Physics of Processes

Nuclear Physics

Nuclear Physics

<u>The structure of the atom</u>

- atoms - nucleus - protons and neutrons

- shell - electrons

- nuclear physics - processes at the level of atomic nuclei

- atomic physics - processes at the level of electron shells of atoms

- protons - one positive elementary electric charge

- electrons - one negative elementary charge

- neutrons - without electric charge

- the number of protons in the nucleus - the proton number Z - uniquely determines which element it is

- the number of neutrons in the nucleus - the neutron number N - can differ for individual atoms of the same element, then they are different isotopes of the same element

Nuclear Physics

- sum of protons and neutrons - nucleon number *A*

- schematic designation of the element nucleus: $^{A}_{Z}X$

- neutral atom - the number of electrons in the shell is the same as the number of protons in the nucleus

- positive ion - fewer electrons than protons - the positive charge of the nucleus predominates and the atom appears positively charged

- negative ion - more electrons than protons - the negative charge of the shell predominates and the atom appears negatively charged

- mass of protons and neutrons about 1800 times greater than the mass of electrons $\Rightarrow$ almost all the mass of an atom is concentrated in the nucleus

- atomic diameters – about 10^{-10} m

- nucleus diameters – about 10^{-15} m

Nuclear Physics

Radioactivity

- nuclide - a collection of atoms with the same number of protons and the same number of neutrons

- nuclide - e.g. a collection of atoms $^{235}_{92}U$ with 92 protons, 143 neutrons

- isotopes - nuclides of the same element (i.e. with the same number of protons), with different numbers of neutrons

- individual isotopes of elements either occur in nature or can be created artificially

- isotopes differ in physical properties, such as the stability of the nucleus

- stability of the nucleus - the ability of the core to remain in an unchanging state

- neutrons affect the distances of individual protons and thus the force ratios in the atomic nucleus – if the force conditions are unfavourable, the nucleus is unstable and will spontaneously transform into a more stable nucleus over time

Nuclear Physics

- radionuclides - unstable nuclides whose nuclei undergo spontaneous transformation accompanied by the emission of radiation

- radioactivity - the ability of unstable nuclei to spontaneously transmute

- the transformation can produce a nucleus that is again unstable or completely stable

