Biophysics I

13. Nuclear radiations

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29. 11. 2023.

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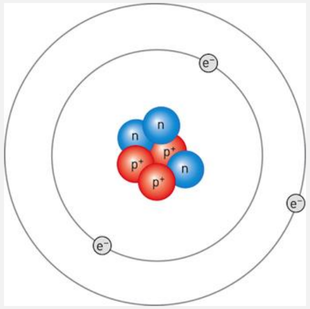


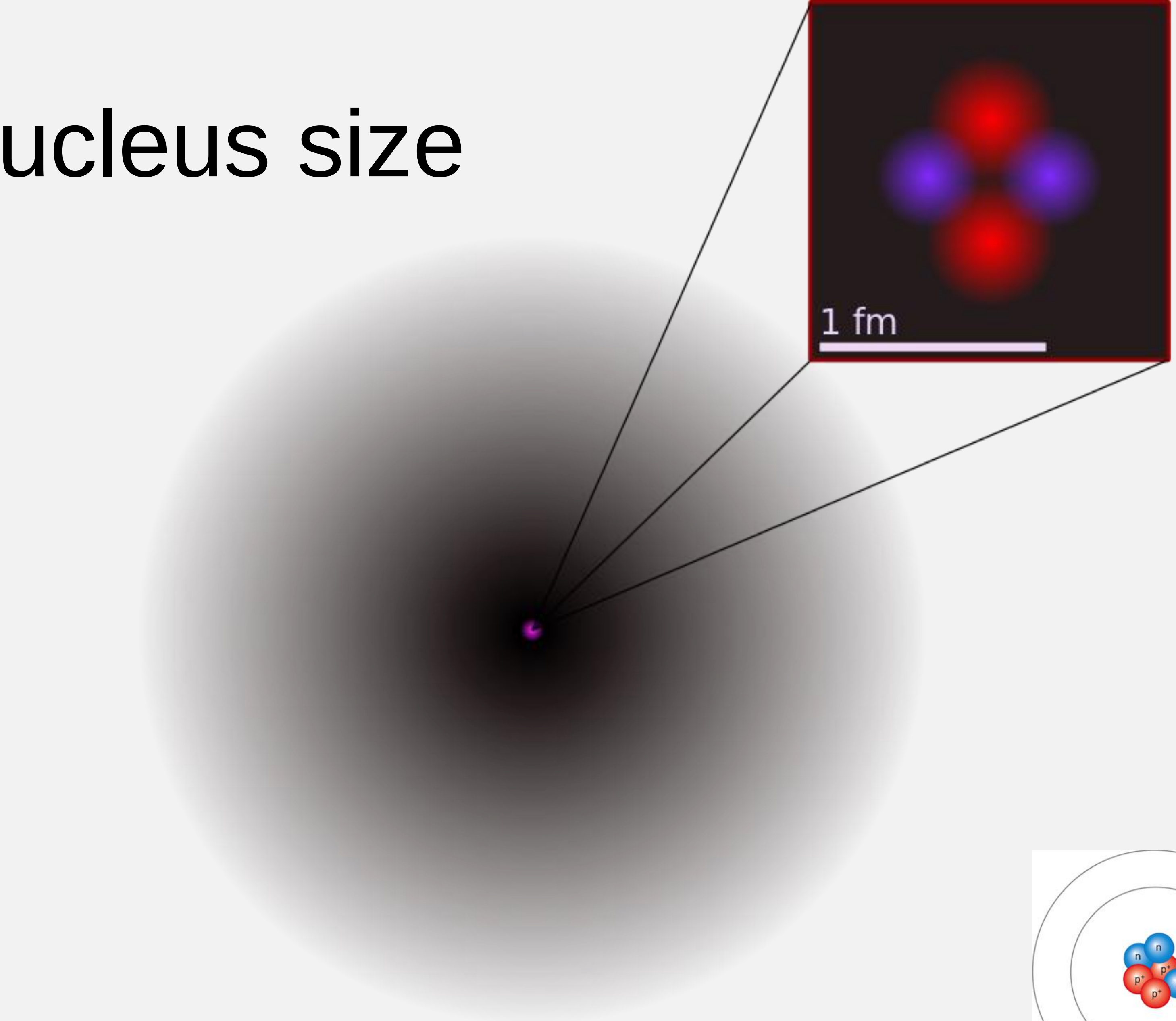
Constituents of atoms

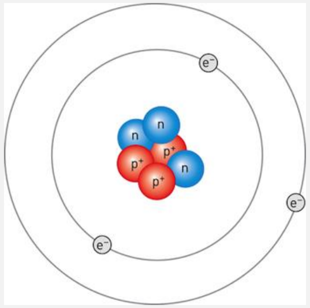
Particle	Symbol	Resting Energy (MeV)	Relative Charge*	Mass (kg)	Relative Mass (AMU)**
electron	e	0.51100	1-	9.11×10^{-31}	$5.4858X10^{-4}$
proton	p	938.272	1+	$1.6726X10^{-27}$	1.0072765
neutron	n	939.566	0	$1.6749X10^{-27}$	1.0086649

***** electrons have an electric charge of -1.602×10^{-19} C

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

Nucleus size

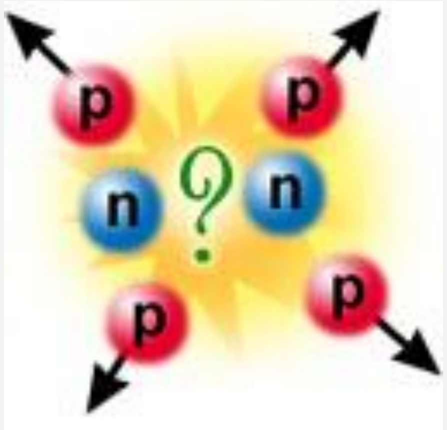




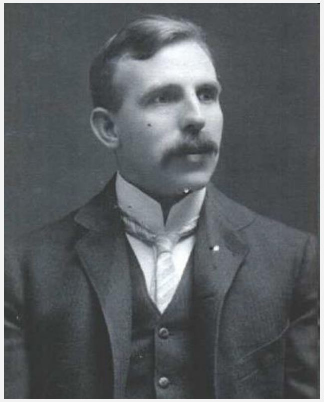
Nuclear stability

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:

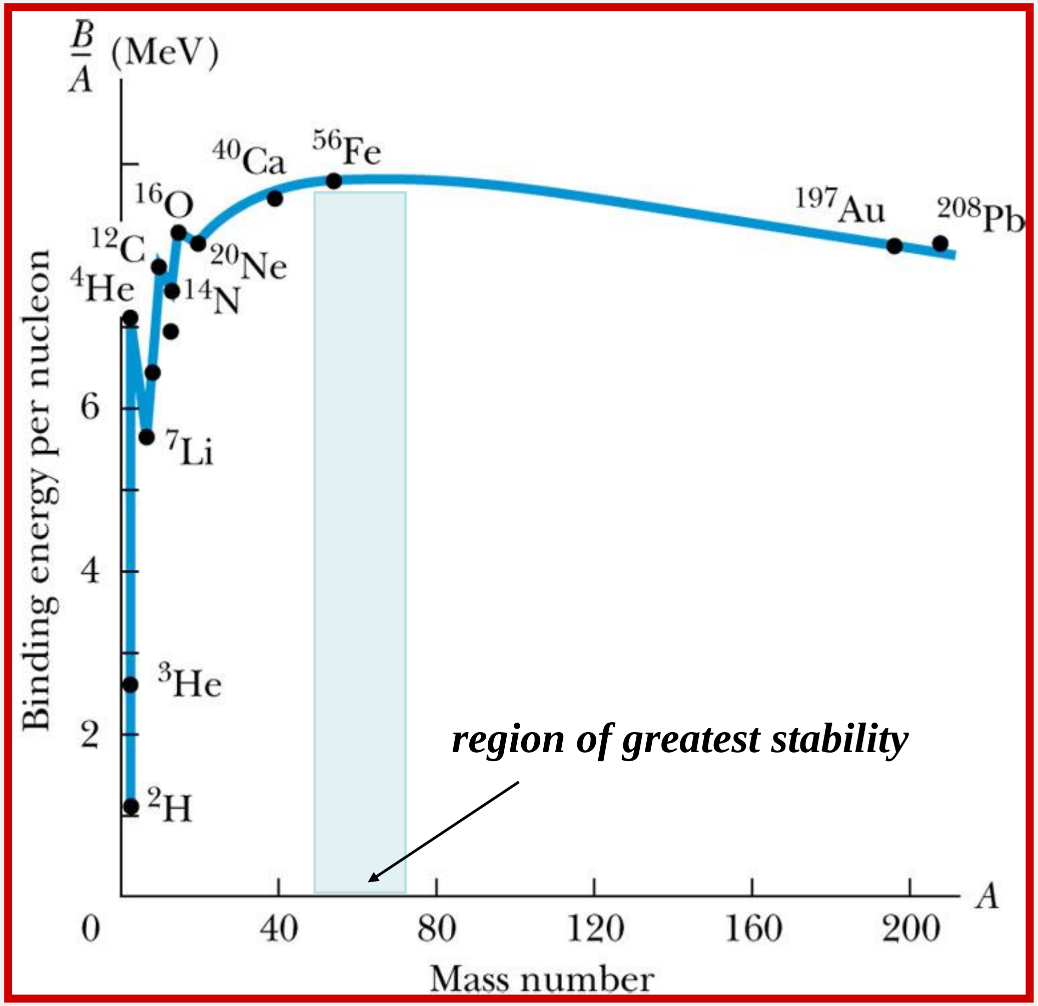
$$\boxed{\Delta E = \Delta M c^2}$$

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 nuclei for ${}^{4}_{2}He$, ${}^{12}_{6}C$, and ${}^{16}_{8}O$
- Maximum is around A=56

nucleon = proton or neutron



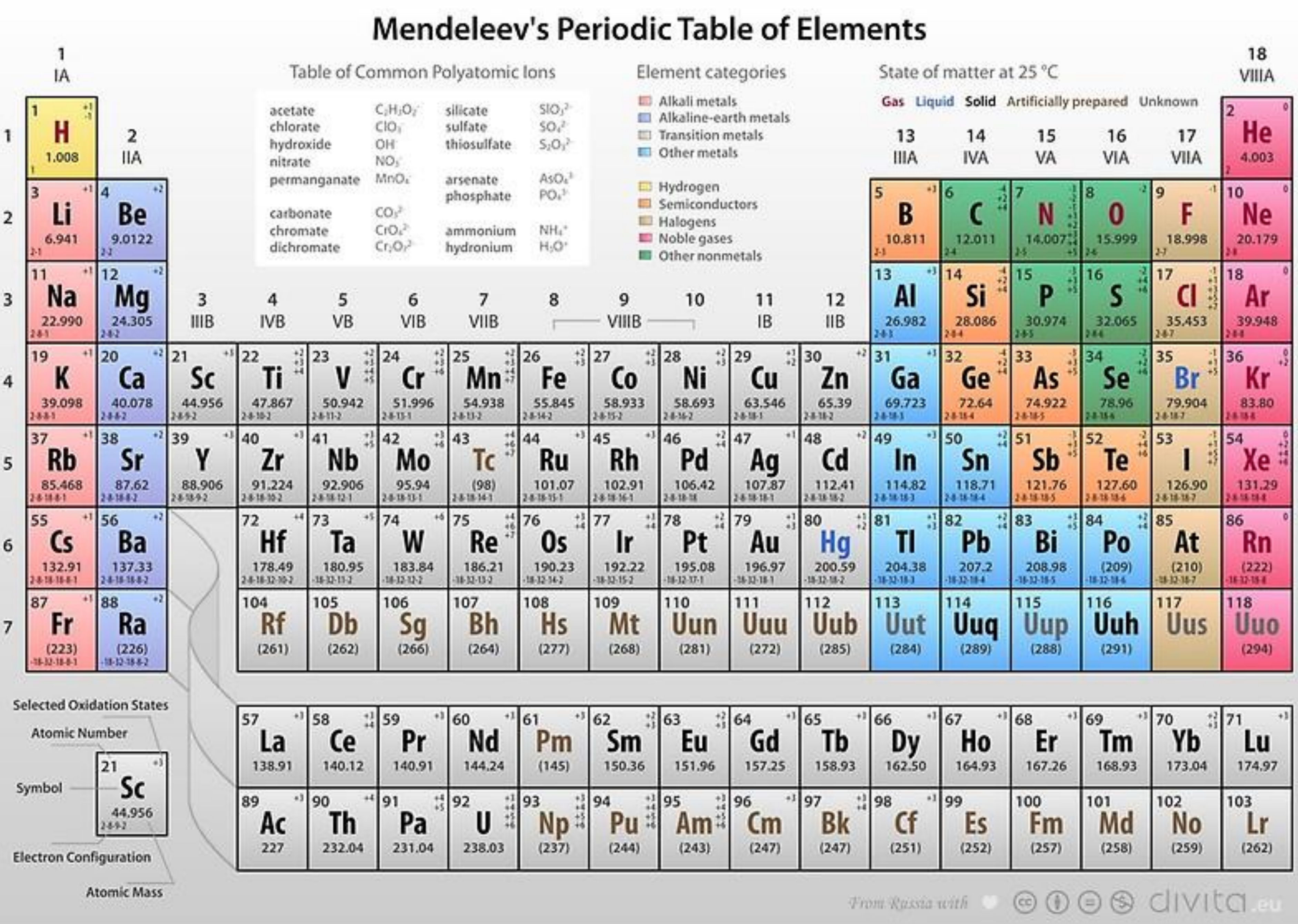
Isotopes

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

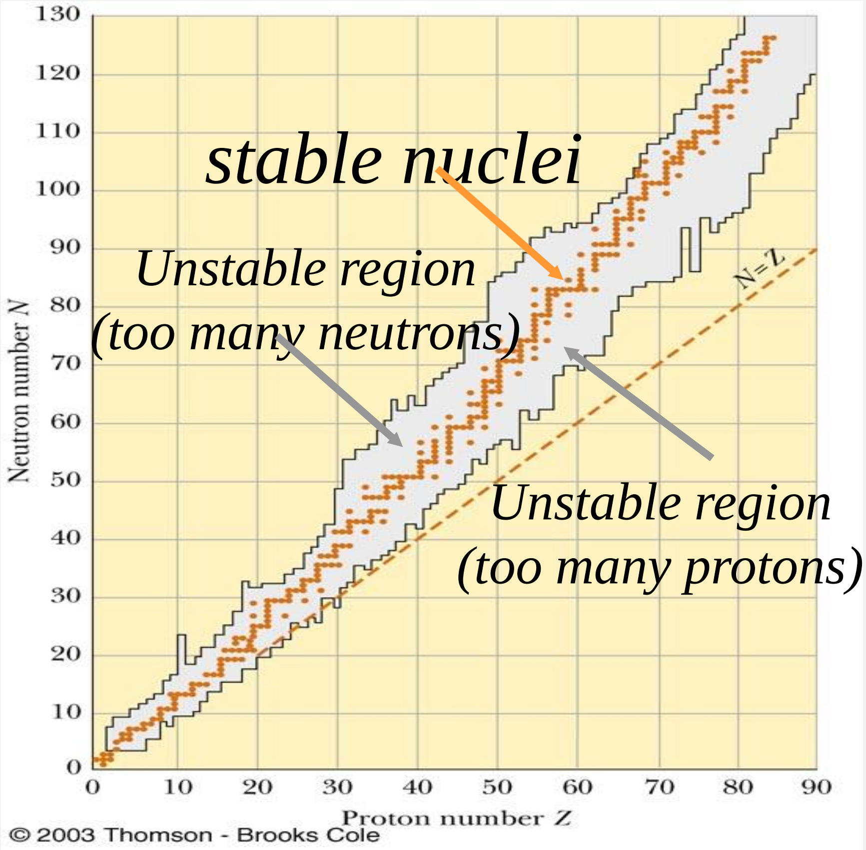


Nuclear stability chart

- 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 „unstable”?

