# Atomic nucleus

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# Atomic nucleus

- The particles forming the atomic nucleus – **neutrons** and **protons** – are called **nucleons**.
- They are attracted by the so-called **strong interaction** (one of fundamental physical interactions: forces – gravitational, electromagnetic, weak and strong).

- **Atomic** (or **proton**) **number** $Z$ – number of protons inside a nucleus.
- **Neutron number** $N$ – number of neutrons inside a nucleus.
- **Atomic mass** (or **nucleon**) **number** $A$ – number of nucleons inside a nucleus ($A = Z + N$).

# Atomic nucleus

- The general symbol for a nucleus should be written in following form: $^{A}_{Z}X$ ,where $X$ is the chemical symbol of an element.
- The electric charge of a nucleus is given by the number of its protons:

$$Q_{nuc} = Ze,$$

- where $e$ is the **elementary charge** (electric charge of one electron or proton, $1.602\times10^{-19}$ C).

# Atomic nucleus

- An **element** is a substance the nuclei of which are made up of the same number of protons (number *Z* is the same in all the nuclei).
- A **nuclide** is a substance the nuclei of which are of identical composition (numbers *Z* and *N* have the same values in all the nuclei).
- **Isotopes** are nuclides of an element the nuclei of which have the same number *Z* but they differ in number of neutrons. Different isotopes cannot be distinguished chemically because they possess identical electron shells. They are of different mass, of course. For example: carbon-12, carbon-14, uranium-235, uranium-238 etc.

# Atomic nucleus

- **Nuclear binding energy:**

- The nucleons are held together by the “strong interaction” (strong nuclear force). The binding energy $E_{nuc}$ can be defined as the energy which would be just necessary to disintegrate the nucleus into individual nucleons.

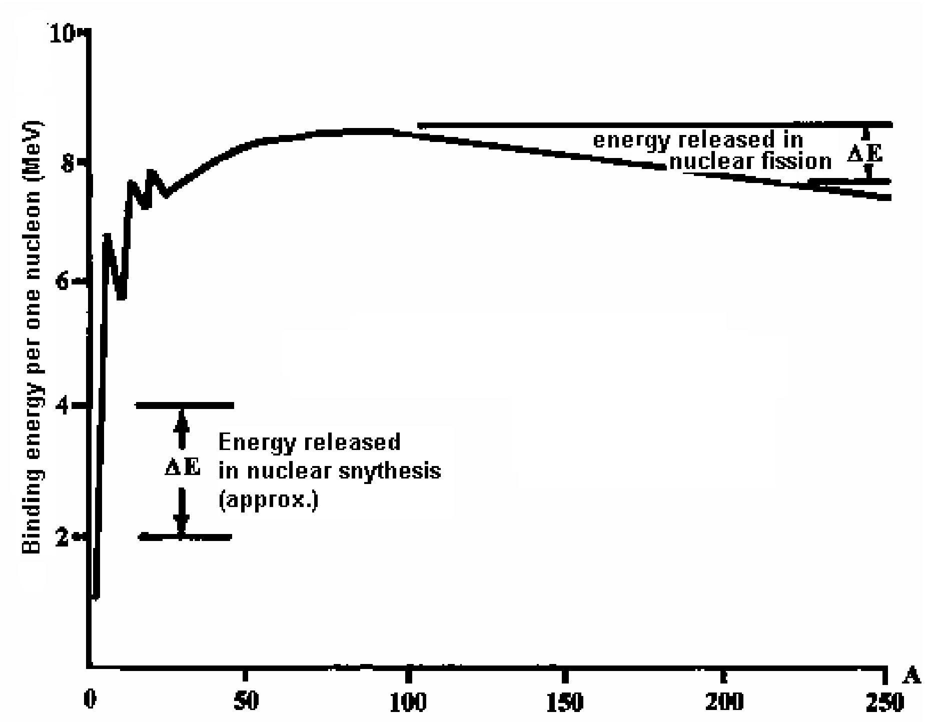
- During synthesis of nuclei from individual nucleons the same amount of energy is liberated.

# Atomic nucleus

- **Nuclear binding energy:**
- The nuclear binding energy per nucleon has different values for different nuclides.
- Maximum binding energy per nucleon (i.e. the highest stability) can be found in nuclei which are in the middle part of the periodic table of elements. The nucleus of the isotope  (iron-56) possesses the greatest value of binding energy; it means that this nucleus is the most stable. Very light and very heavy nuclei are not so stable which is a fact of extraordinary importance: during synthesis of light elements (thermonuclear synthesis or fusion) and splitting of heavy nuclei (nuclear fission) considerable amount of nuclear energy are liberated.