General laws of radioactive transformations

- naturally occurring radioactive radionuclides - found in nature

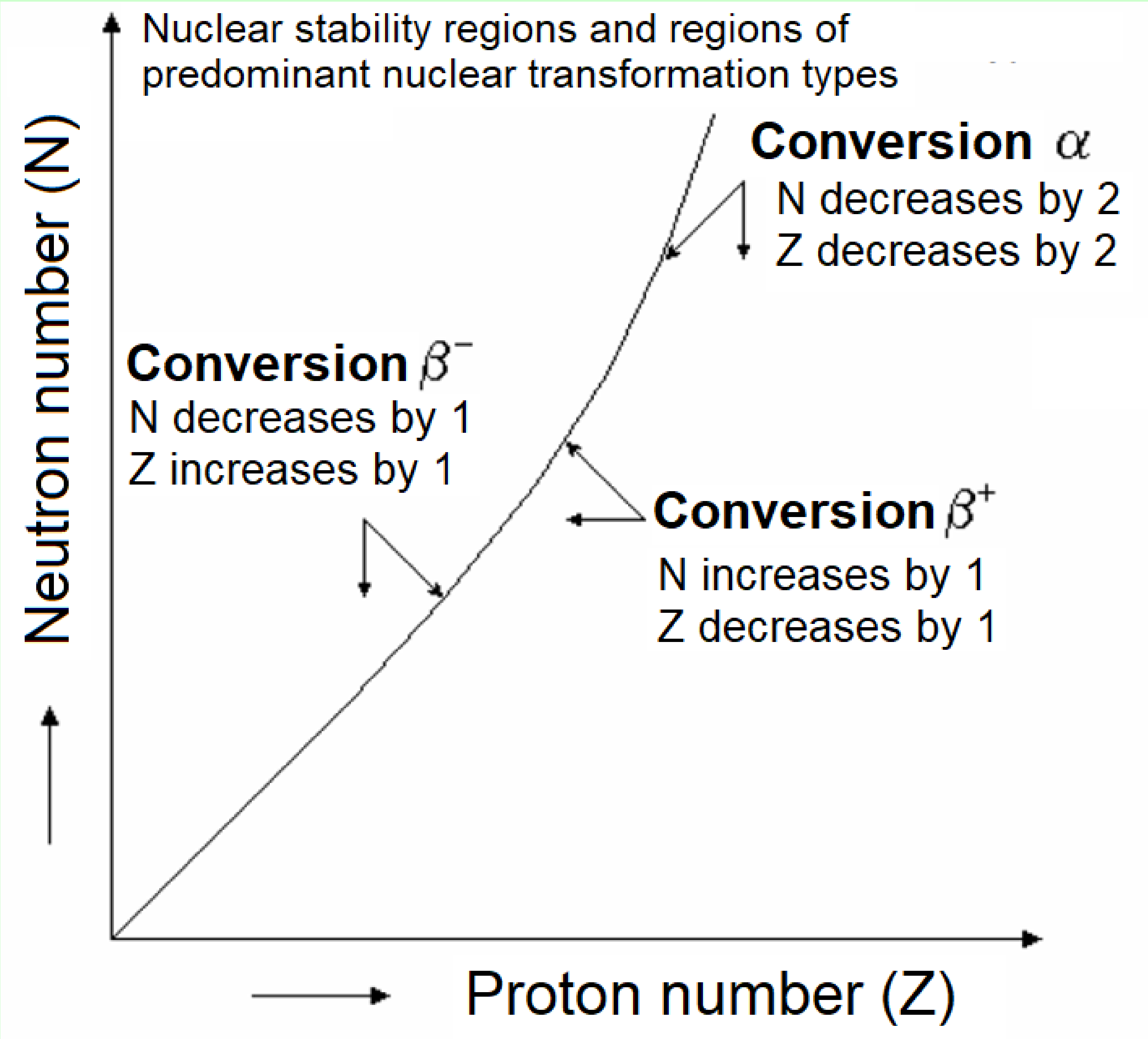
x artificial radionuclides

- the conversion of radionuclides results in the emission of alpha particles (helium nuclei) or electrons or positrons, as well as high-energy photons (gamma radiation)

- radioactive transformations - in the nuclei of atoms, independent of external conditions

- random processes - governed by the laws of statistics; it is not possible to predict for individual kernels whether they will transform or not in a certain time interval

Nuclear Physics



Nuclear Physics

- decrease in the number of untransmuted radioactive nuclei $-dN$ from the original number N in time dt: $-dN = N \lambda dt \Rightarrow$

