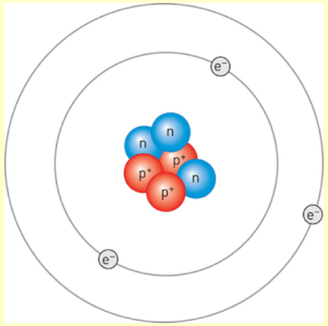
Nuclear radiation

types, characteristics of them,

principles of tracing with radioisotopes

30-11-2020

Liliom, Károly



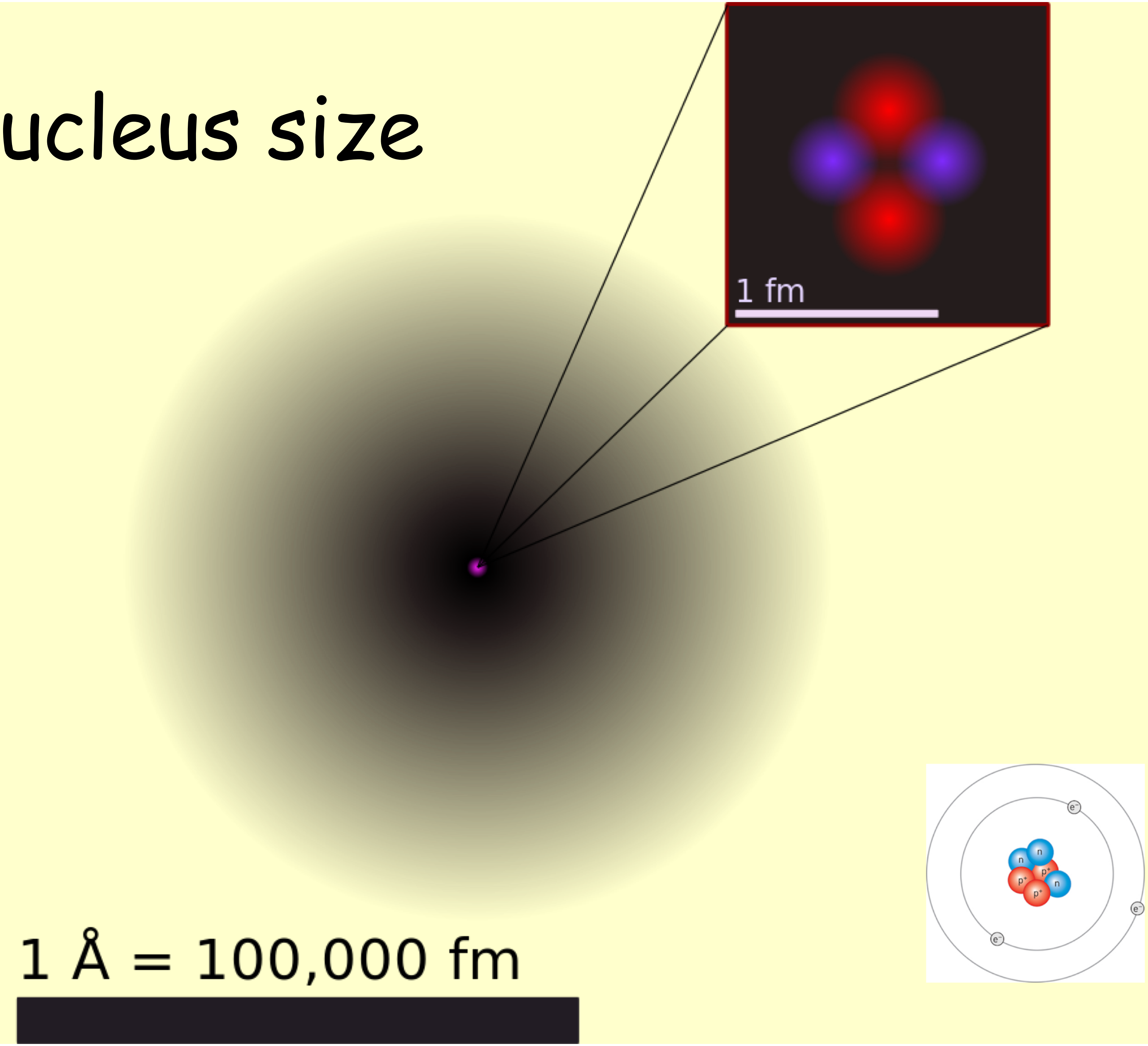
Constituents of atoms

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

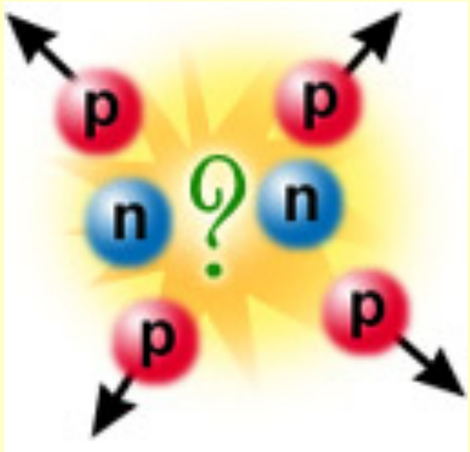
Nucleus size



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

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

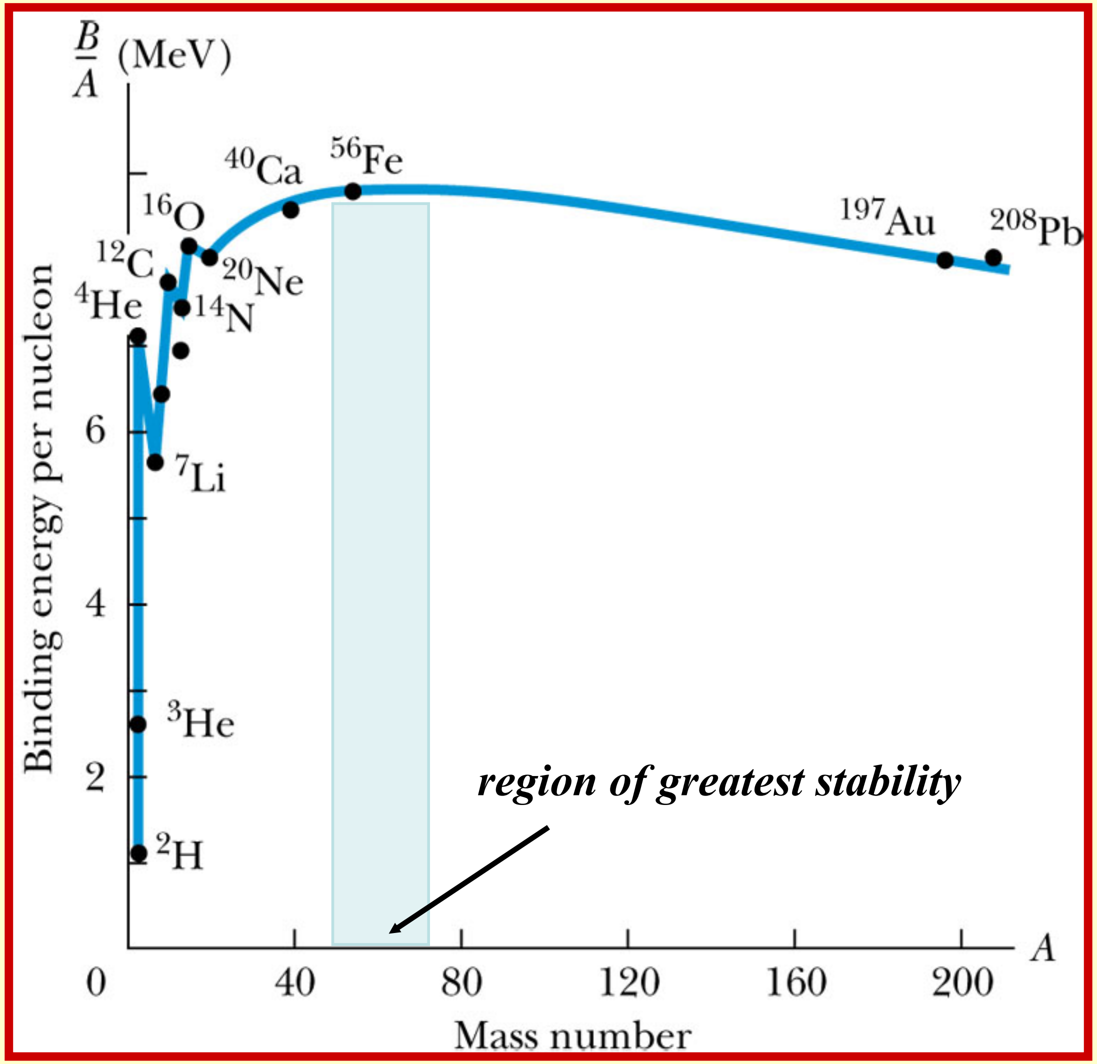
The mass defect (or mass deficit) problem: the mass of a nucleus is less than the mass of its constituent nucleons. The difference can be explained by Einstein's law of mass-energy equivalence:

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

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

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

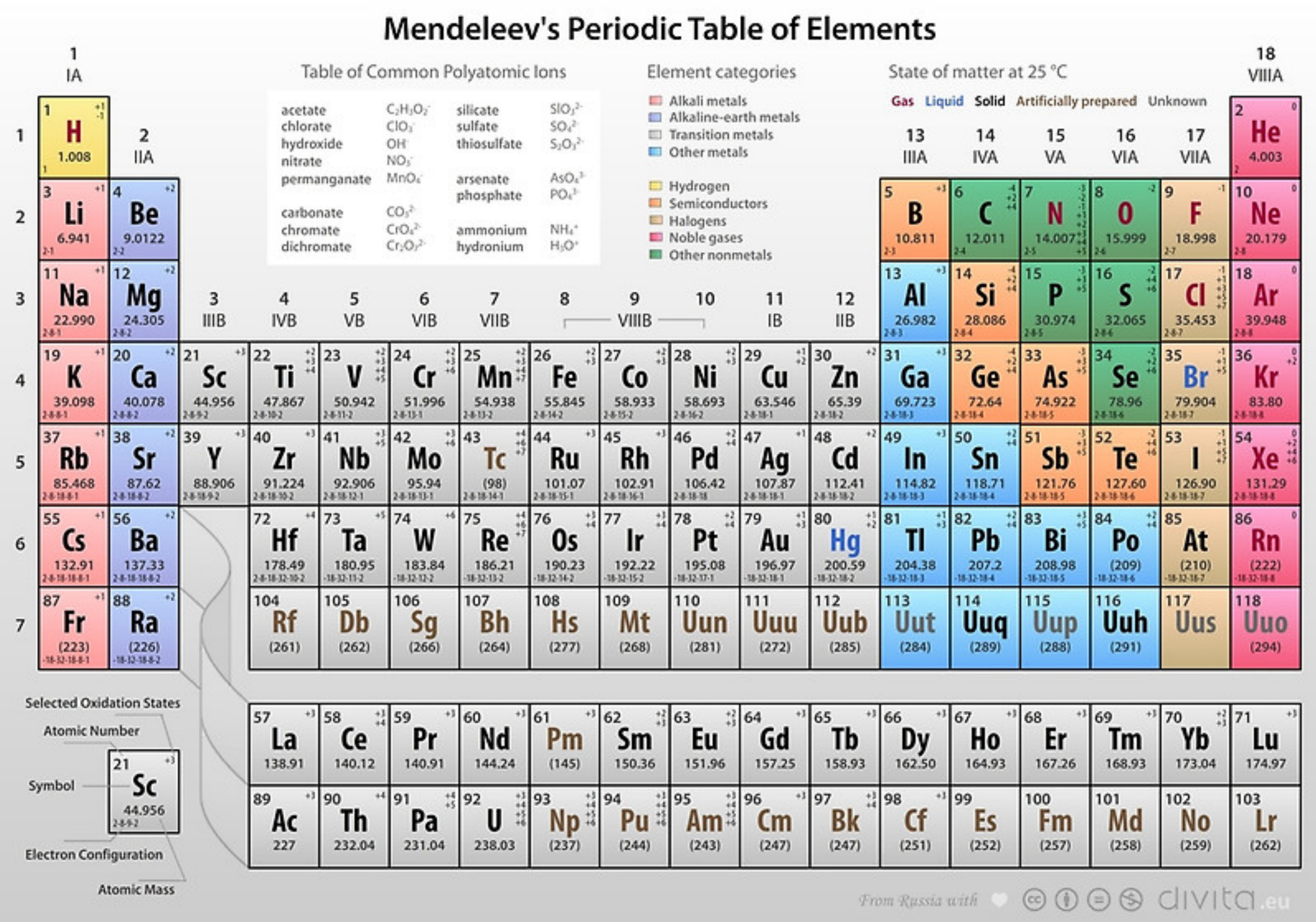
Isotopes

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



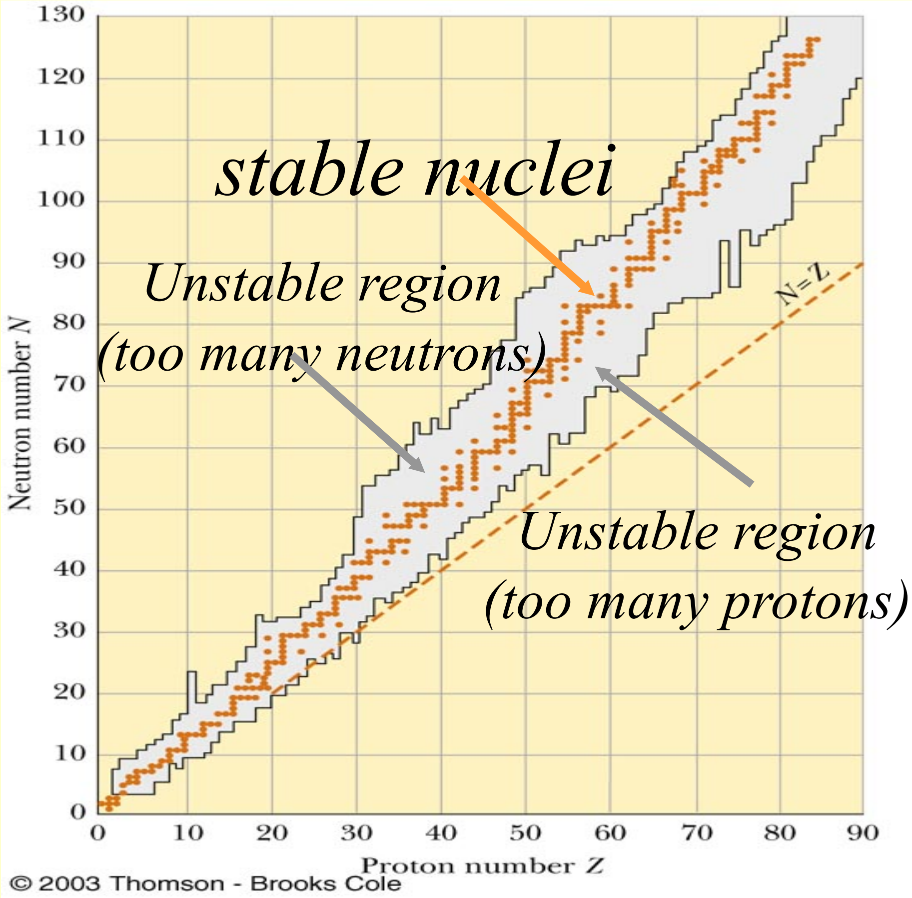
Nuclear stability chart

- 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 (α) particles

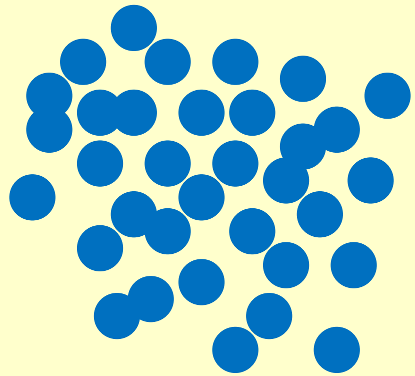
Beta (β) particles

Gamma (γ) 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

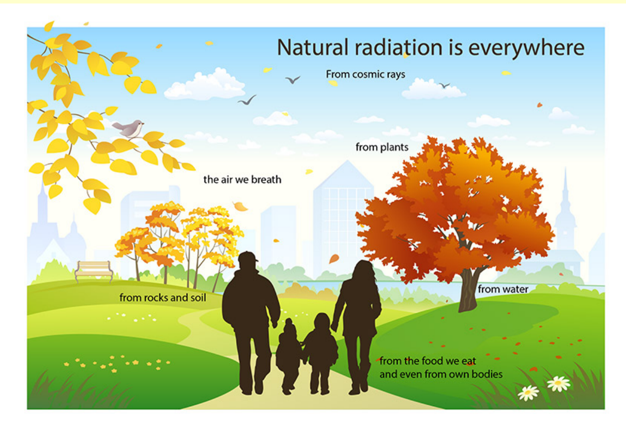
***Activity*:** $\Lambda = \left|\frac{\Delta N}{\Delta t}\right|$