# Atomic nucleus

- **Nuclear binding energy:**



# Atomic nucleus

- **Nuclear binding energy:**
- The greater the binding energy the more stable is the nucleus. This energy can be calculated from the difference $\Delta m$ between the mass of the nucleus $m_{nuc}$, and the sum of masses of the number of individual (free) protons and neutrons ($m_p$, $m_n$) which are contained in the respective nucleus.

$$\Delta m = Zm_p + Nm_n - m_{nuc}$$

- Now it is possible to use Einstein's formula of **mass – energy equivalence**:

$$E_b = \Delta\, mc^2,$$

- where $E_b$ is the binding energy and $\Delta m$ is the above defined mass difference (**mass defect**).

# Atomic nucleus

- **Nuclear binding energy:**
- Examples:
- (thermonuclear synthesis of helium-3)

$$ {}_{1}^{2}H + {}_{1}^{1}H \rightarrow {}_{2}^{3}He + \gamma $$

energy liberated: 5.49 MeV

- (nuclear fission of uranium-235 induced by neutron)

$$ {}_{0}^{1}n + {}_{92}^{235}U \rightarrow {}_{56}^{144}Ba + {}_{36}^{89}Kr + 3\left({}_{0}^{1}n\right) $$

energy liberated: about 200 MeV

# Atomic nucleus

- **Nuclear reactor:**
- Is a complex device in which a controlled nuclear fission takes place. Numerous rods made of uranium enriched by the isotope are placed in a large steel container. A **chain reaction** is started if a neutron interacts at low velocity (a moderated or thermal neutron) with a nucleus of the isotope uranium-235, and causes its fission. The two or three neutrons which are liberated by fission are slowed down (decelerated) to be able to cause new fission. The deceleration of neutrons is achieved by a **moderator** (water, graphite or another substance composed of light nuclei).

# Atomic nucleus

- **Nuclear reactor:**
- The fine regulation of neutron flux in the reactor is ensured by insertion of control rods made of cadmium, for example. These control rods reduce the number of neutrons able to induce fission. The large amount of heat produced is utilized for heating water or other suitable liquid in the primary loop of the reactor. This very hot and more or less radioactive liquid warms up the water in the secondary loop, which drives a powerful steam turbine to produce electric energy. The neutron flux produced by a nuclear reactor can be also used for production of artificial radioactive elements – radionuclides.

# Atomic nucleus

- **Natural and artificial radioactivity:**
- Radioactivity is the ability of a nucleus to emit particles or quanta of energy. This process is also called radioactive decay or disintegration.
- Radioactive nuclides are called radionuclides (more than 1600 radionuclides have been identified in nature or prepared artificially).
- The radioactivity is accompanied by nuclear transformation. It means that during the radioactive decay new (daughter) nuclei arise.

# Atomic nucleus

- **α (alpha)-radiation**
- Helium **nuclei** are emitted from a radionuclide. These particles are electrically charged (+2*e* charge) and relatively heavy. They cause direct ionization of ambient atoms, and all their energy is transmitted to the medium along a very short track. It means that this radiation is only little penetrating.
- Scheme: $^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$
- Example: $^{226}_{88}Ra\ (radium) \rightarrow {}^{222}_{86}Rn\ (radon) + {}^{4}_{2}He$

# Atomic nucleus

- **$\beta^-$ (beta-minus)-radiation**
- Electrons are emitted from a radionuclide. One nuclear neutron is transformed into a proton, an electron and a very light particle called “electron antineutrino” (shown in the scheme and reaction below).
- Interaction of these particles with matter was described in the paragraph dealing with the origin of X-rays. The ionization ability of β-particles is relatively low hence their penetration into matter is easier in comparison with a-particles.
- Scheme: $^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{1}e^- + {}^{0}_{0}\bar{\nu} + \gamma$

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{1}e^-$$

Example: $^{14}_{6}C \rightarrow {}^{14}_{7}N + e^-$

# Atomic nucleus

- **$\beta^+$ (beta-plus)-radiation**
- Positrons are emitted from radionuclides. The positron is an antiparticle of the electron. One nuclear proton is transformed into a neutron, a positron and a very light particle called "positron neutrino" (shown in the scheme and reaction below).