$\Rightarrow$ transformation (decay) law: $N = N_0 e^{-\lambda t}$, where

N - instantaneous number of original nuclei in time t,

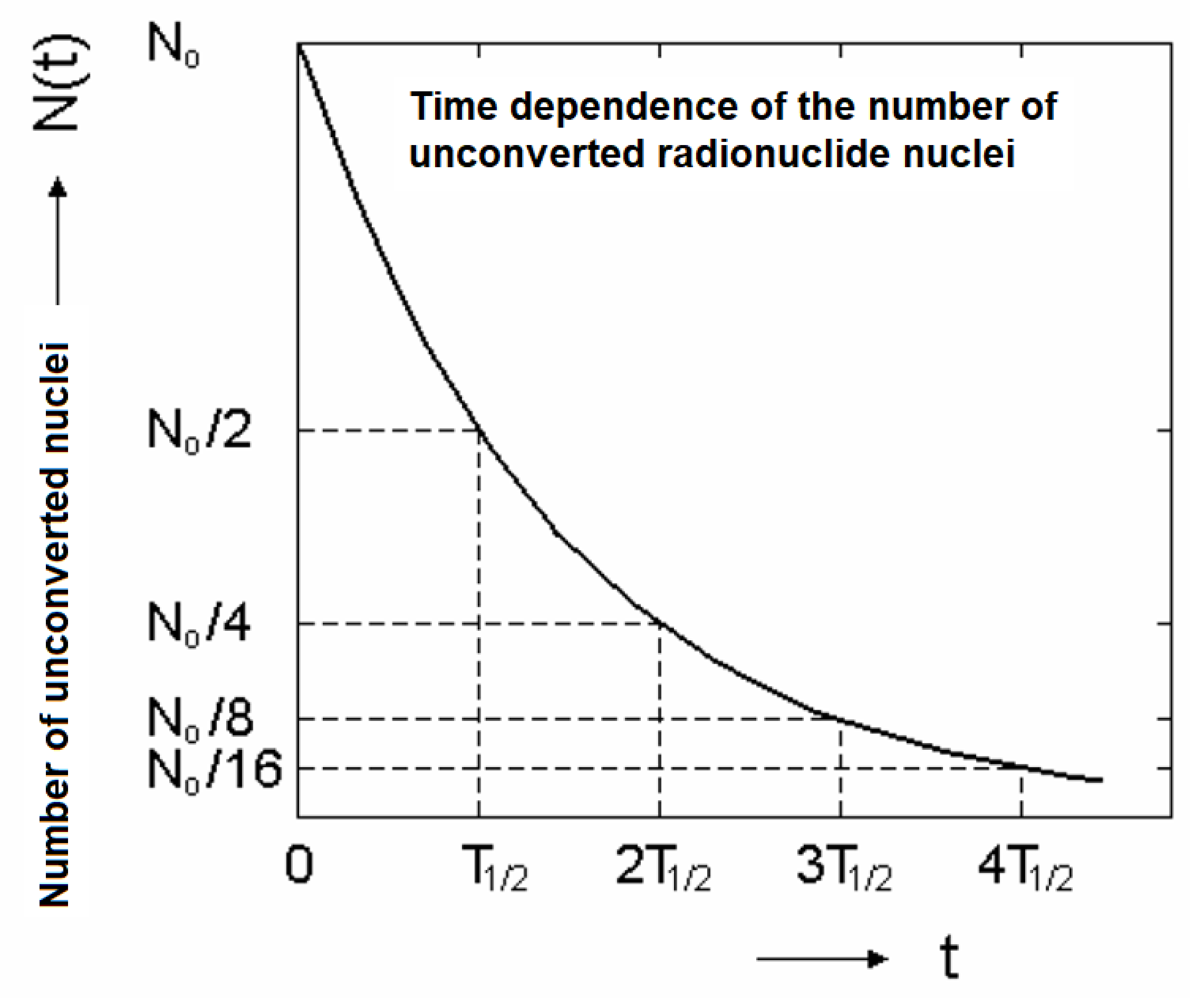
N_0 - original number of nuclei in time 0

λ - decay constant expressing the rate of conversion of a given radionuclide

- radionuclide characteristics - half-life $T_{1/2}$ - the mean time for the original number of atoms of a given radionuclide to be halved

- after substitution into the decay law: $T_{1/2} = \frac{\ln 2}{\lambda}$

Nuclear Physics



Nuclear Physics

- the $T_{1/2}$ half-life value is characteristic of a particular radionuclide
- half-lives of known radionuclides over a wide range $T_{1/2} \approx 10^{-7} - 10^{22}$ s

Examples of half-life values for selected radionuclides:

Radionuclide	$^{232}_{90}Th$	$^{90}_{38}Sr$	$^{13}_{7}N$	$^{6}_{2}He$	$^{212}_{84}Po$
Halftime of conversion	$1{,}4 \,.\, 10^{10}$ years	28 years	0,9993 min	0,823 s	$3 \,.\, 10^{-7}$ s

- according to the mode of radioactive conversion, alpha conversion and beta conversion are distinguished

Alpha conversion

- particle α (nucleus $^{4}_{2}He$) emitted from the nucleus
- the nucleon number decreases by 4 and the proton number decreases by 2
- can be expressed schematically: $^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$

Nuclear Physics

- specific examples: ${}^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + {}^{4}_{2}He$, ${}^{241}_{95}Am \rightarrow {}^{237}_{93}Np + {}^{4}_{2}He$

- energy of emitted α particles in the range 4 - 9 MeV

- alpha conversion exclusively for heavy radionuclides

Beta conversion

- the nucleon number of nucleus *A* does not change, only the proton number *Z* changes