N: number of nuclei to be decayed
t: time

Activity = number of nuclei decayed in a unit time

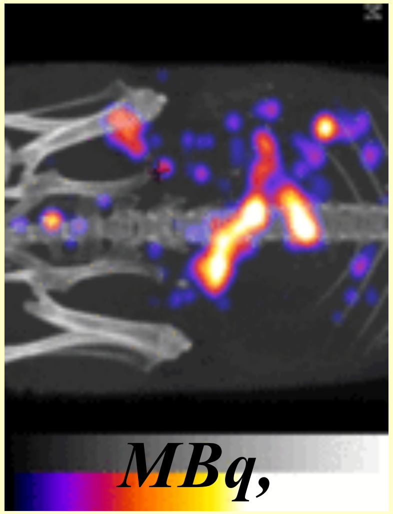
unit: bequerel (Bq)   1Bq = 1 decay/sec

background



kBq,

diagnostics

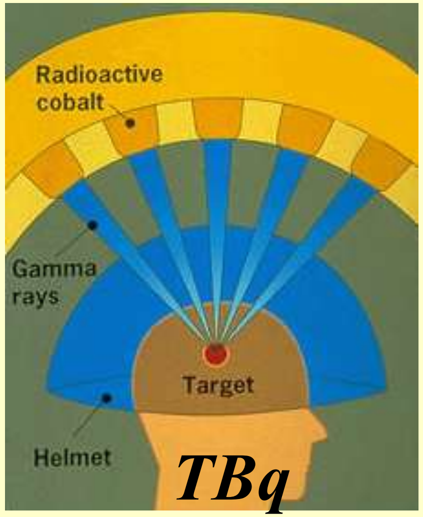


MBq,

laboratory practice

GBq,

therapy



TBq

Radioactive decay law

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

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,

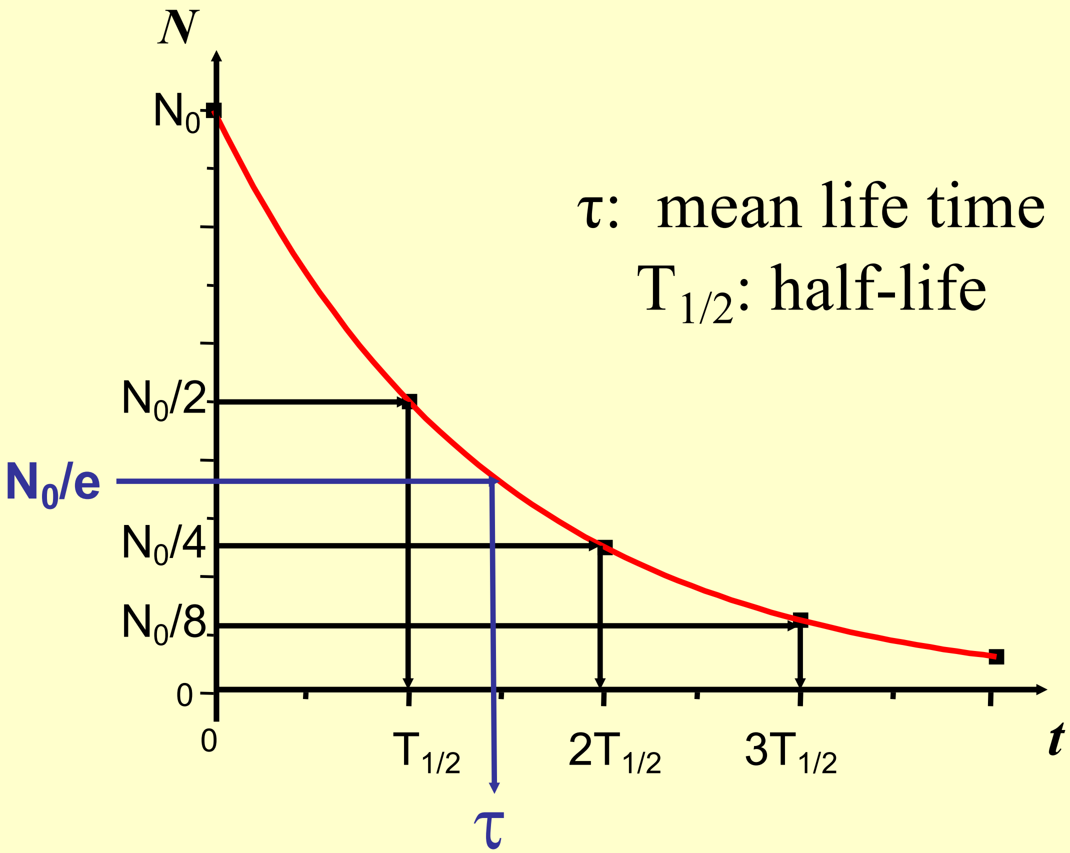
N: number of remaining radioactive nuclei at a later time t

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

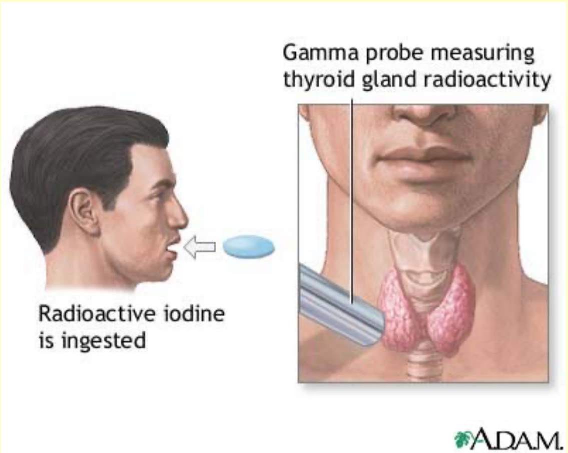
If t = τ

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

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

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

Half-lives in Medical Practice

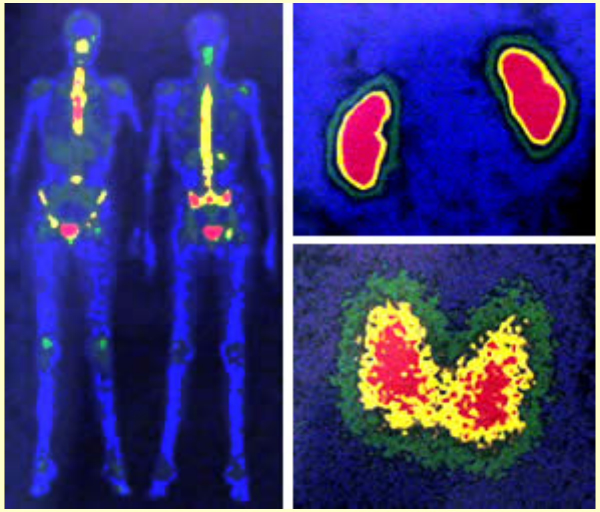


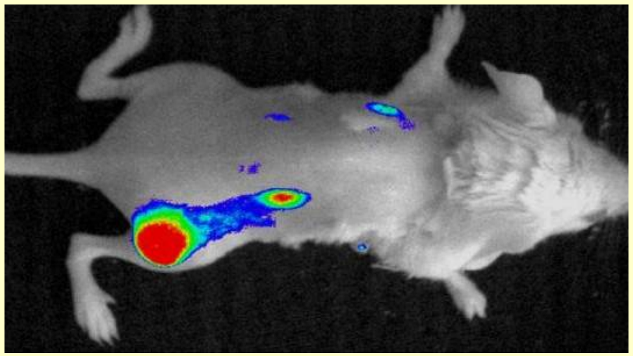
Iodine - 131 (^{131}I) ***-*** $T_{1/2}$ ***= 8 days***