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 an 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 (α) particles

  Beta (β) particles

  Gamma (γ) rays

- 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

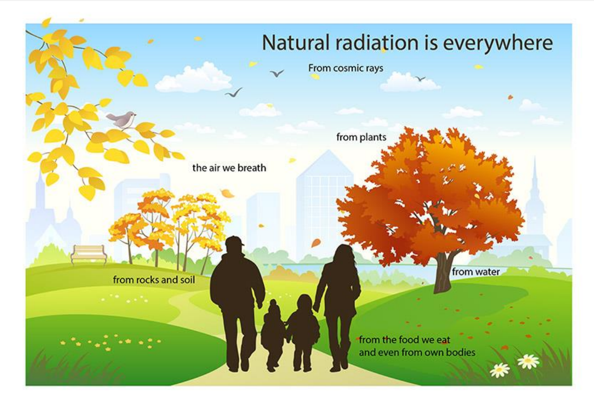
***Activity*:** $\Lambda = \left|\frac{\Delta N}{\Delta t}\right|$

N: number of nuclei to be decayed
t: time

Activity = number of nuclei decayed in a unit time

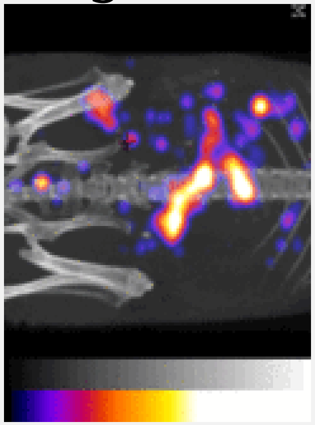
unit: becquerel (Bq)   1Bq = 1 decay/sec

background



kBq,

diagnostics

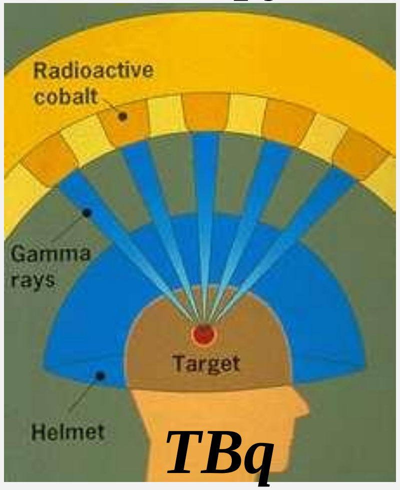


MBq,

laboratory practice

GBq,

therapy



TBq

Radioactive decay law

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

solution

λ **:** decay constant, characteristic for isotopes (1/s)

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

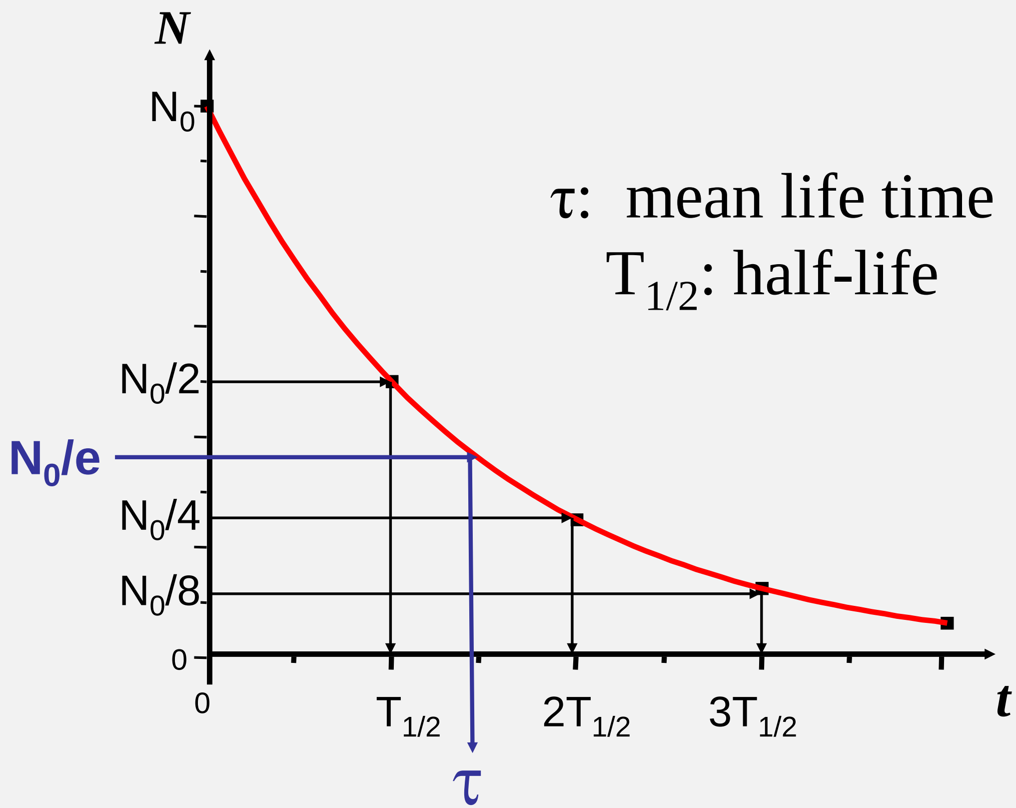
N_0: number of radioactive nuclei at t=0,
N: number of remaining radioactive nuclei at a later time t