- conversion of beta in two different ways:

1) conversion of β^- - electron and antineutrino emission from the nucleus

- the neutron turned into a proton and the electron (electron is particle β^-)

- schematically: ${}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e \Longrightarrow {}^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + {}^{0}_{-1}e + \bar{\nu}$

- specific example: ${}^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + {}^{0}_{-1}e + \bar{\nu}$, $T_{1/2}$ = 5,26 year

Nuclear Physics

<u>Beta conversion</u>

2) conversion of β^{+} **- positron and neutrino emission from the nucleus**

- positron - antiparticle to electron

- the proton turned into a positron and a neutron (positron is particle β^{+}**)**

- schematically: $^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{1}e \Longrightarrow {}^{A}_{Z}X \rightarrow {}_{Z-1}^{A}Y + {}^{0}_{1}e + \nu$

- specific example: $^{22}_{11}Na \rightarrow {}^{22}_{10}Ne + {}^{0}_{1}e + \nu$, $T_{1/2}$ **= 2,58 year**

- energy of emitted β **particles max. units of MeV**

- beta conversion even for lighter radionuclides

Nuclear Physics

Oxygen isotopes, their abundance in nature and, for unstable ones, the types of conversions:

Isotope	${}^{13}_{8}O$	${}^{14}_{8}O$	${}^{15}_{8}O$	${}^{16}_{8}O$	${}^{17}_{8}O$	${}^{18}_{8}O$	${}^{19}_{8}O$	${}^{20}_{8}O$
% representation in nature	0	0	0	99,40	0,40	0,20	0	0
Type of conversion	β^+	β^+	β^+	stable			β^-	β^-

<u>**Electron capture (capture of an electron by the nucleus)**</u>

- schematically: $\boldsymbol{{}^{1}_{1}p + {}^{0}_{-1}e \rightarrow {}^{1}_{0}n + \nu \rightarrow {}^{A}_{Z}X + {}^{0}_{-1}e \rightarrow {}_{Z-1}^{A}Y + \nu}$

- specific example: $\boldsymbol{{}^{65}_{30}Zn \rightarrow {}^{65}_{29}Cu + \nu}$

Nuclear Physics

Gamma ray emission

- usually accompanies alpha or beta transformations, since these transformations produce nuclei that are in an excited state

- excess energy is emitted after the transition to the lower excited state or to the ground state in the form of gamma rays, i.e. photons with very short wavelengths and energies up to several MeV

- photons are emitted only with certain energy values that correspond to the energy difference between the excited states of the nucleus

- in addition to the mechanism of direct emission of gamma rays from the excited nucleus, there is another way for the nucleus to get rid of excess energy:

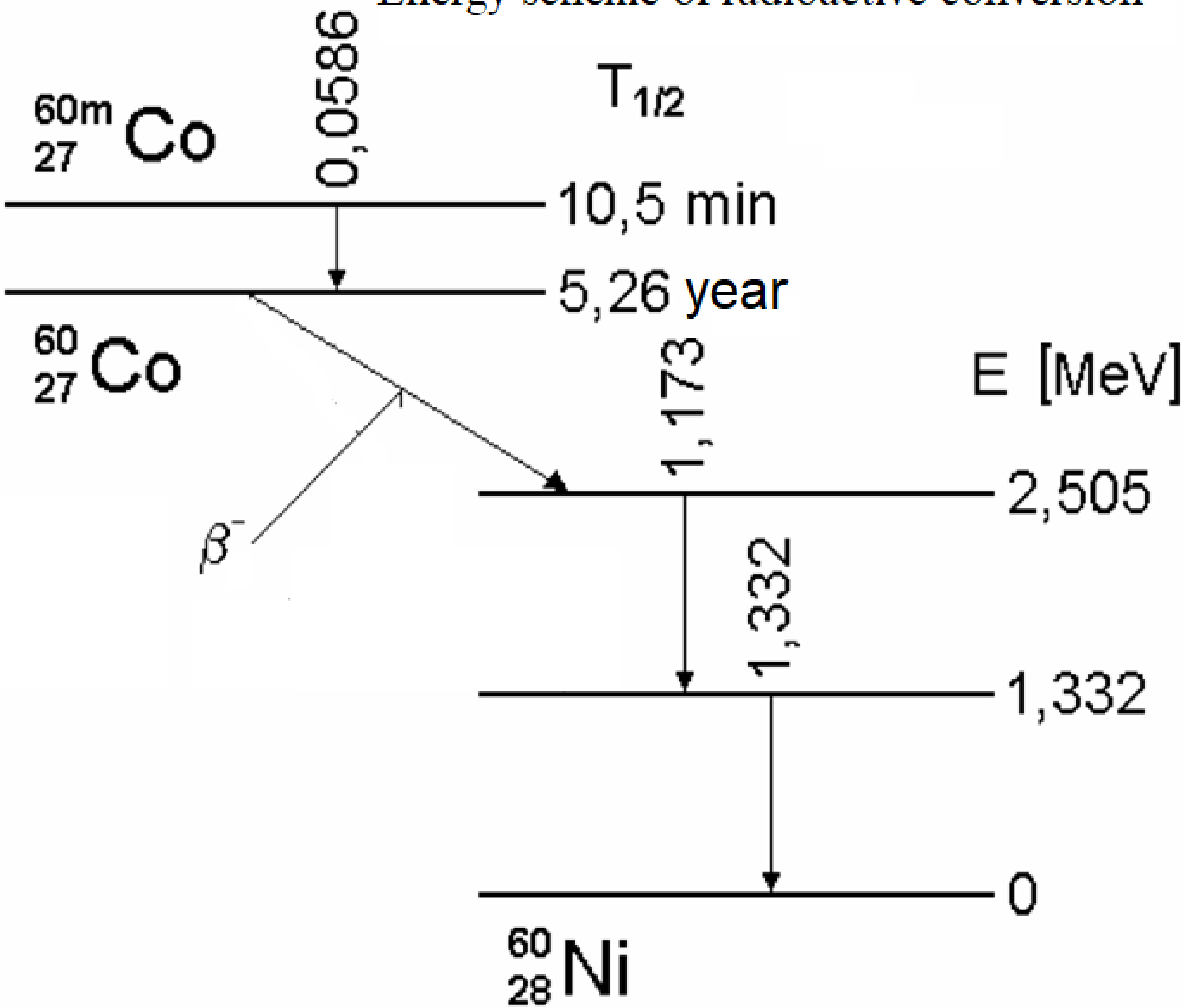
- the excitation energy is transferred to the electron from the electron shell of the atom

- the electron is then released with a kinetic energy equal to the difference between the excitation energy imparted by the nucleus and the binding energy of the electron in the atom

- this phenomenon is called internal conversion

Nuclear Physics

Energy scheme of radioactive conversion



Nuclear Physics

- most nuclei in the excited state emit excess energy almost immediately after alpha or beta conversion

- however, there are also nuclei called isomers, which can remain in the excited state for a long time

- such a state of the nucleus is called metastable

- if the nucleus produced by the transformation is unstable, one of the transformations described above will occur again in time

- example of a gradual transformation : $^{90}_{38}Sr \rightarrow ^{90}_{39}Y \rightarrow ^{90}_{40}Zr$**,**

both transformations are of type β^-

- the first takes place with a half-life of 28.8 years

- the second takes place with a half-life of 64.1 hours

- these are so-called transformation series, at the end of which there is a stable nucleus

Nuclear Physics

<u>**Interaction of ionizing radiation with the environment**</u>

- ionizing radiation can cause chemical changes in cells and damage DNA

- ionizing radiation (alpha, beta, gamma, neutrons, etc.) interacts with the atoms of a substance as it passes through it

- for charged particles with non-zero magnetic moment - mainly electromagnetic interaction

- between neutrons and the environment - interaction mainly due to nuclear forces (so-called strong interaction)

- due to interactions, particles of ionizing radiation change their direction of travel and lose energy

- energy losses are due to elastic and inelastic scattering of radiation on electrons and nuclei of surrounding atoms, due to nuclear reactions, etc.

