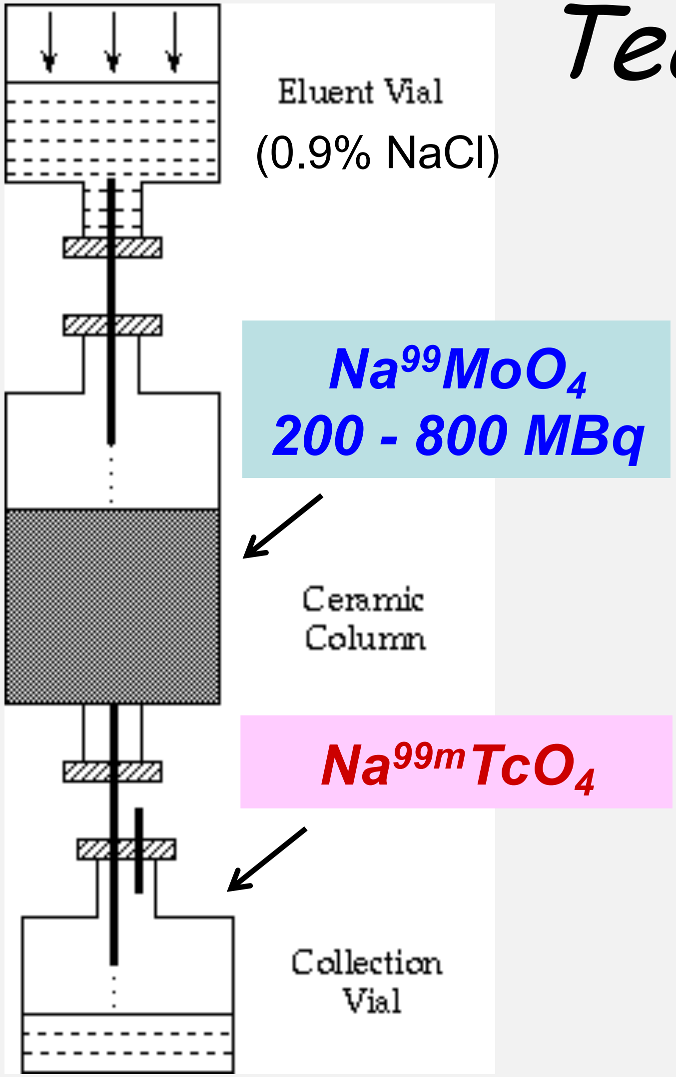


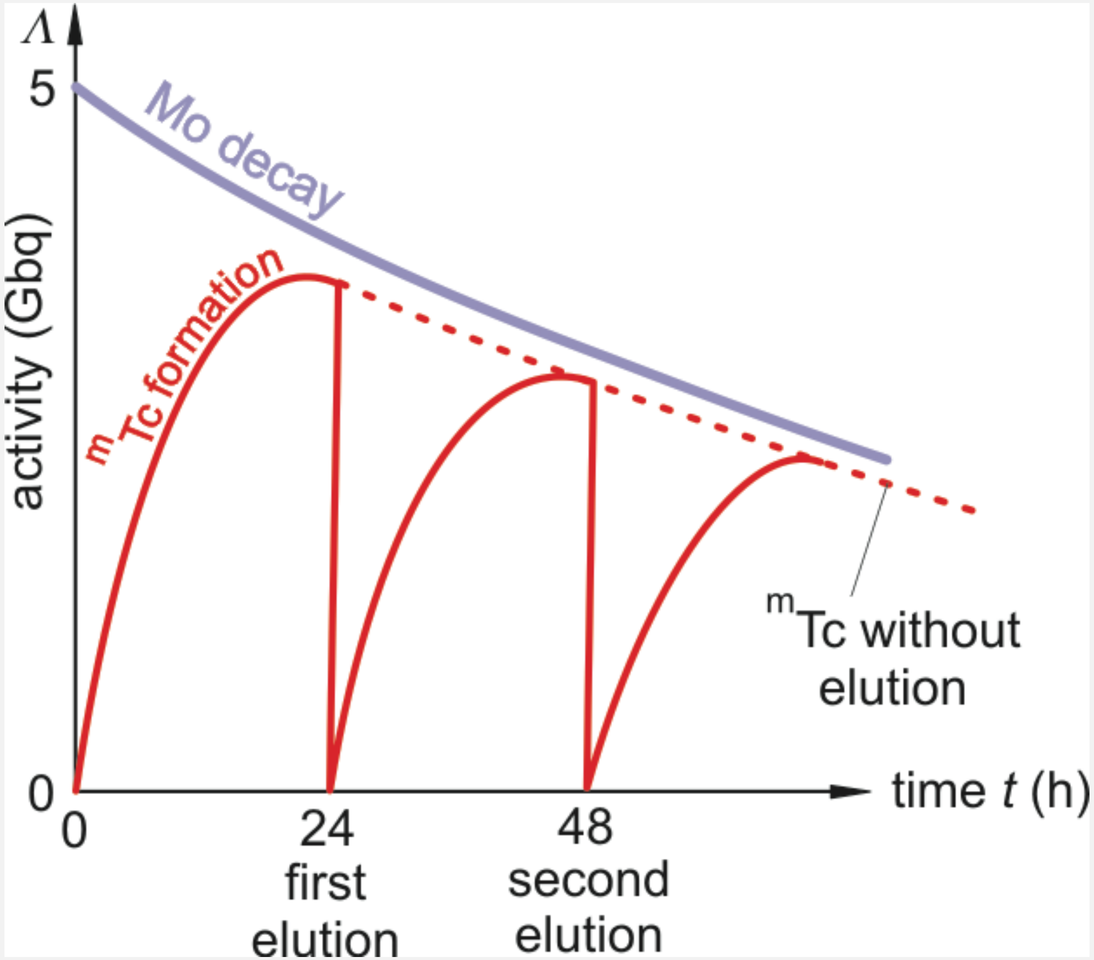



*Bone scan using $^{99m}$Tc labeled phosphate compound*

Diagnostics: ideal for isotope diagnostics

# *Technetium-99m generator*




$$^{99}_{42}Mo \rightarrow ^{99m}_{43}\mathrm{Tc} + \beta^{-} \rightarrow ^{99}_{43}\mathrm{Tc} + \gamma$$

$T_{1/2}$=67 hours $T_{1/2}$=6 hours

## *Checklist*

Composition and stability of the nucleus

Origin of nuclear force

Radioactive decay law – differential and integral form

Decay constant, half-life, mean life time

Types of nuclear radiation and their characteristics

*Damjanovich, Fidy, Szöllősi: Medical Biophysics*

- I. 1.5
  - 1.5.1
  - 1.5.2
  - 1.5.4
- II.3.2
  - 3.2.1
  - 3.2.2
  - 3.2.3
  - 3.2.4