Radioactive isotopes and radiations

Dr. Tamás Bozó

Department of Biophysics and Radiation Biology

8th december 2022

SEMMELWEIS EGYETEM 1769

Topics

Lecture

- (Photon concept. Radiations; Law of attenuation of intensity of radiation - *see. lecture 6*)
- (Atom, electron. Most important experiments. H-atom; Bohr's model - see *lecture 7*)
- **Structure of nucleus**
  - Structure, properties
  - Nuclide, isotope, isobar, isoton
  - Nuclear forces
  - Nuclear models
  - Stability
- **Nuclear radiations**
  - α-, β-, γ- and other radiations
  - Spectrum, ionization,
- **Law of radioactive decay, activity**

Related practices

- Nuclear medicine
- Gamma absorption
- Dosimetry
- Gamma energy (2. semester)
- Isotope diagnostics (2. semester)

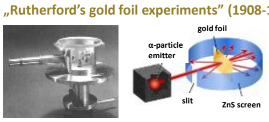
Related textbook* chapters

- I/1.1.1. Atoms, electrons, nuclei
- I/1.5. The Structure of the Nucleus
- II/3.2. Nuclear Radiation and Radioactive Isotopes

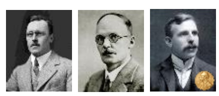
**Damjanovich, Fidy, Szöllősi (eds.): Medieval Biophysics. Medicina, Budapest, 2009*

Discovery of atomic nucleus

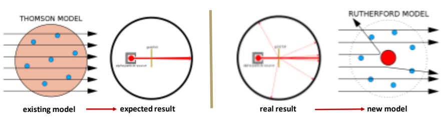
„Rutherford's gold foil experiments" (1908-13)



Replica of the Geiger-Marsden device and model of the experiment

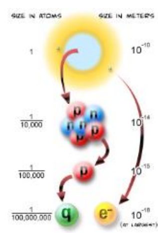


Ernest Marsden 1889-1970   *J. W. Geiger* 1882-1945   *Ernest Rutherford* 1871-1937



Rutherford atomic model 1911

The Structure of the Nucleus



https://particleadventure.org/

Properties:

- Size: 10^{-15} - 10^{-14} m (1-10 fm)
- Atomic Mass Unit (AMU)

$$AMU = \frac{m_{^{12}C}}{12} = 1.6605 \cdot 10^{-27} kg$$

- Nucleons: proton (p^+), neutron (n)

$$m_{p^+} = 1.6726 \cdot 10^{-27} kg \qquad m_n = 1.6749 \cdot 10^{-27} kg$$

$$q_{p^+} = 1.6 \cdot 10^{-19} C \qquad q_n = 0\ C$$

$$(m_{e^-} = 9.31 \cdot 10^{-31} kg\ ;\ \ q_{e^-} = 1.6 \cdot 10^{-19} kg)$$

The Structure of the Nucleus

- **Characteristic numbers:**

$$A = Z + N$$

A: mass number

Z: atomic number (number of protons)

N: neutron number

- **Nuclide:** (also known as nuclear species) is a class of atoms characterized by their number of protons (Z), their number of neutrons (N) and their nuclear energy state. *(IUPAC, Gold book)*

Nuclide naming and symbol:

$${}^{A}_{Z}X_{N} \qquad {}^{A}_{Z}X \qquad {}^{A}X$$

mass number (A), atomic number (Z), chemical symbol (X), neutron number (N)

Pl.: technetium-99m (metastable technetium)

energy state

$${}^{99m}_{43}Tc_{56} = {}^{99m}_{43}Tc = {}^{99m}Tc$$

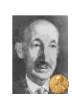
Types of Nuclides

Isotope: one of two or more species of atoms of a chemical element with the same atomic number but with different atomic masses.

Pl. carbon isotopes

${}^{12}_{6}C$	${}^{13}_{6}C$	${}^{14}_{6}C$
Z=6; A=12; N=6	**Z=6**; A=13; N=7	**Z=6**; A=14; N=8
m=12 AMU	m=13.00335 AMU	m=14.003244 AMU
98.89%	1.109%	1 ppt
stable	**stable**	**radioactive** (β^-)
		T=5730 year

A chemical element can have stable and radioactive isotopes.