Nuclear Physics

- one of the main results of interactions when ionizing radiation passes through the environment is the so-called ionization, when electrons are released from the electron shells of atoms in the material environment

- ionizing radiation - directly ionizing and indirectly ionizing:

- directly ionizing radiation - charged particles (electrons, positrons, alpha particles, etc.) that have sufficient energy for ionization

- indirectly ionizing radiation (photons, neutrons, etc.) - as a result of various processes, it releases directly ionizing charged particles or induces nuclear reactions that are accompanied by the emission of directly ionizing particles

- the description of the passage of ionizing radiation through the environment is divided according to the modes of interaction into three groups - charged particles, photons, neutrons

Nuclear Physics

<u>Interaction of charged particles with the environment</u>

- ionization - a consequence of inelastic scattering of electrically charged particles of ionizing radiation on the electrons of atoms in the environment, which occurs as a result of electromagnetic interaction

- in doing so, the ionizing particles lose the part of their kinetic energy that is needed to release the electron from the electron shell (e.g. the mean ionization energy for air under normal conditions is about 34 eV)

- during the passage of a charged particle through the material environment this process is repeated (multiple scattering) until the kinetic energy of the charged particle is no longer sufficient to ionize or excite the surrounding atoms (during excitation the electron is not released from the atomic envelope, but only goes to one of the higher energy levels)

Nuclear Physics

- ionizing particles change their direction of motion in addition to losing energy - this is caused not only by inelastic scattering but also by elastic scattering

- elastic scattering - kinetic energy of particles is not consumed for ionization or excitation of atoms $\Rightarrow$ energy state of an atom is the same before and after scattering

- scattering takes place mainly on the electrons of the electron shells of atoms in the environment $\Rightarrow$ beta radiation, which contains electrons or positronsis, is scattered significantly more than alpha radiation consisting of helium nuclei, which are about three orders of magnitude more massive $\Rightarrow$ heavy particles move along nearly straight paths, but the paths of electrons or positrons are significantly distorted at greater depths

- electron motion is often referred to as diffusive electron motion

Nuclear Physics

- different behaviour of heavy and light particles in ionization energy losses:

- linear braking ability - describes the energy loss of a particle due to ionization per unit path as it passes through a substance - characterizes the properties of the environment in terms of ionization

- this quantity depends inversely proportional to the square of the particle velocity $\Rightarrow$ ionizing particles with the same energy but different masses ionize the surrounding environment differently:

- heavy particles at the same energy have a lower velocity and ionisation losses are therefore greater than for light particles

- the greatest loss of particle energy occurs at the end of the path, when the particle velocity in the environment is already relatively low

Nuclear Physics

Interaction of gamma rays with the environment

- gamma rays - electromagnetic radiation consisting of photons - electrically neutral quasiparticles with zero rest mass moving at the speed of light

- photons interact with other particles differently than electrically charged particles due to their zero rest mass

- interaction of photons with matter through three basic processes - photoelectric effect, Compton scattering and pair formation

- these phenomena take place in the interaction with electrons or in the case of pair formation in the electrostatic field of atomic nuclei

- in addition, interactions with the nuclei of atoms - nuclear photoeffect and nuclear reactions - can also exceptionally take place

- as a result of these processes, electrons are released, which further interact with the environment

Nuclear Physics

1) Photoelectric effect **- can only take place on bound electrons in the electron shell**

- its probability decreases with increasing photons energy and increases with the fifth power of the atomic number *Z*

- during the photoelectric effect, the photon interacts with the atom as with the whole

- photon energy $E = h\nu$, where h – Planck's constant, ν – frequency

- all the energy of the photon is transferred to an electron from the electron shell of the atom, which is released from the atom

- the released electron leaves the atom with energy $E_e = h\nu - W$,

where W – the output work, i.e. the binding energy of the electron, or the energy needed to release it from the atom

- output work - for different elements in the range 10^1eV - 10^5 eV

Nuclear Physics

2) Compton scattering **- elastic scattering of photons on free electrons (free electron - its binding energy is much lower than the photon energy)**

- the energy of the original photon is split between the scattering electron and the scattered photon

- a scattered photon is a single photon with less energy and therefore a longer wavelength