Thyroid treatment

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

Isotope diagnostics

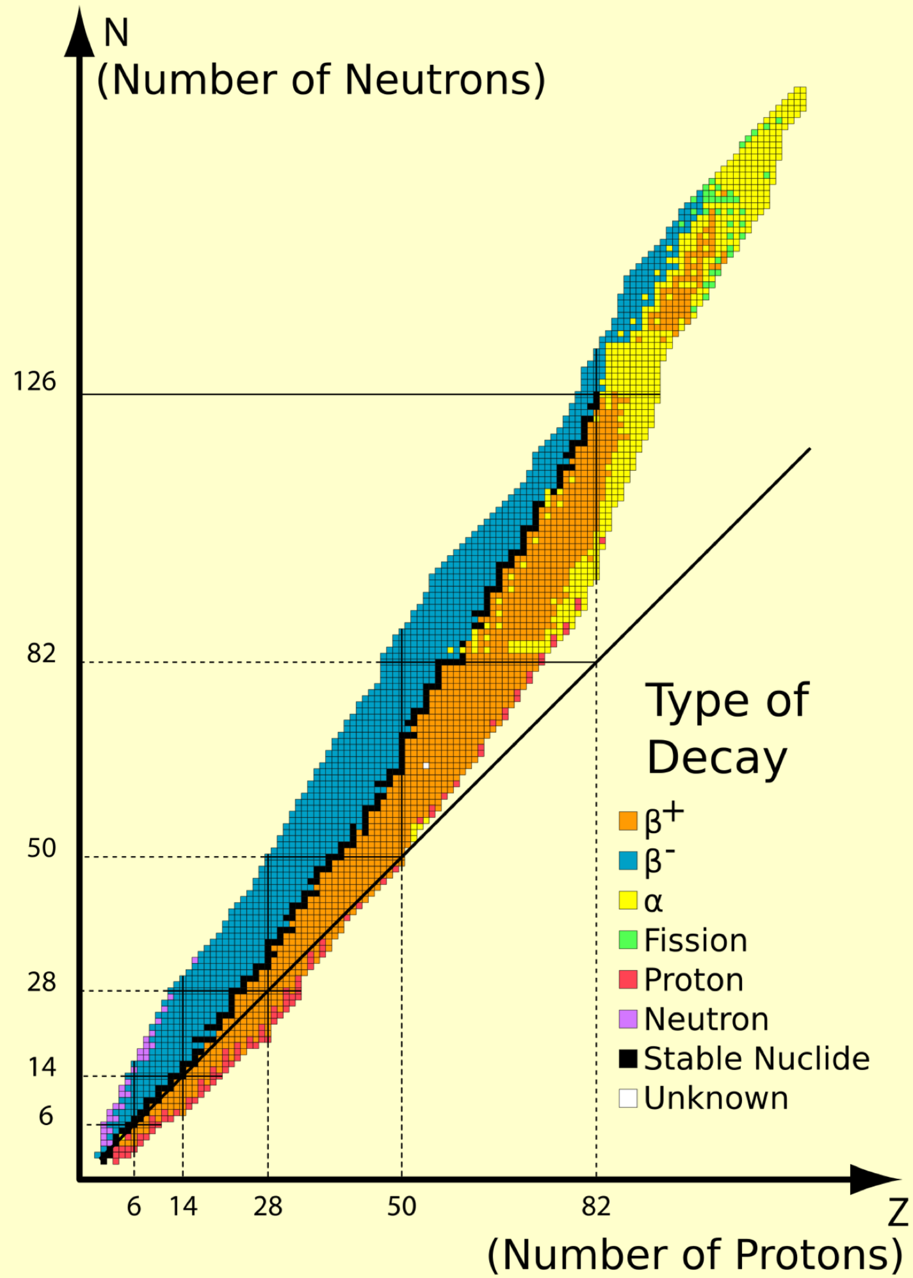


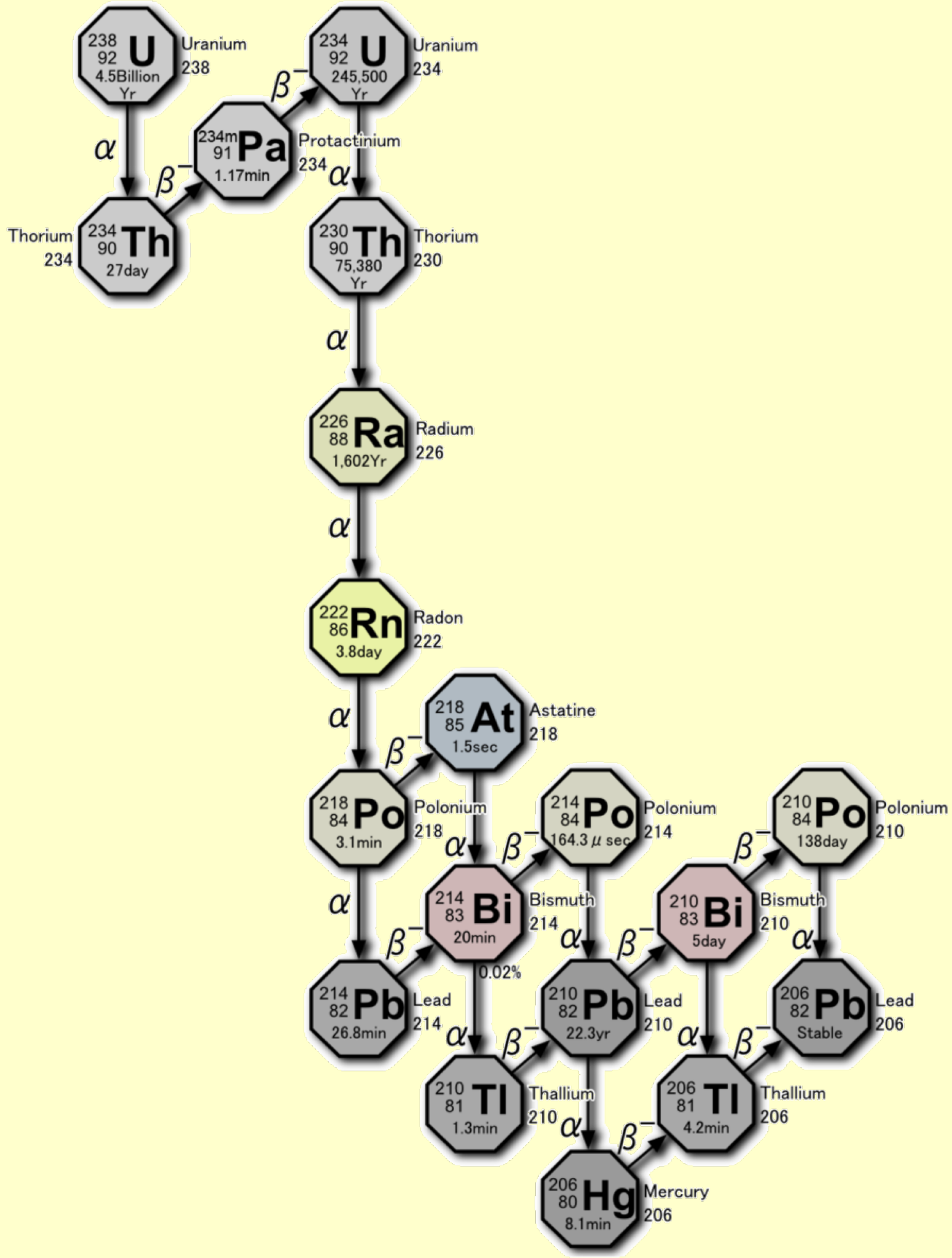


Gold-198 (^{198}Au) ***-*** $T_{1/2}$ ***= 2.7 days***

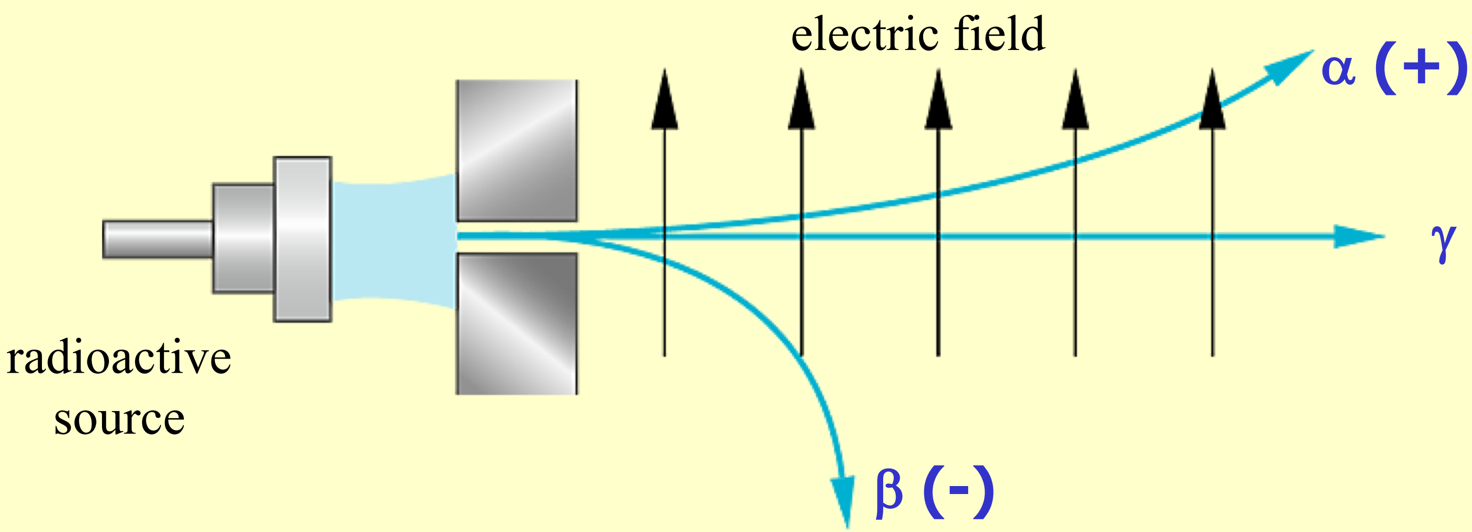
Tumor therapy

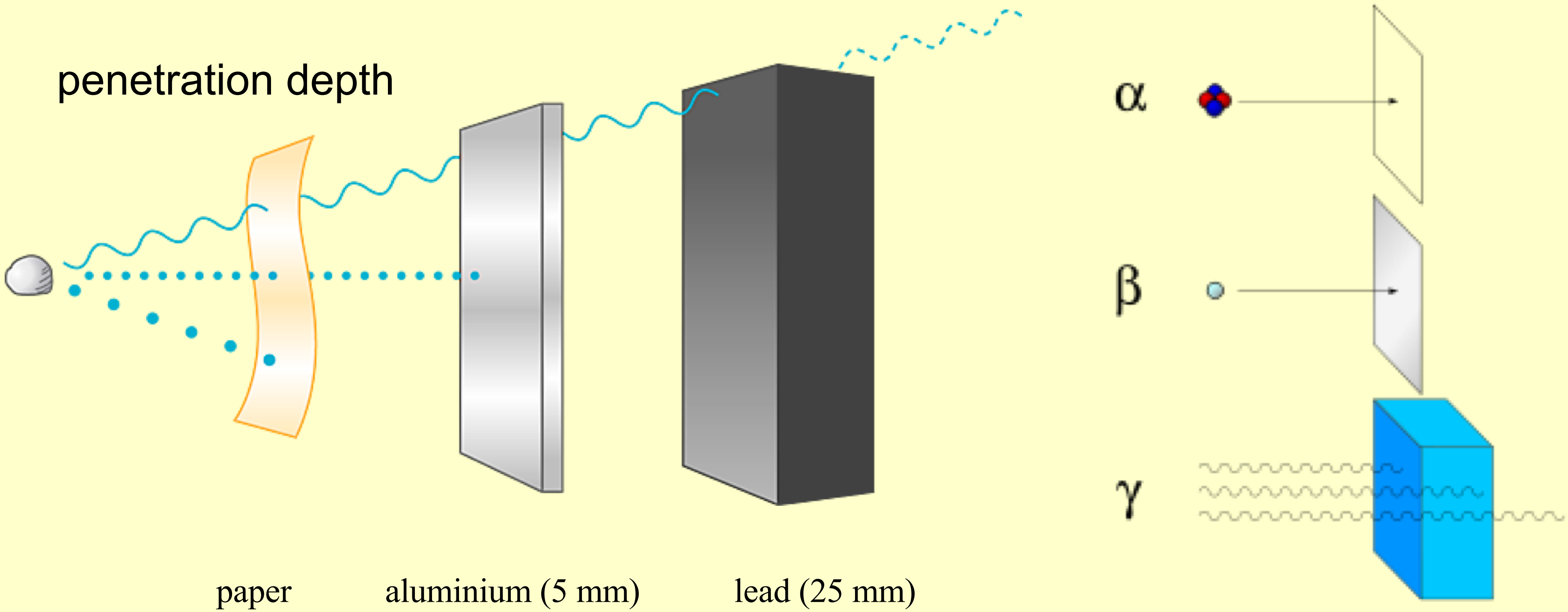
Types of radioactive decay



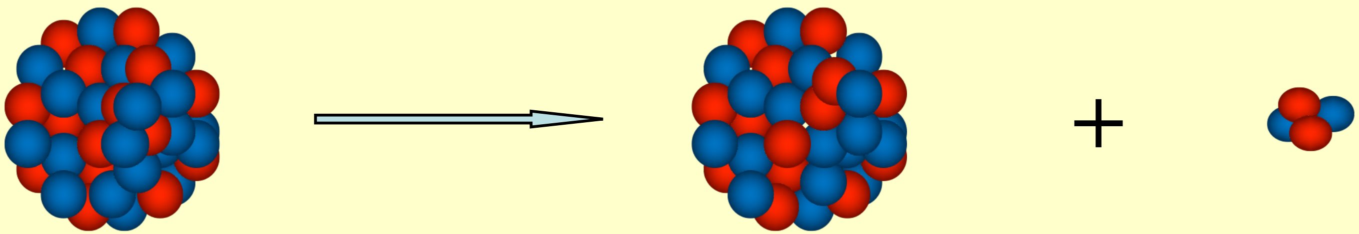


Types of radioactive decay





α decay



parent nucleus *daughter nucleus* *α particle*

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

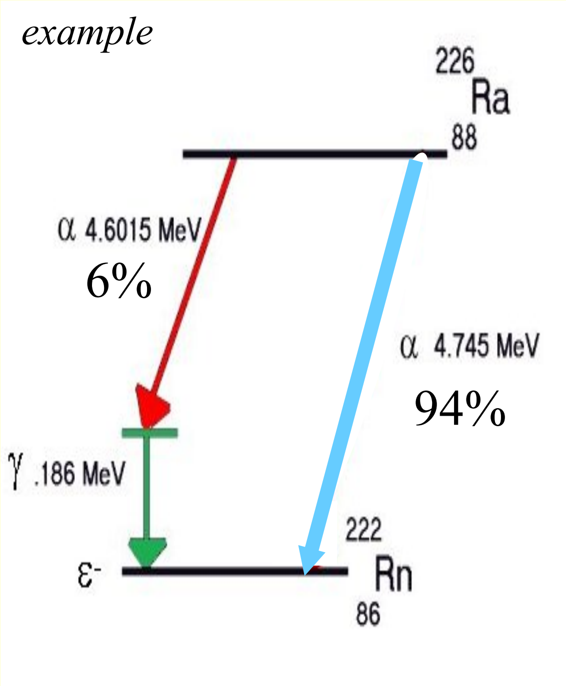