György Hevesy 1885-1966

The Absorption and Translocation of Lead by Plants.Biochem J.1923;17: 439.

1943: Nobel prize in chemistry *„for his work on the use of isotopes as tracers in the study of chemical processes"*

- Same Z → same number of electrons → identical chemical properties
- Different A → different physical properties

Types of Nuclides

Isotope: one of two or more species of atoms of a chemical element with the same atomic number but with different atomic masses

e.g. hydrogen isotopes

$^{1}_{1}H$	$^{2}_{1}H$	$^{3}_{1}H$
protium **Z=1**; N=0 stable	deuterium **Z=1**; N=1 stable	tritium **Z=1**; N=2 radioactive (β⁻) T=12.32 year

e.g. helium isotopes

$^{3}_{2}He$	$^{4}_{2}He$
helium-3 **Z=2**; N=1 radioactive	helium-4 **Z=2**; N=2 stable

Isobar: nuclides that have the same number of nucleons (A), but different proton number (Z).

$^{3}_{1}H$	$^{3}_{2}He$
tritium **A=3**; Z=1; N=2 radioactive (β⁻) T=12.32 year	helium-3 **A=3**; Z=2; N=1 stable

Isotone: nuclides that have the same neutron number (N), but different proton number (Z).

$^{2}_{1}H$	$^{3}_{2}He$	$^{3}_{1}H$	$^{4}_{2}He$
deuterium Z=1; **N=1** stable	helium-3 Z=2; **N=1** stable	tritium Z=1; **N=2** radioactive (β⁻) T=12.32 year	helium-4 Z=2; **N=2** stable

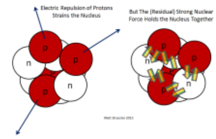
The Structure of the Nucleus

What holds the nucleus together?

(1) Coulombic forces: p⁺-p⁺ repulsion

(2) Gravity: weak attraction

(3) Nuclear force: „strong interaction" attraction between nucleons. Independent of charge.



4 Fundamental interactions in physics

Charged	Acts on…	Effective range	Relative strenght
Gravity	all particles	infinite ($\sim 1/r^2$)	10^{-40}
Electro-magnetic	charged particles	infinite ($\sim 1/r^2$)	10^{-2}
Strong nuclear	nucleons	10^{-15} m	1
Weak nuclear	all particles	10^{-18} m	10^{-13}

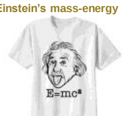
SEMMELWEIS EGYETEM 1769 | Department of Biophysics and Radiation Biology | Dr. Tamás Bozó

Mass deficiency

Mass defect: mass of nucleus ($M_{A,Z}$) is smaller than the sum of the masses of nucleons.

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

Einstein's mass-energy relation:



E: energy
m: mass
c: speed of light in vacuum

- Strong nuclear force is attractive → as nucleons enter the nucleus their E_{pot} decreases.

$$E_{nucleus} < \Sigma E_{nucleons}$$

- Binding energy of nucleus:

$$\Delta E = \Sigma E_{nucleons} - E_{nucleus}$$

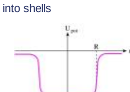
- This energy is released as a photon/particle upon the formation of the nucleus.
- The mass deficiency is equivalent to this energy difference:

$$\Delta E = \Delta M \cdot c^2$$

SEMMELWEIS EGYETEM 1769 | Department of Biophysics and Radiation Biology | Dr. Tamás Bozó

Nuclear models

Nuclear shell model (analogy: electron shells)
- Bound nucleons
  - have quantized energy states
  - generate a common potential field
  - move freely and independently
- Solving Schrödinger equation
- Using 4 quantum numbers
- Pauli principle
- Nucleons arranges into shells