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

$$\downarrow$$

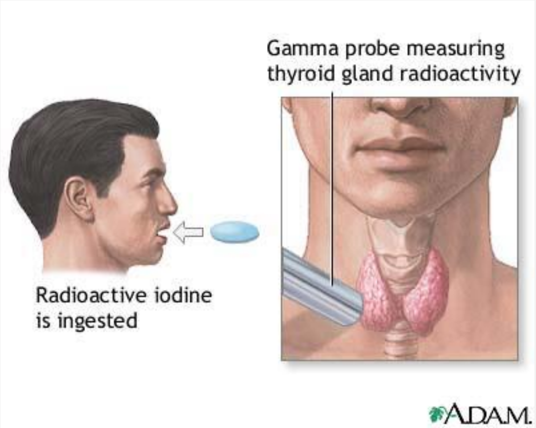
$$N_0 / e = N_0 e^{-\lambda \tau}$$

$$\downarrow$$

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

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

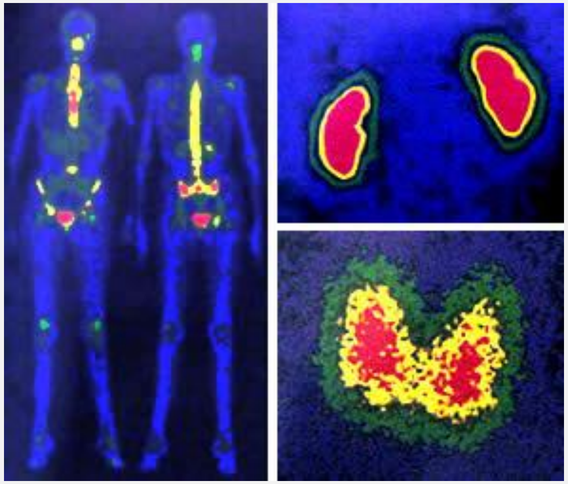


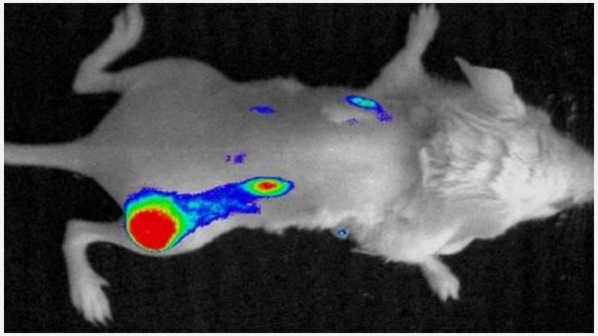
Iodine - 131 (^{131}I) ***- $T_{1/2}$ = 8 days***

Thyroid treatment

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

Isotope diagnostics

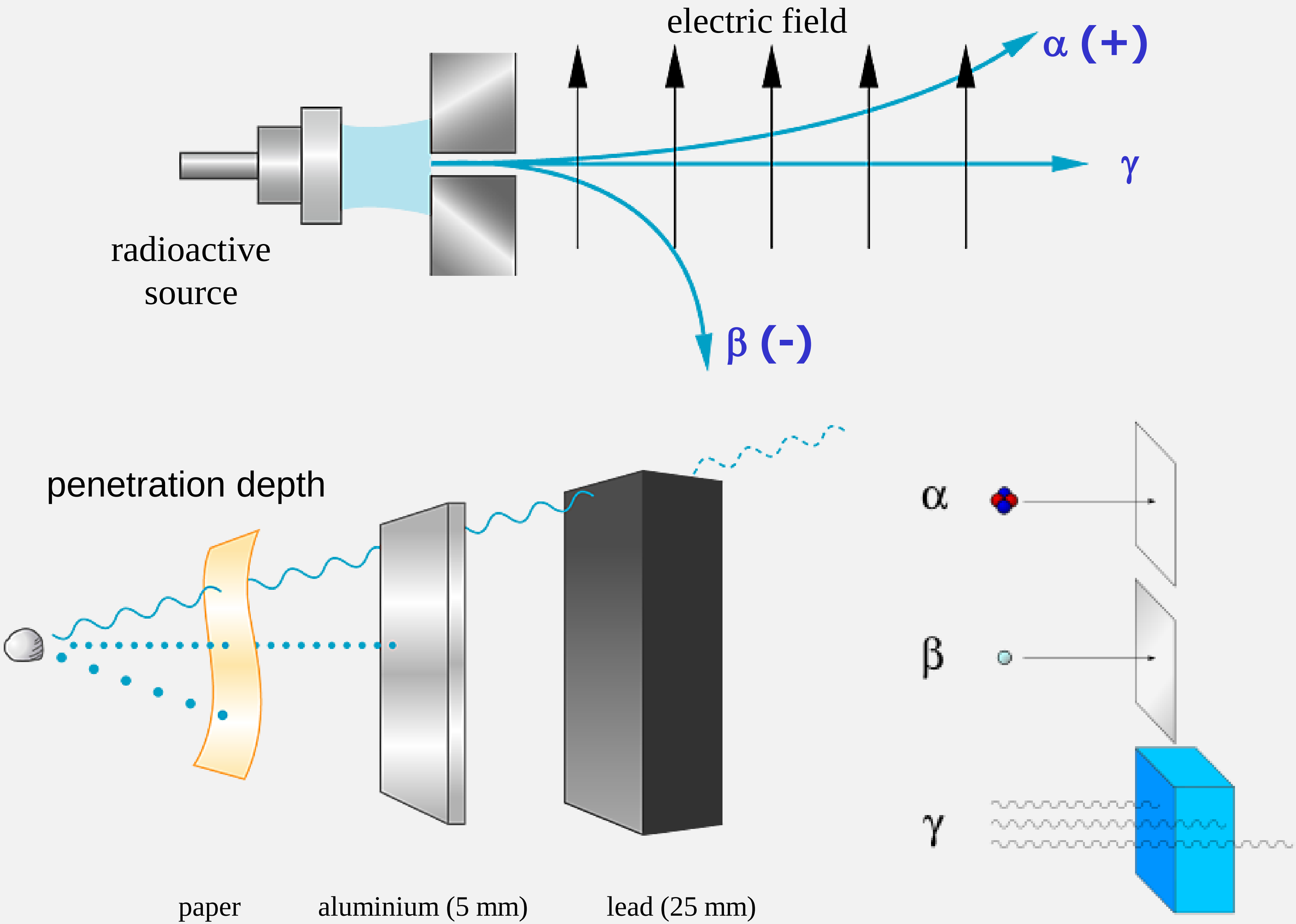




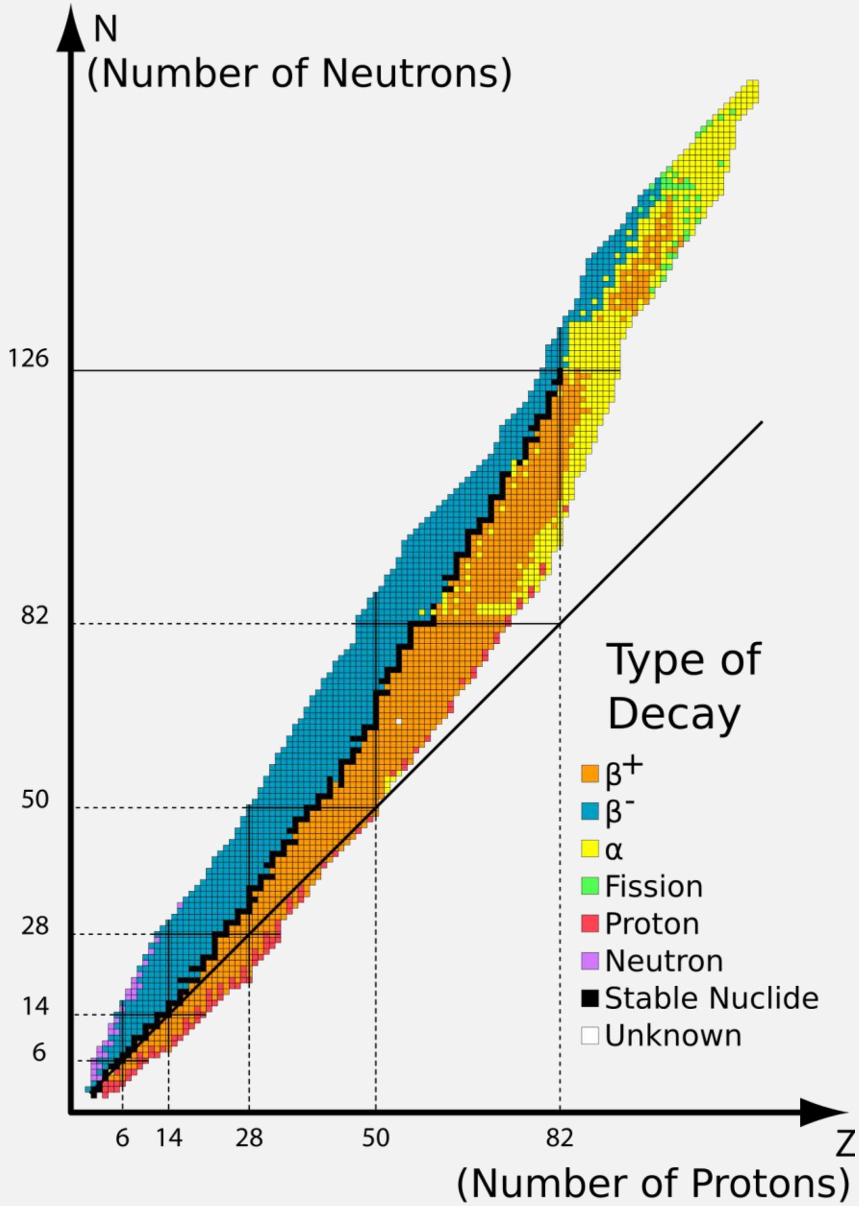
Gold-198 (^{198}Au) ***- $T_{1/2}$ = 2.7 days***