α particle is a nucleus of helium containing two neutrons and two protons

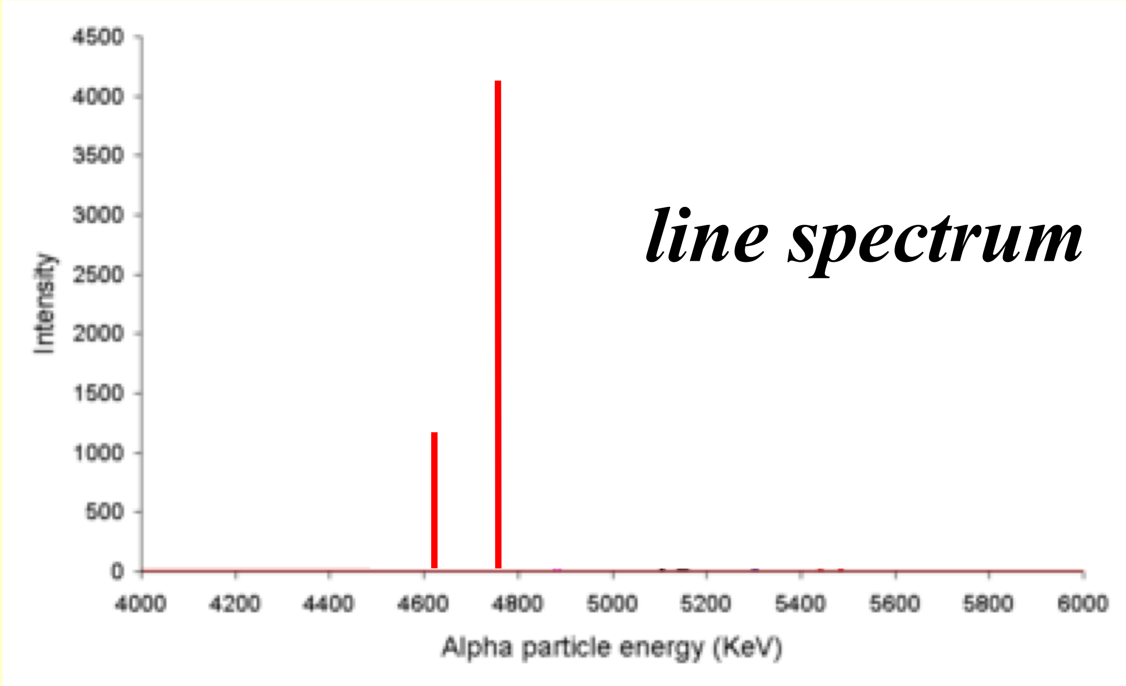
Heavy nuclei (A > 150) can disintegrate by emission of an α particle

example:

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

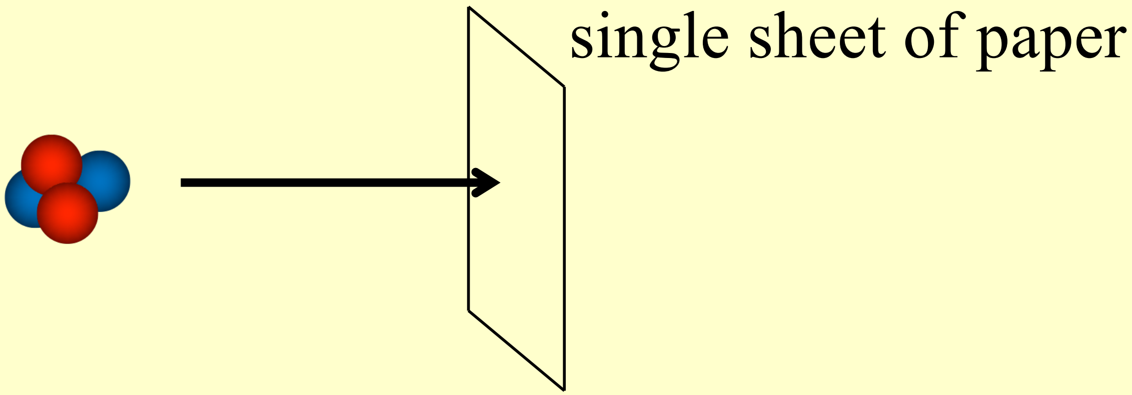
Energy spectrum of α radiation





Energy is characteristic for the nucleus

Penetration depth of α particles

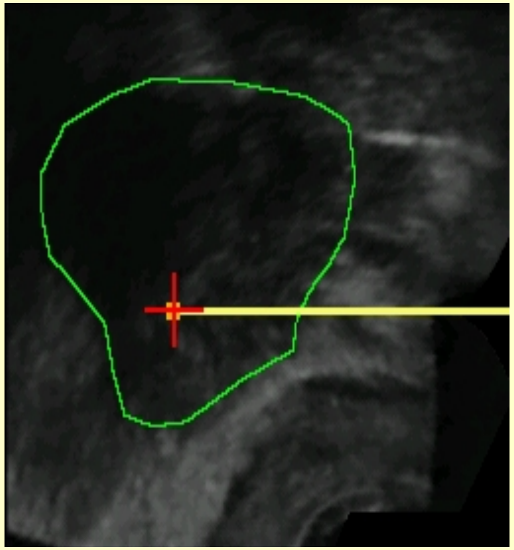


absorber	**density**	**alpha range**
air (STP)	1.2 mg/cm^3	3.7 cm
paper (20lb)	0.89 g/cm^3	53 μm
water (soft tissue)	1.0 g/cm^3	45 μm