R: radius of nucleus

Liquid drop model (analogy: liquid droplet)
- Nucleus is a sphere
- Density independent of it's size
- Nucleons interact only with their neighbours
- Radius of the nucleus:

$$r = r_0\sqrt[3]{A}$$

$$(r_0 = 2 \cdot 10^{-15})$$

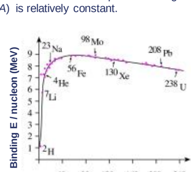
Binding energy is determined by:
- Volumetric E: increases with the number of nucleons
- Superficial E: negative contribution, as surface nucleons cannot fully participate in binding
- Coulomb E: more p⁺ → higher repulsion

SEMMELWEIS EGYETEM 1769 | Department of Biophysics and Radiation Biology | Dr. Tamás Bozó

Stability of nucleus

Specific binding energy

ΔE increases with Z. The specific binding energy (*ΔE/A*) is relatively constant.

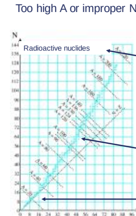


- ΔE/A varies within a narrow range 6,5-5,8 MeV
- ΔE/A has a maximaum at approx. A=55-60
- Energetically favorable:
  - Fission of big (A>200) nuclei,
  - Fusion of small (A~1-5) nuclei
  - Due to tending toward the energy minimum (E_{pot})
- Energy production: fission (and fusion) reactors

SEMMELWEIS EGYETEM 1769 | Department of Biophysics and Radiation Biology | Dr. Tamás Bozó

Stability of nucleus

Too high A or improper N/Z ratio → unstable nucleus → radioactive decay



Line of stable nuclides

Direction of decay: N/Z decreases (might increase at certain steps)

$^{3}_{2}He$ The sole stable nuclide with Z>N

Stability rules:
- There are more stable nuclei with:
- Even that odd Z,
- Even than odd N
- Even than odd A
- Usually stable nuclei with an even A have an even Z as well. Exemptions:

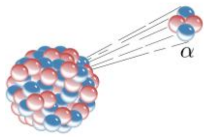
$^{2}_{1}H$ $^{6}_{3}Li$ $^{10}_{5}B$ $^{14}_{7}N$

SEMMELWEIS EGYETEM 1769 | Department of Biophysics and Radiation Biology | Dr. Tamás Bozó

Nuclear radiations

α-decay

- Characteristic to high Z elements
- He nucleus (He^{2+}) is emitted



alpha decay of uranium – 236

https://ftloscience.com/alpha-beta-gamma-ionizing-radiation/

alpha particle

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

mother nuclide   *daughter nuclide*

E.g. decay of radium-226

$${}^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + He^{2+}$$

Nuclear radiations

α-radiation

- Line spectrum
- α-kinetic energy: ~0,4-0,8 MeV
- mass: $6{,}7\cdot10^{-27}$ kg
- velocity: 2-20 000 km/s
- **Effective range:** 2-9 cm in air, ~ 0,1 mm in soft tissues
- Direct ionization: Coulomb effect

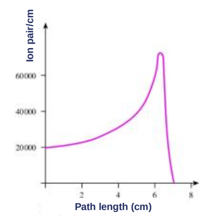
Application: **therapy**

$$\text{linear ion density} = \frac{n}{l}$$

$$LET = \frac{\Delta E}{l} = \frac{n}{l}\cdot E_{ion\ pair}$$

n: number of produced ion pairs
l: path length
LET: stopping power
ΔE: energy lost
$E_{ion\ pair}$: energy necessary to create an ion pair