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

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{1}e^{+}$$

- Example: $^{30}_{15}P \rightarrow {}^{30}_{14}Si + e^{+}$

# Atomic nucleus

- **K - capture**

Electron is captured from K shell by nucleus…

Scheme: $^{1}_{1}p + {}^{0}_{1}e^{-} \longrightarrow {}^{1}_{0}n + \gamma$

$$^{A}_{Z}X + {}^{0}_{1}e^{-} \longrightarrow {}^{A}_{Z-1}Y$$

# Atomic nucleus

- **γ (gamma)-radiation**
- These high energy photons are emitted from a radionuclide. A nucleus possessing some excess energy [*] emits a photon of electromagnetic radiation. The γ-emission often accompanies other types of radioactive decay. The ionization ability of this radiation is relatively very low hence it penetrates very deeply into matter. For interactions with matter, see the paragraphs dealing with the photoelectric effect and Compton scatter.

Scheme: $^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma$

- Example: $^{99}_{43}Tc^{*} \rightarrow {}^{99}_{43}Tc\ (technetium) + \gamma$

# Atomic nucleus

- **Neutron radiation**
- A neutron is emitted from a radionuclide or can be liberated after collision of two accelerated nuclei.
- Example: $${}^{4}_{2}He \quad + \quad {}^{27}_{13}Al \quad \rightarrow \quad {}^{30}_{15}P \quad + \quad {}^{1}_{0}n$$
- This nuclear reaction, followed by reaction $${}^{30}_{15}P \rightarrow {}^{30}_{14}Si + e^{+}$$ represents the first case of artificial radioactivity observed by Frédéric and Irène Joliot-Curie in 1934.
- The neutron ionizes matter indirectly. Fast neutrons transmit their energy by impacts. This process is highly effective in collisions with some light nuclei (such as hydrogen nucleus). Moderated (slow, thermal) neutrons can enter inside some heavy nuclei (such as uranium nucleus) and cause their disintegration – fission.

# Atomic nucleus

- **Proton radiation**
- Protons are emitted from a radionuclide, or liberated after collision of two accelerated nuclei.
- Example: $${}^{4}_{2}He \quad + \quad {}^{14}_{7}N \quad \rightarrow \quad {}^{17}_{8}O \quad + \quad p\left({}^{1}_{1}H\right)$$
- This nuclear reaction was the first case of artificial nuclear transmutation (transformation). It was performed by Rutherford in 1919. Nitrogen was bombarded by α-particles.
- All kinds of nuclear radiation, together with X-rays, are called **ionizing radiation** because they are able to ionize atoms along their tracks (trajectories) through matter. Chemical changes of various substances or even damage to biological systems can be caused in this way.

# Radioactive transmutation law – decay law

- Radioactivity is a stochastic (probabilistic) process which can be described in terms of probability. However, in great assemblies of radioactive nuclei it can be also described by equations:

$$A_t = A_0 e^{-\lambda t} \quad or \quad N_t = N_0 e^{-\lambda t}$$

- where $A_t$ is the **activity** of a radioactive sample at time $t$ = t, $A_0$ is the initial activity of the sample at time $t$ = 0, $N_t$ is the number of nuclei left at time $t$ = t, and the value $N_0$ is the initial number of radioactive nuclei at the time $t$ = 0. $\lambda$ is the **decay** (or disintegration) **constant** [$s^{-1}$] and $t$ is the time of observation (i.e. the time during which the individual radioactive decays were counted).

# Radioactive transmutation law – decay law

- *Activity A of a radioactive emitter expresses the number of decays (transmutations) in it per 1 second.*

***1 decay per 1 s = 1 Bq (becquerel) [$s^{-1}$]***

older unit of radioactivity is the curie, Ci, which was originally defined as "the quantity or mass of radium emanation in equilibrium with one gram of radium (element)".

Today, 1 curie (Ci) = $3.7 \times 10^{10}$ Bq

# Half-life (time)

- **Half-life (time)** *T* of a radionuclide is a quantity used for characterization of the decay rate; it is better understandable then the activity itself. It is the time during which the number of radioactive nuclei (or the activity of a sample) decreases to one half of the initial value. It is possible to derive (substitute $N_t = N_T = N_0/2$ and $t = T$ in the above formula) that

$$T = \frac{\ln 2}{\lambda}$$

where λ is the decay constant.

# Main applications of ionising radiation and radionuclides

- Attenuation of X-rays is utilized in medical imaging (radiography and CT - computerized tomography) to show inner structures of our body. g-radiation is used for this purpose in some other imaging methods.

- The strong biological effects of ionizing radiation (including killing of tumour cells) is used in radiotherapy,

- Heat production during nuclear fission is used for production of electricity in the nuclear reactors.

# Main applications of ionising radiation and radionuclides

- Chemical compounds (metabolites) labelled by radioisotopes make it possible to follow metabolic pathways in living organisms – these methods are called “tracing” techniques.

- Measurement of the content of various radionuclides is often used for dating of different organic and inorganic samples (e.g., radiocarbon method used in archaeology.