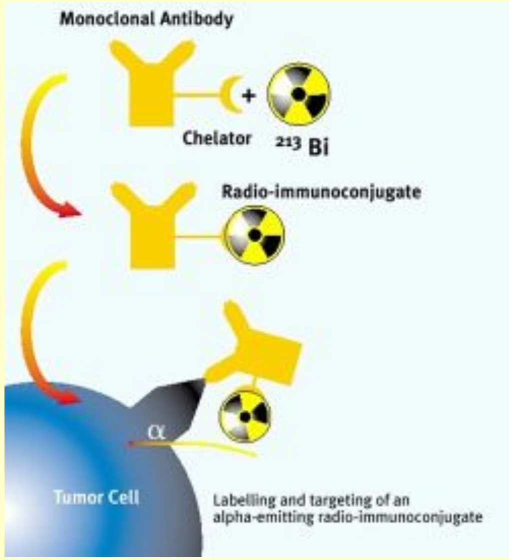
Medical application of α radiation

Diagnostics: none

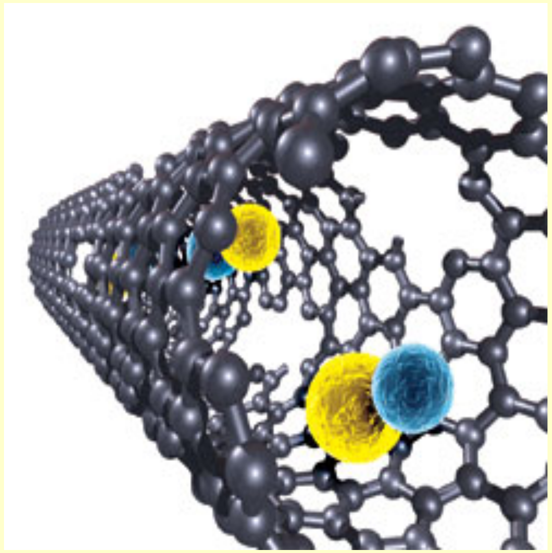
Targeted alpha **therapy** of cancer



Seed implantation by needle



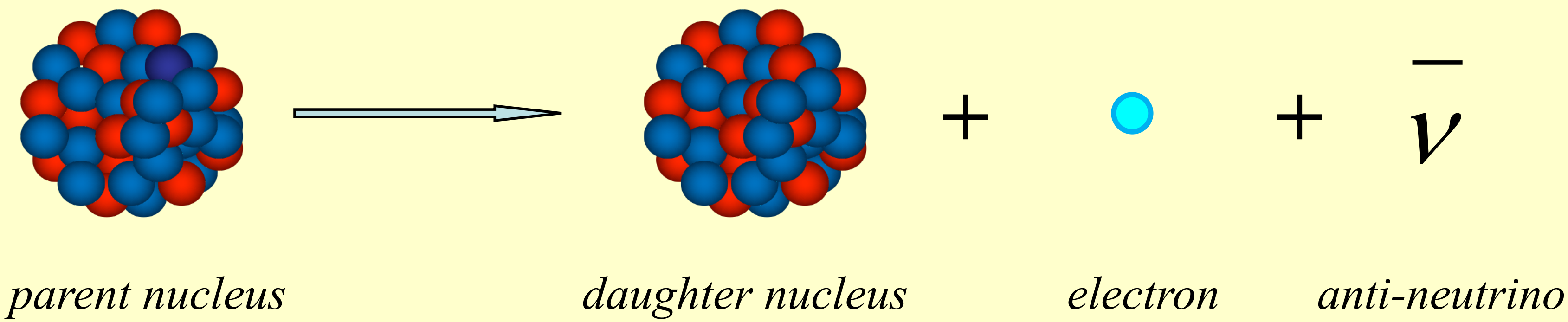
Monoclonal antibody



Carbon nano-tube

β decay

1. Neutron excess: β⁻ decay



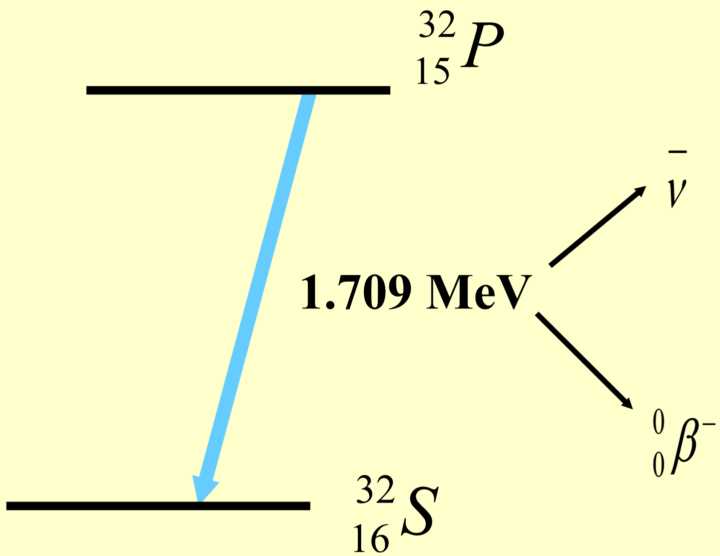
$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + e^{-} + \bar{\nu} $$

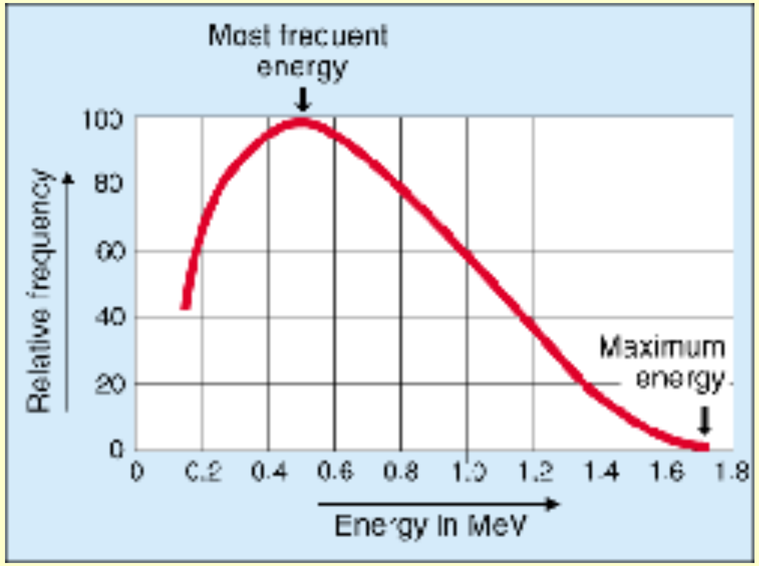
$$ {}^{1}_{0}n \longrightarrow {}^{1}_{1}p^{+} + {}^{0}_{0}\beta^{-} + \bar{\nu} $$

example:

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

Energy spectrum of β radiation



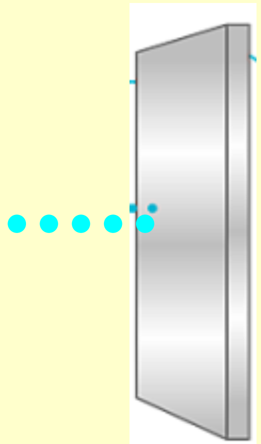


Energy distribution of the β- particles emitted during the β- decay of ^{32}P.

continuous spectrum

with a maximum kinetic energy for the β particle

Penetration depth of β^- particles



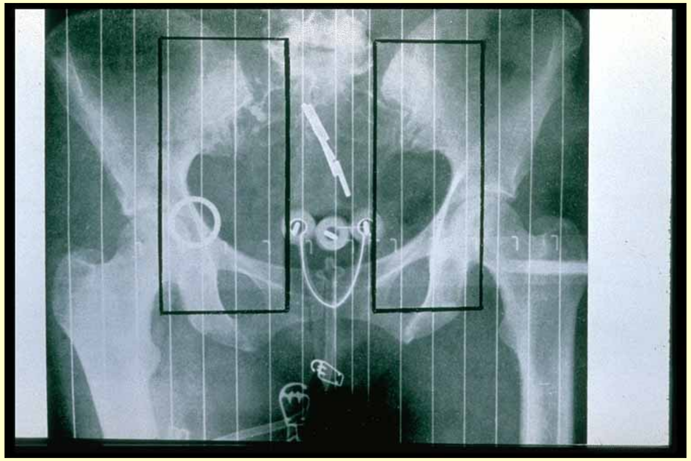
5 mm aluminum

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 β^- radiation

Diagnostics: none

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

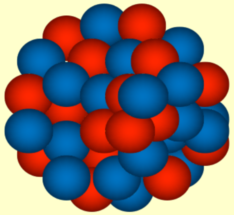
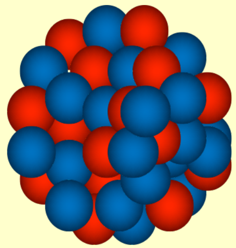


Brachytherapy: implants into the tumours

Endovascular irradiation

β decay

2. Proton excess: β^+ decay

 $\longrightarrow$  +  + ν

parent nucleus *daughter nucleus* *positron* *neutrino*

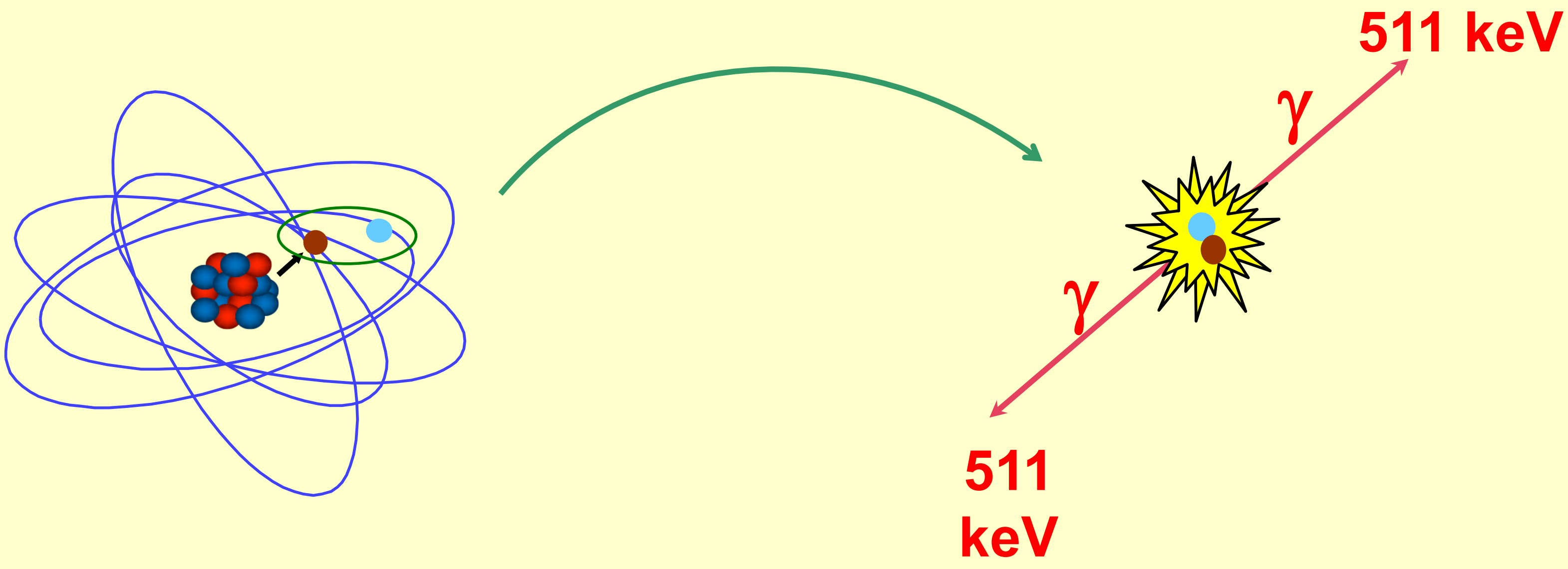
$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y + e^{+} + \nu $$