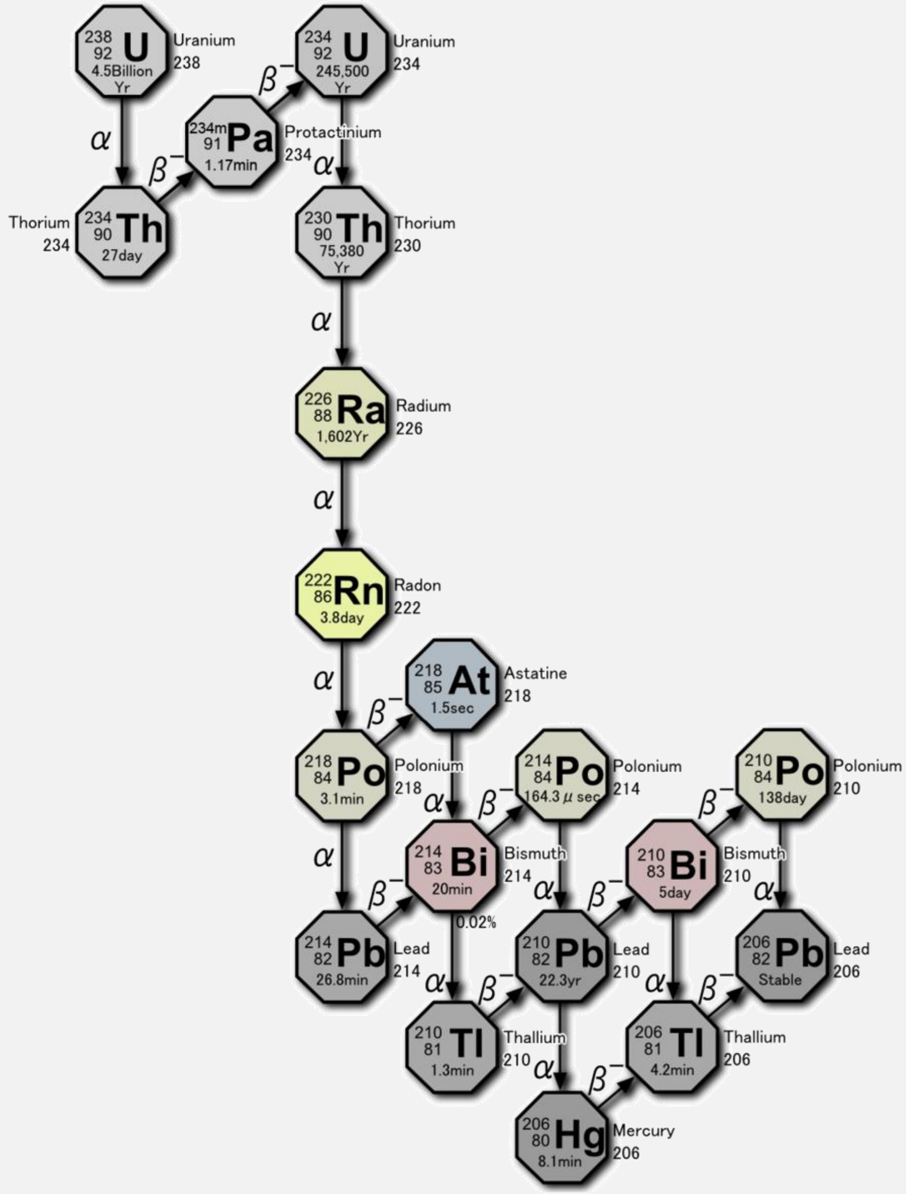
Tumor therapy

Types of radioactive decay

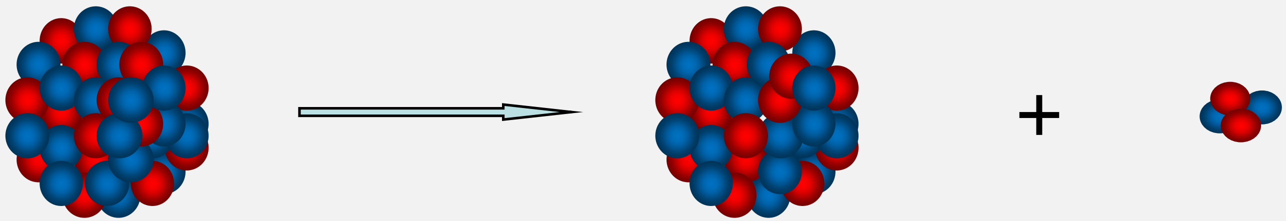


Types of radioactive decay





α decay



parent nucleus *daughter nucleus* *α particle*

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

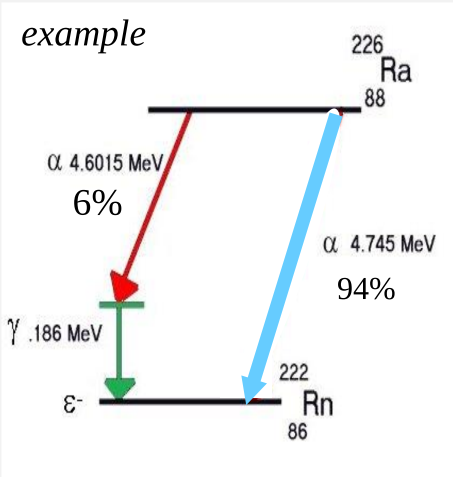
α particle is a nucleus of helium containing **two neutrons and two protons**

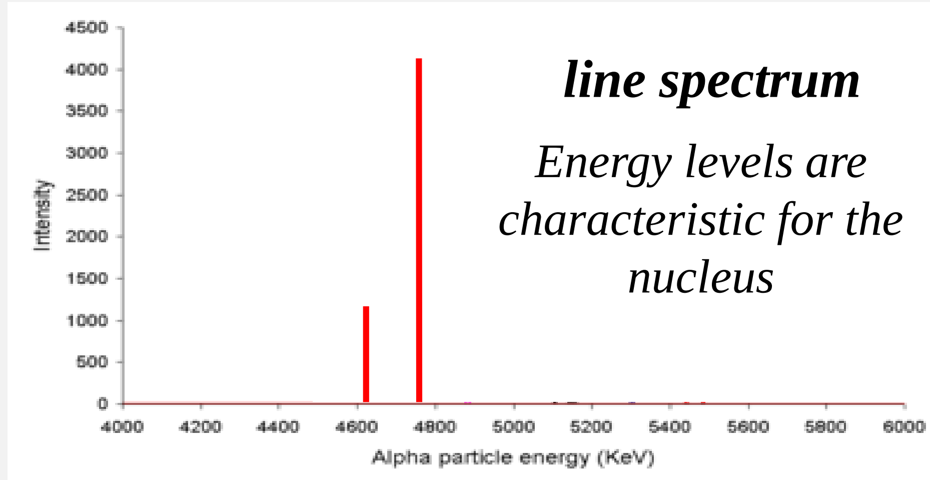
Heavy nuclei (A > 150) can disintegrate by emission of an α particle