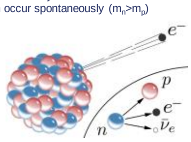
Ionizing power of α-radiation in air



Nuclear radiations

Negative β-decay

- Nucleon transformation: $n \rightarrow p^{+}$
- Z increases by 1 → new element
- Can occur spontaneously ($m_n > m_p$)



negative beta decay

https://ftloscience.com/alpha-beta-gamma-ionizing-radiation/

antineutrino

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

mother nuclide   *daughter nuclide*   *electron*

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

E.g. decay of phosphorus-32

$${}^{32}_{15}P \rightarrow {}^{32}_{16}S + e^{-} + \bar{\nu}$$

Nuclear radiations

β-radiation

- Continuous spectrum → Antineutrino

$$m_{e^-} = 9.31\cdot10^{-31}kg\,;\quad q_{e^-} = 1.6\cdot10^{-19}kg$$

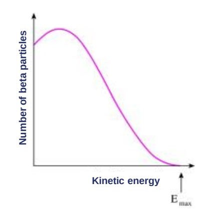
- Low mass → scatter on electrons, zig-zagged path
- Lower charge → lower Coulomb effect → smaller n/l
- E_{max} cca. < 2MeV
- **Max. effective range:** fem m-s in air, few mm in soft tissue

 → Application: **therapy**

- **INVERSE beta decay**: electron capture from K-shell (characteristic X-ray emission), Z decreases by 1

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

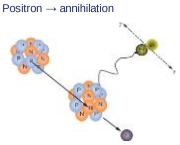
Energy spectrum of beta particles



Nuclear radiations

Positive β-decay and radiation

- Nucleon transformation : $p^{+} \rightarrow n$
- Z decreases by 1→ new element
- Doesn't occur spontaneously ($m_n > m_p$), excess energy needed→ artificial nuclides
- Positron → annihilation



neutrino

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

mother nuclide   *daughter nuclide*   *positron*

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

diagnostics: PET

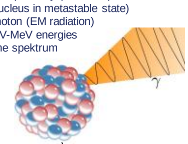
E.g. decay of phosphorus-30

$${}^{30}_{15}P \rightarrow {}^{30}_{14}Si + e^{+} + \nu$$

Nuclear radiations

Gamma-decay

- Accompanies α or β decay
- Daughter nucleus in excited state
- Prompt decay ($T=10^{-19}$ s) vs. nuclear isomerism (nucleus in metastable state)
- Photon (EM radiation)
- keV-MeV energies
- Line spektrum



gamma decay

https://ftloscience.com/alpha-beta-gamma-ionizing-radiation/

E.g. decay of molibdenum-99

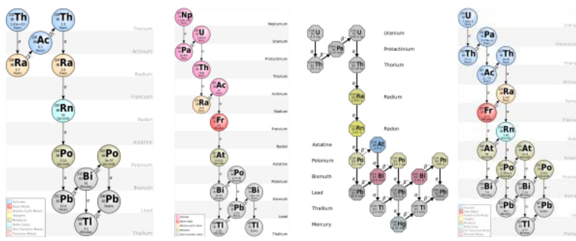
$${}^{99}_{42}Mo \rightarrow {}^{99m}_{43}Tc \rightarrow {}^{99}_{43}Tc$$

β^{-} T=66h   *metastable nuclide* γ T=6h

- Indirect ionization (photoeffect, Compton scattering, Pair production)
- Absorption depends on E_{photon}
- Can cross thick layers of soft tissue

diagnostics: gamma camera, SPECT

Radioactive decay families



Law of Radioactive Decay

Exponential kinetics

$$\frac{\Delta N}{\Delta t} = -\lambda N$$

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

$\frac{\Delta N}{\Delta t}$: *decay rate*

N: *number of undecayed nuclei*

λ: *decay constant.* $[1/s]$

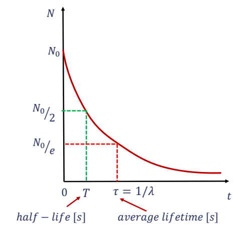
t: *time*

Activity: number of decaying atomic nuclei per unit time

$$A = -\frac{\Delta N}{\Delta t} = \lambda N \quad [1/s = Bq] \qquad A = A_0 e^{-\lambda t}$$

Specific activity: $\frac{A}{m}$ $[\frac{Bq}{g}]$

Activity conentration: $\frac{A}{V}$ $[\frac{Bq}{ml}]$



Thank you!

Dr. Tamás Bozó

SEMMELWEIS EGYETEM 1769