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

example:

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

Annihilation - particle-antiparticle pairs annihilate each other



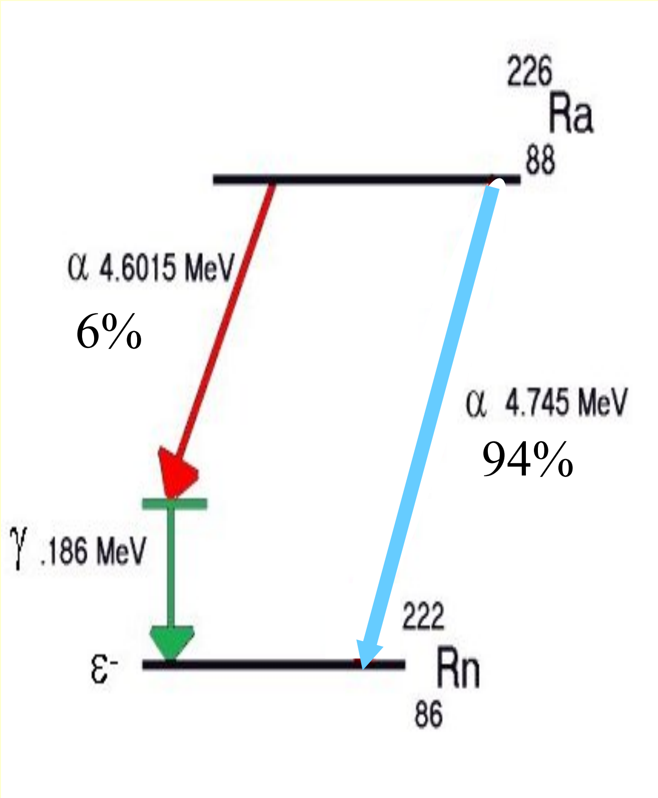
1. Conservation of momentum: two photons with opposite direction are produced

2. Energy balance:

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

mass–energy equivalence

γ decay – Isomeric transition



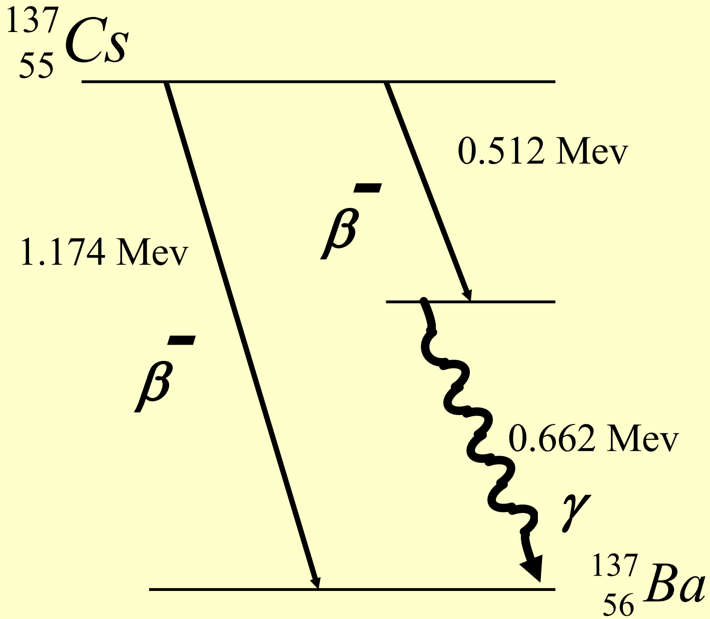
Sometimes the newly formed isotopes (after α or β decay) appear in the excited state.

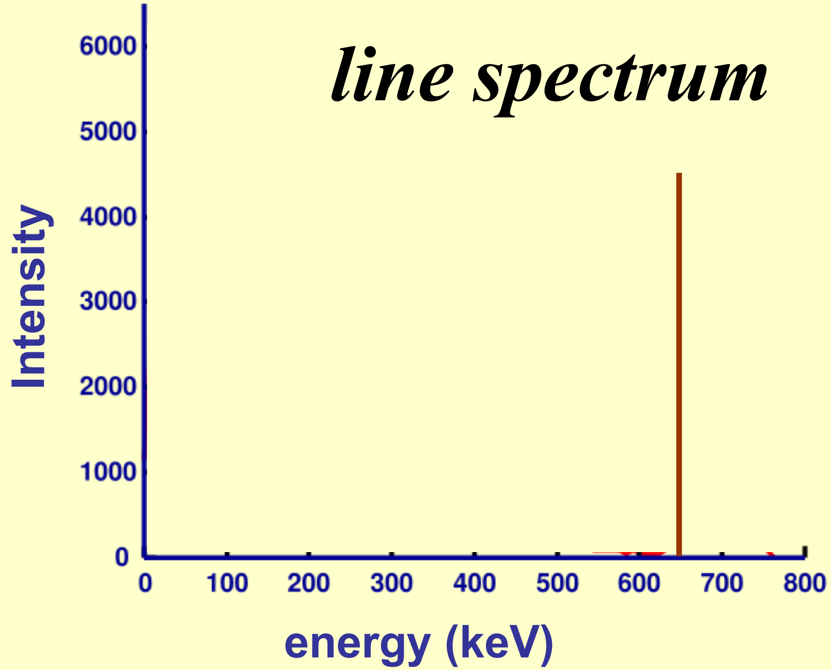
Excited nuclides release the excess of energy by emission of gamma rays.

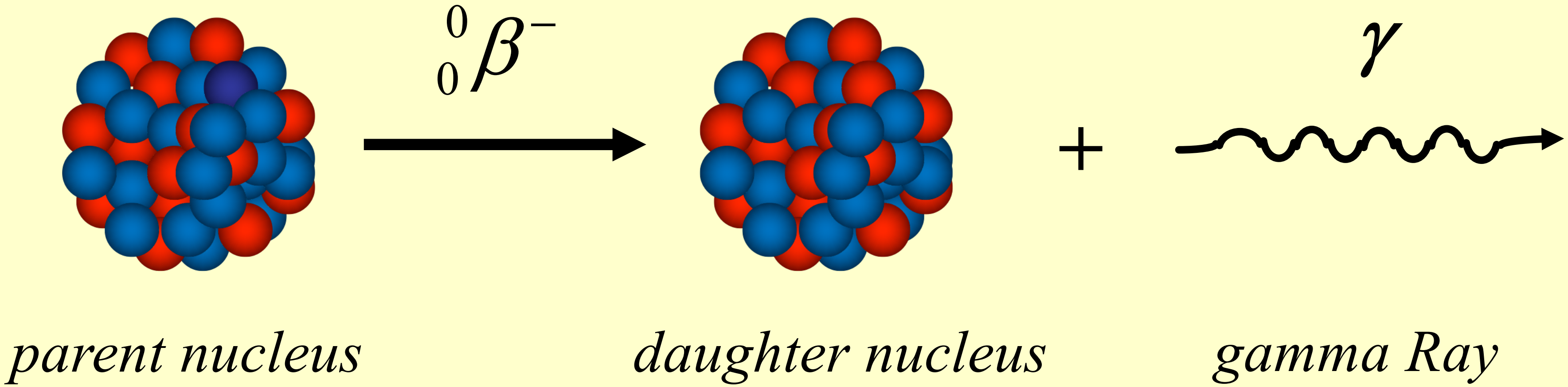
half-life ranging from hours up to more than 600 years