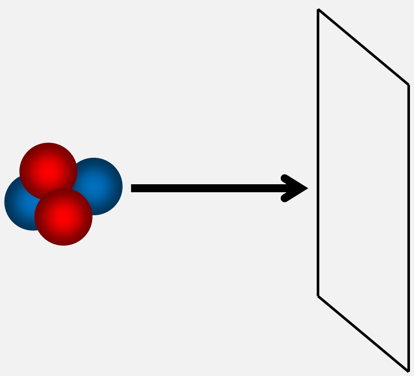
example:

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

Energy spectrum, penetration depth, application of α **radiation**





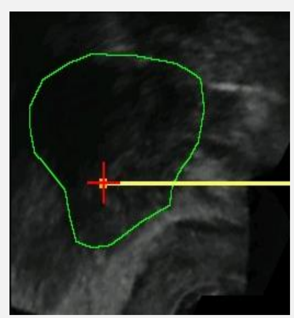


single sheet of paper

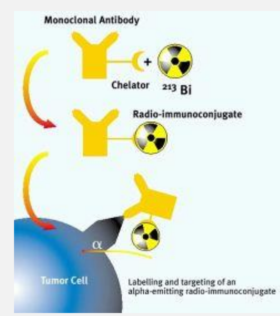
absorber	density	alpha range
air (STP)	1.2 mg/cm^3	**3.7 cm**
paper (20lb)	0.89 g/cm^3	**53 µm**
water (soft tissue)	1.0 g/cm^3	**45 µm**

Diagnostics: none!!!

Targeted alpha **therapy** of cancer



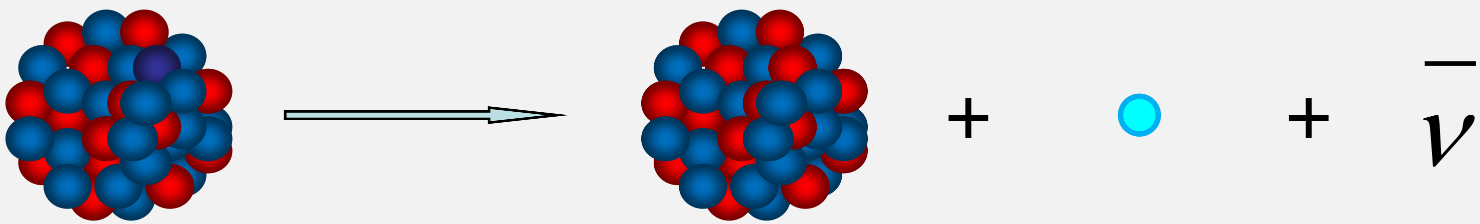
Seed implantation by needle



Monoclonal antibody

β decay

1. Neutron excess: β^- decay



parent nucleus *daughter nucleus* *electron* *anti-neutrino*

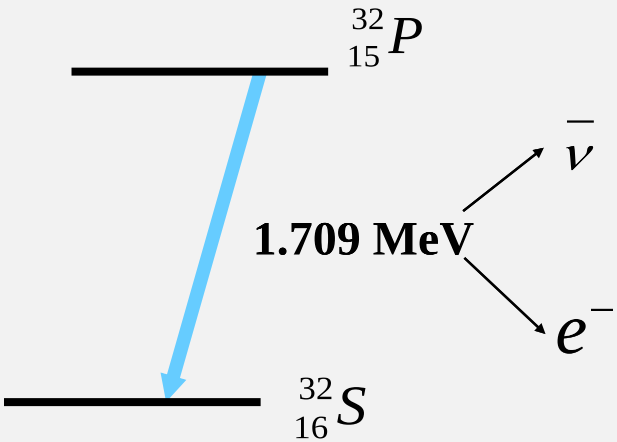
$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + e^{-} + \bar{\nu} $$

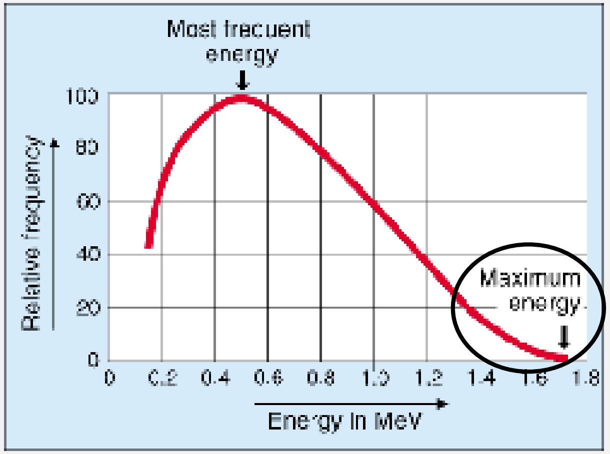
$$ {}^{1}_{0}n \longrightarrow {}^{1}_{1}p^{+} + e^{-} + \bar{\nu} $$

example:

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

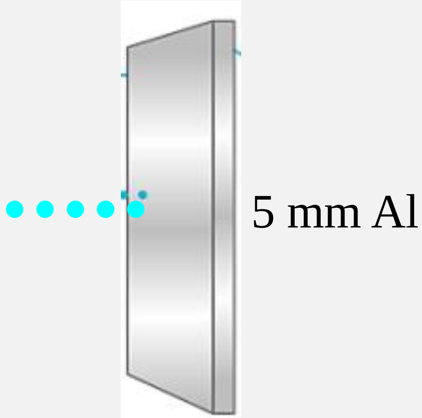
Energy spectrum, penetration depth, application of **β- radiation**





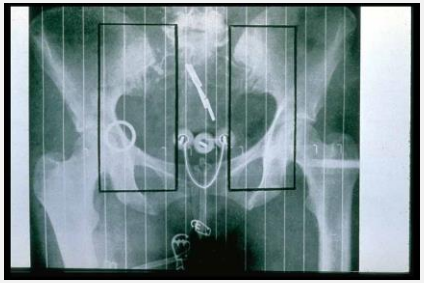
continuous spectrum
with a maximum kinetic energy for the β particle

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



Diagnostics: **none!!!**

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

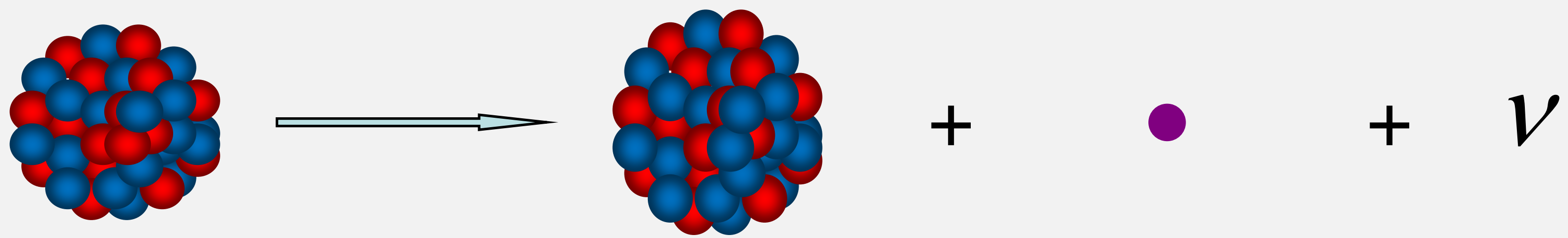


Brachytherapy: implants into the tumours

Endovascular irradiation

β decay

2. Proton excess: β^{+} decay



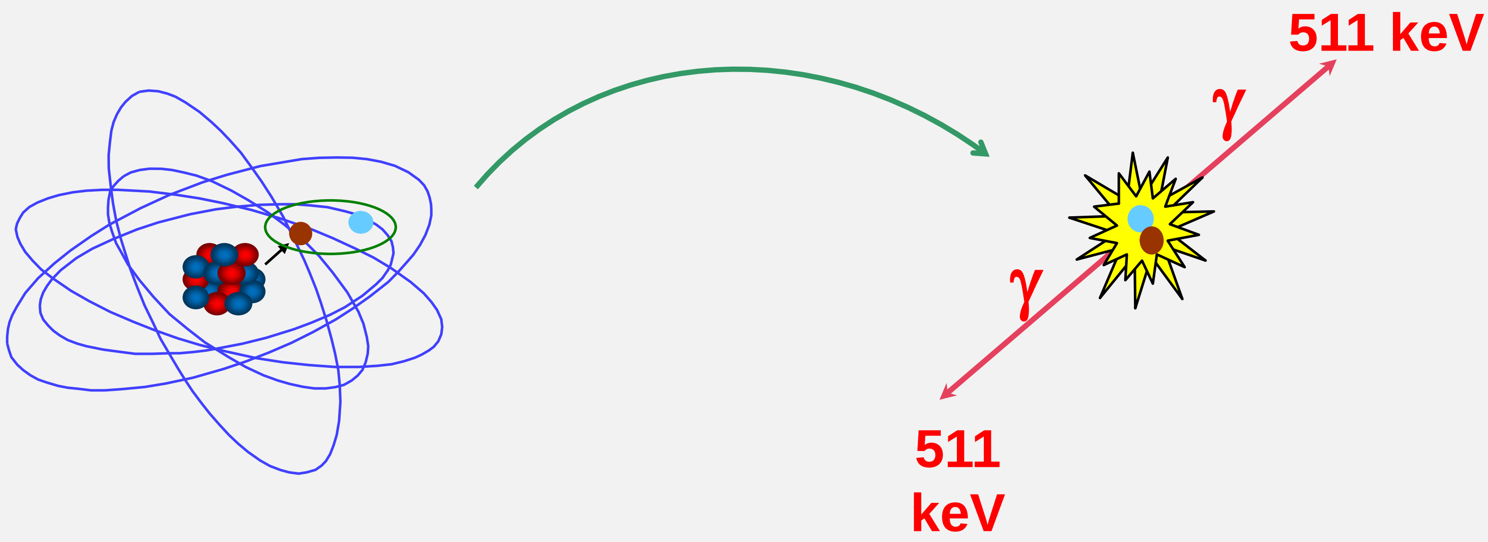
$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y + e^{+} + \nu $$

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

example:

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

Annihilation - particle-antiparticle pairs annihilate each other



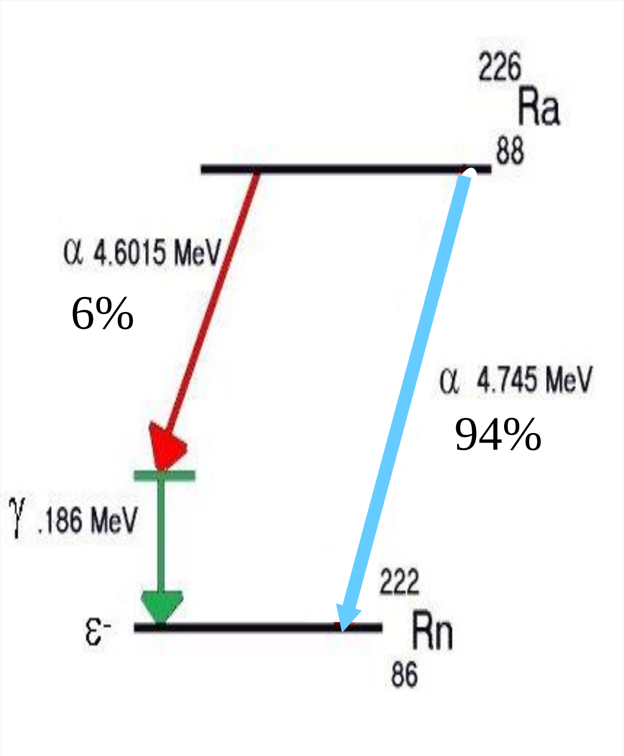
1. Conservation of momentum: two photons with opposite direction are produced

2. Energy balance:

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

mass–energy equivalence

γ decay – Isomeric transition



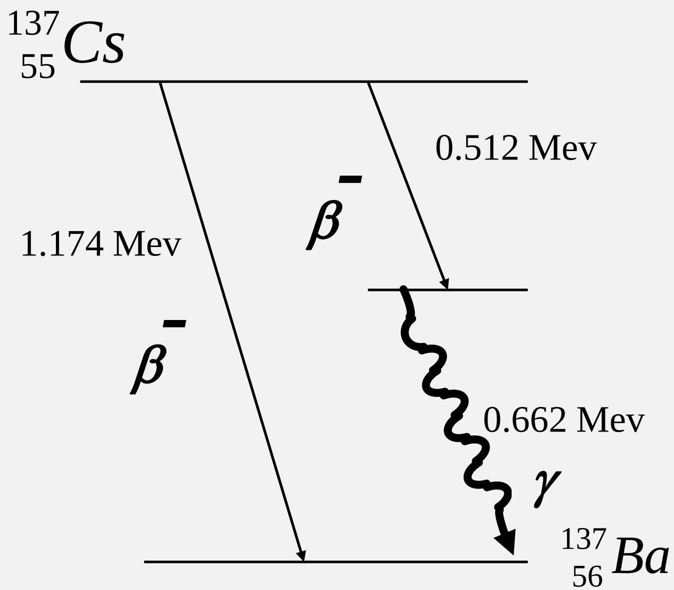
Sometimes the newly formed isotopes (after α or β decay) appear in the excited state.

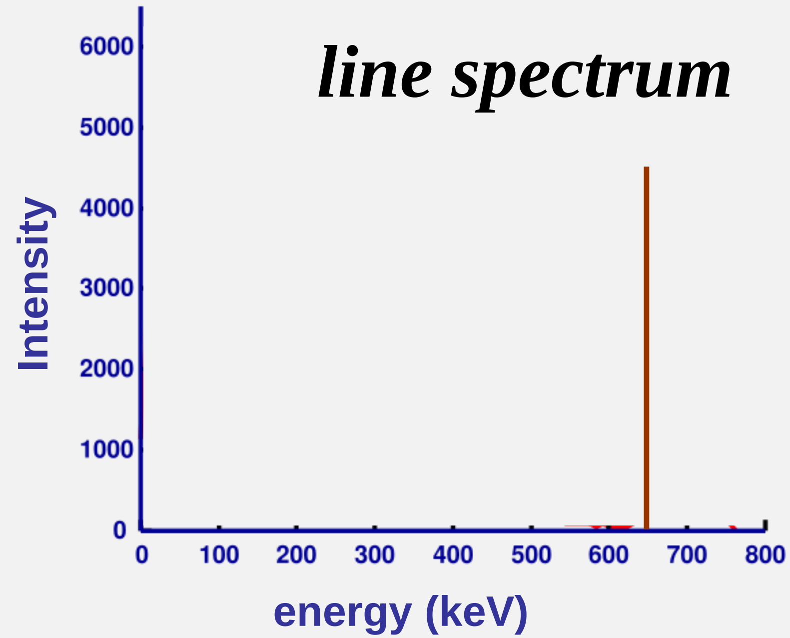
Excited nuclides release the excess of energy by emission of gamma rays.