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

Energy spectrum of γ radiation

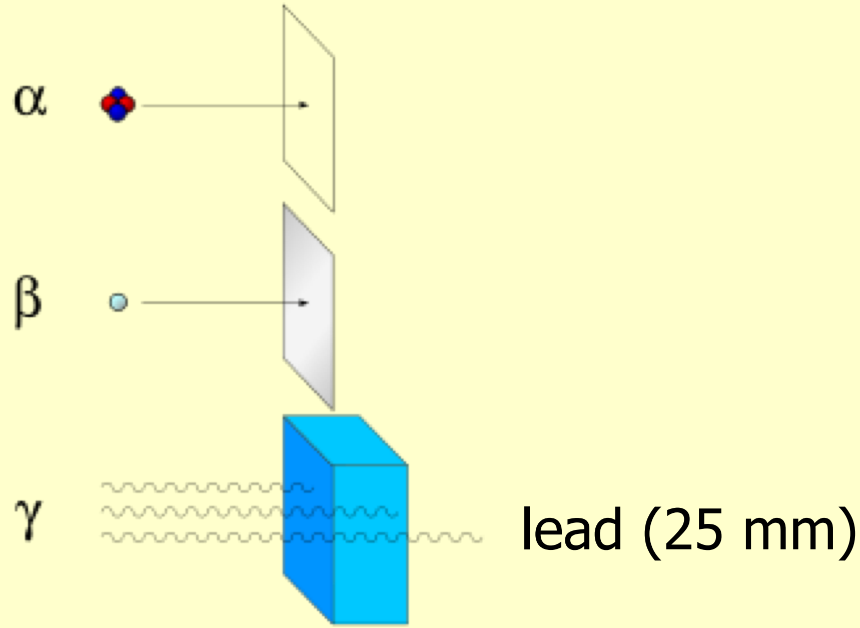






Energy is characteristic for the nucleus

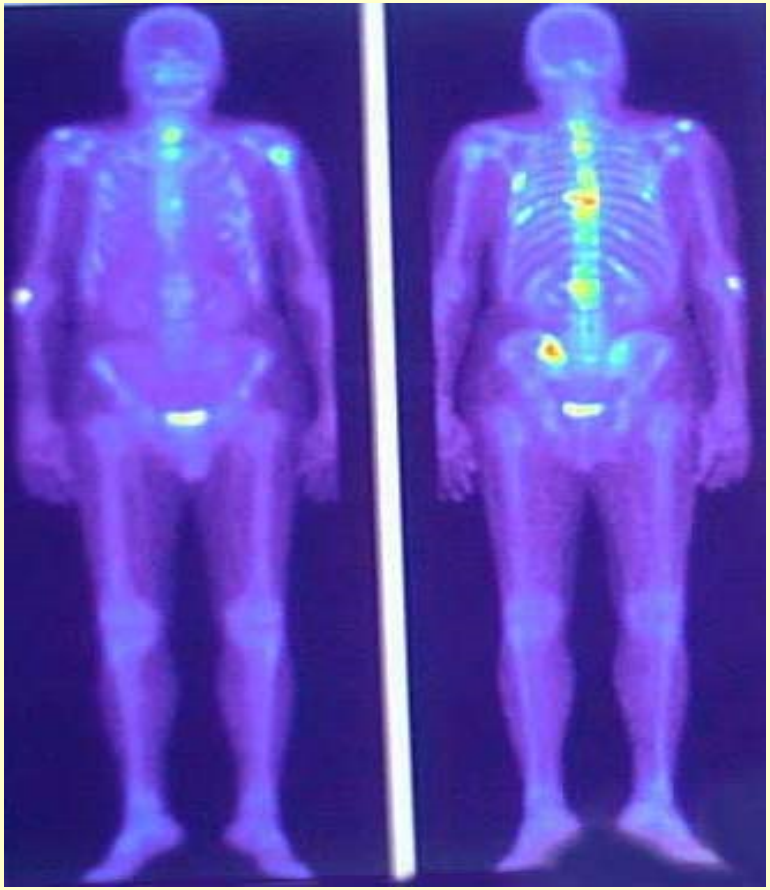
Penetration depth of γ radiation



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

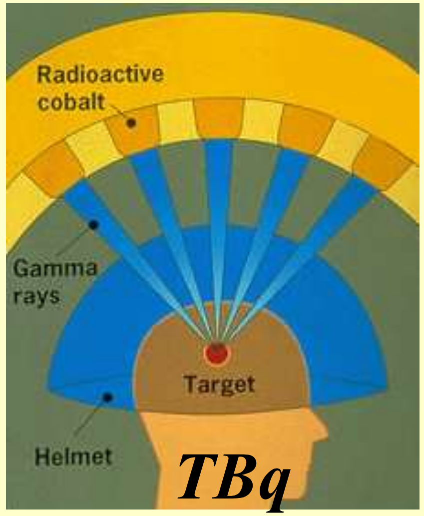
Gamma rays can travel from 1 to 100s of meters in the air and can easily go right through people (~dm).

Medical application of γ rays



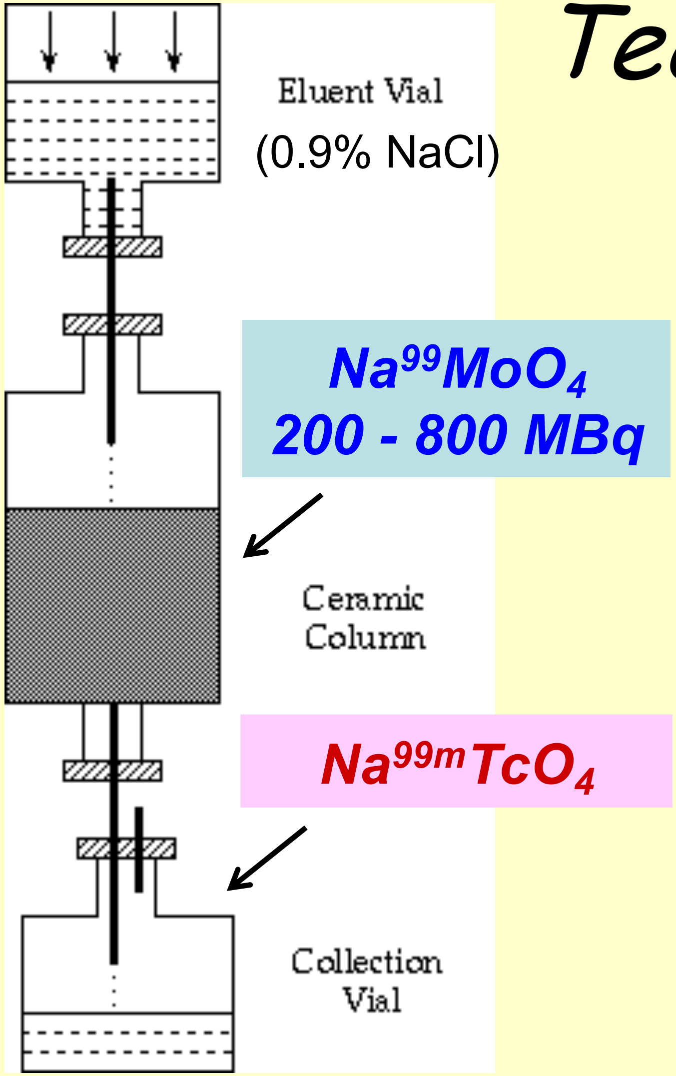
Bone scan using ^{99m}Tc labeled phosphate compound

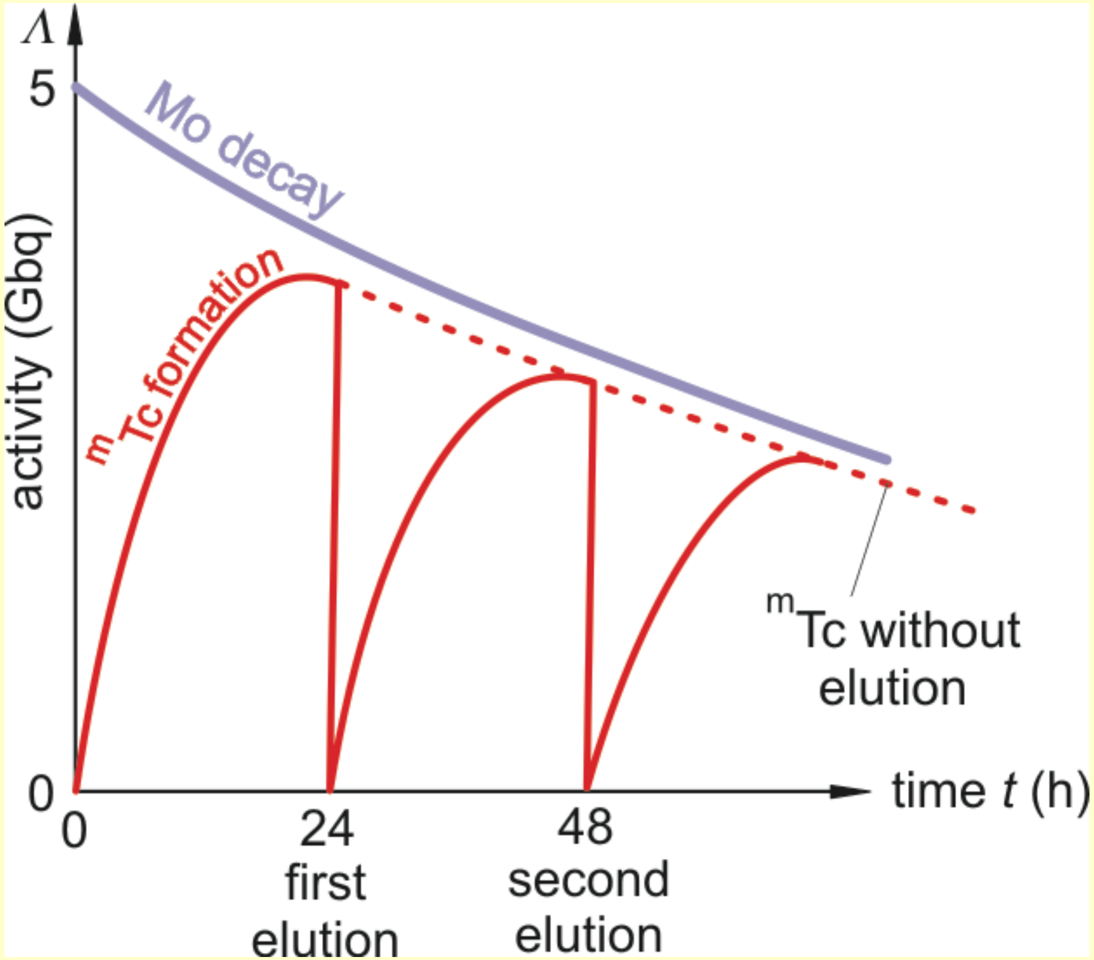
therapy: γ-knife



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 $\quad$ $T_{1/2}$=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