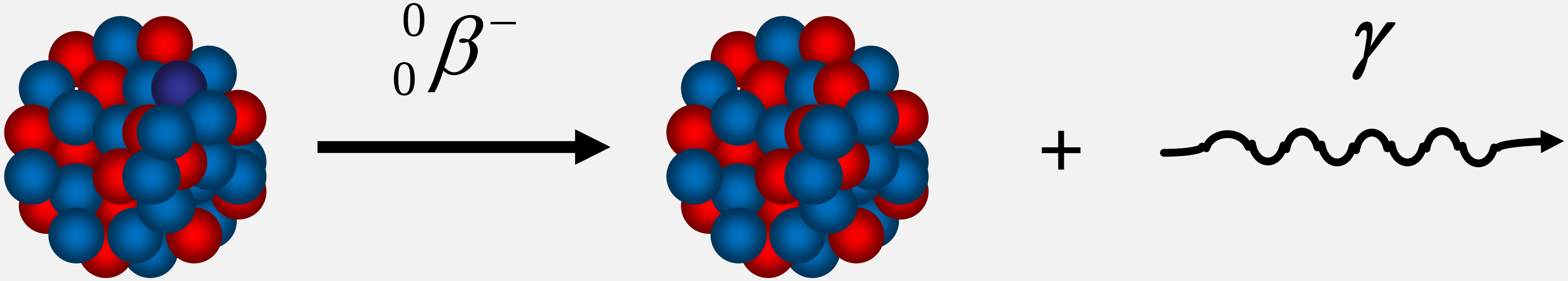
half-life ranging from hours up to more than 600 years

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

Energy spectrum of γ radiation



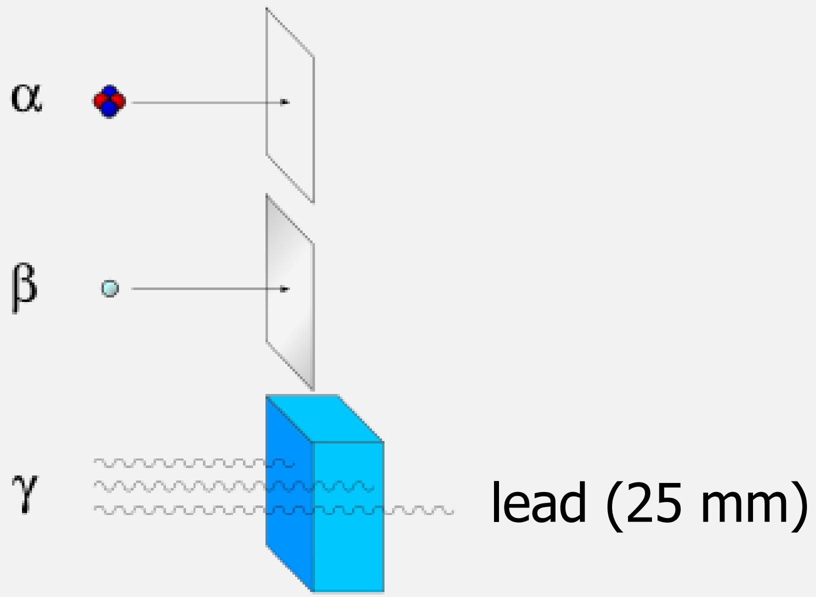




parent nucleus *daughter nucleus* *gamma Ray*

Energy is characteristic for the nucleus

Penetration depth of γ radiation

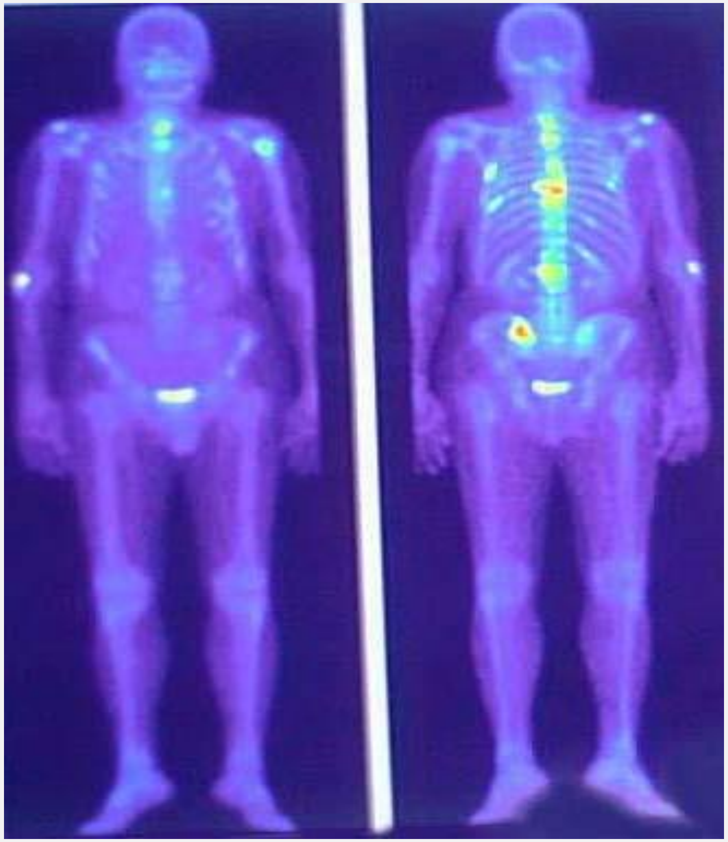


Penetration depth is higher than that of α or β particles, but it is highly energy dependent.

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

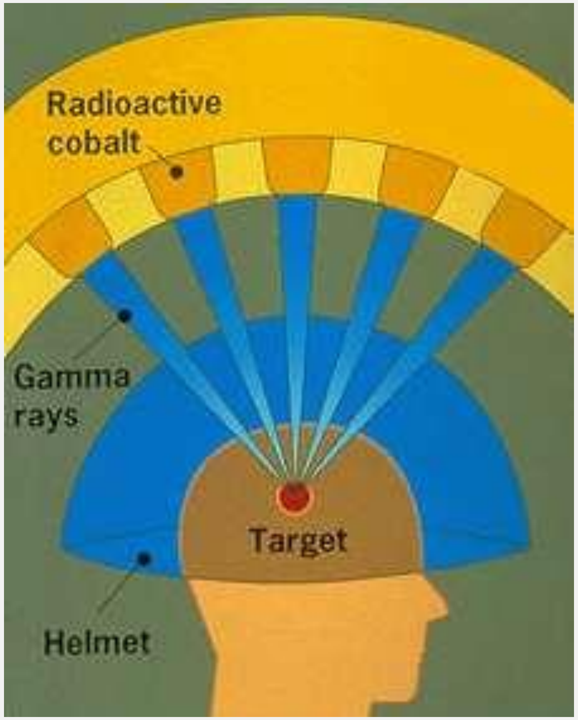
Medical application of γ rays

Diagnostics:
ideal for isotope diagnostics



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

Therapy: γ-knife



TBq

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