- the original photon has disappeared in the interaction

- the laws of conservation of energy and momentum give a relation for the wavelength λ and the energy of the scattered photon *E* as a function of the scattering angle φ:

$$\Delta\lambda = \frac{h}{mc}(1 - \cos\varphi), E = h\,v = \frac{h\,c}{\lambda},$$

where *c* – speed of light, *h* – Planck's constant, ν – frequency

Nuclear Physics

3) Pair formation **– when a photon moves in the electromagnetic field of a charged particle, it can be transformed into a particle-antiparticle pair**

- a phenomenon with a threshold energy, i.e. the photon energy must be at least equal to the sum of the rest energies of the particle and the antiparticle

- particle and antiparticle have the same mass ⇒ minimum required photon energy $W_{min} = 2\, m_0\, c^2$, where c – speed of light, m_0 – rest mass of the resulting particle (antiparticle)

- the most common formation of electron-positron pairs (the positron is the antiparticle to the electron), because this process has the lowest threshold energy - 1,02 MeV

- if the photon has a higher energy than the threshold energy, the remaining energy is divided equally between the particle and the antiparticle

- the probability of electron-positron pair formation increases with increasing photon energy and with the square of the atomic number of the environment

Nuclear Physics

- number of photons decreases gradually during their passage through the medium

- this decrease is described by an exponential relationship for the absorption law:

$$N = N_0 e^{-\mu x}$$, **where**

N_0 – original number of photons,

N – number of photons after passing through a material medium of thickness x

μ – linear attenuation coefficient

- attenuation coefficient μ is the sum of the attenuation coefficients for the individual phenomena - photoelectric effect, Compton scattering and pair formation: $\mu = \mu_f + \mu_C + \mu_P$

- the attenuation coefficients depend on the atomic number Z and the energy of photons

Nuclear Physics

<u>Interaction of neutron radiation with the environment</u>

- neutrons - electrically neutral particles - they behave differently than charged particles when passing through a medium

- the interaction of neutrons with electrons via electromagnetic interaction is six orders of magnitude weaker than the electromagnetic interaction in the case of charged particle

- the passage of neutrons through the environment is mainly influenced by the strong interaction (nuclear forces) with atomic nuclei

5 basic processes triggered by strong interaction:

- the brackets (*a,b*) denote the symbolic designation of the nuclear reaction, where *a* denotes the particle hitting the nucleus *X*

- after the particle *a* collides with nucleus *X*, an interaction occurs, after which nucleus *Y* is formed, from which the particle *b* is emitted

Nuclear Physics

1) Elastic scattering (n,n) - **the initial energy of the neutron is split between the neutron and the nucleus**

- after this scattering the nucleus remains in the ground energy state

- as the mass of the nucleus decreases, the fraction of kinetic energy imparted by the neutron to the nucleus increases $\Rightarrow$ use of light nuclei to slow down neutrons in nuclear reactors

2) *Inelastic scattering (n,n)* - process only possible for neutrons with energies from 0,5 MeV až 20 MeV (fast neutrons)

- after this scattering the nucleus remains in an excited state - part of the kinetic energy of the interacting neutron is consumed for this

Nuclear Physics

3) Radiation capture (n,γ) - **the neutron is captured by the nucleus, which as a result goes into an excited state**

- during the transition of the nucleus to the ground state gamma radiation is emitted

- radiation capture is only possible for slow neutrons that have energies in the range 10^{-6} eV až 10^{-3} eV

- the above phenomenon is used to shield neutron radiation that was previously slowed down by the moderator

4) *Nuclear reactions (n,p), (n,α)* - process most likely for light nuclei

- due to the interaction, the neutron is absorbed by the nucleus and a charged particle is emitted from the nucleus

- specific examples of mentioned reactions:

(n,p) $\Rightarrow {}_{2}^{3}He + {}_{0}^{1}n \rightarrow {}_{1}^{3}H + {}_{1}^{1}p$

(n,α) $\Rightarrow {}_{3}^{6}Li + {}_{0}^{1}n \rightarrow {}_{1}^{3}H + {}_{2}^{4}\alpha$, ${}_{5}^{10}B + {}_{0}^{1}n \rightarrow {}_{3}^{7}Li + {}_{2}^{4}\alpha$

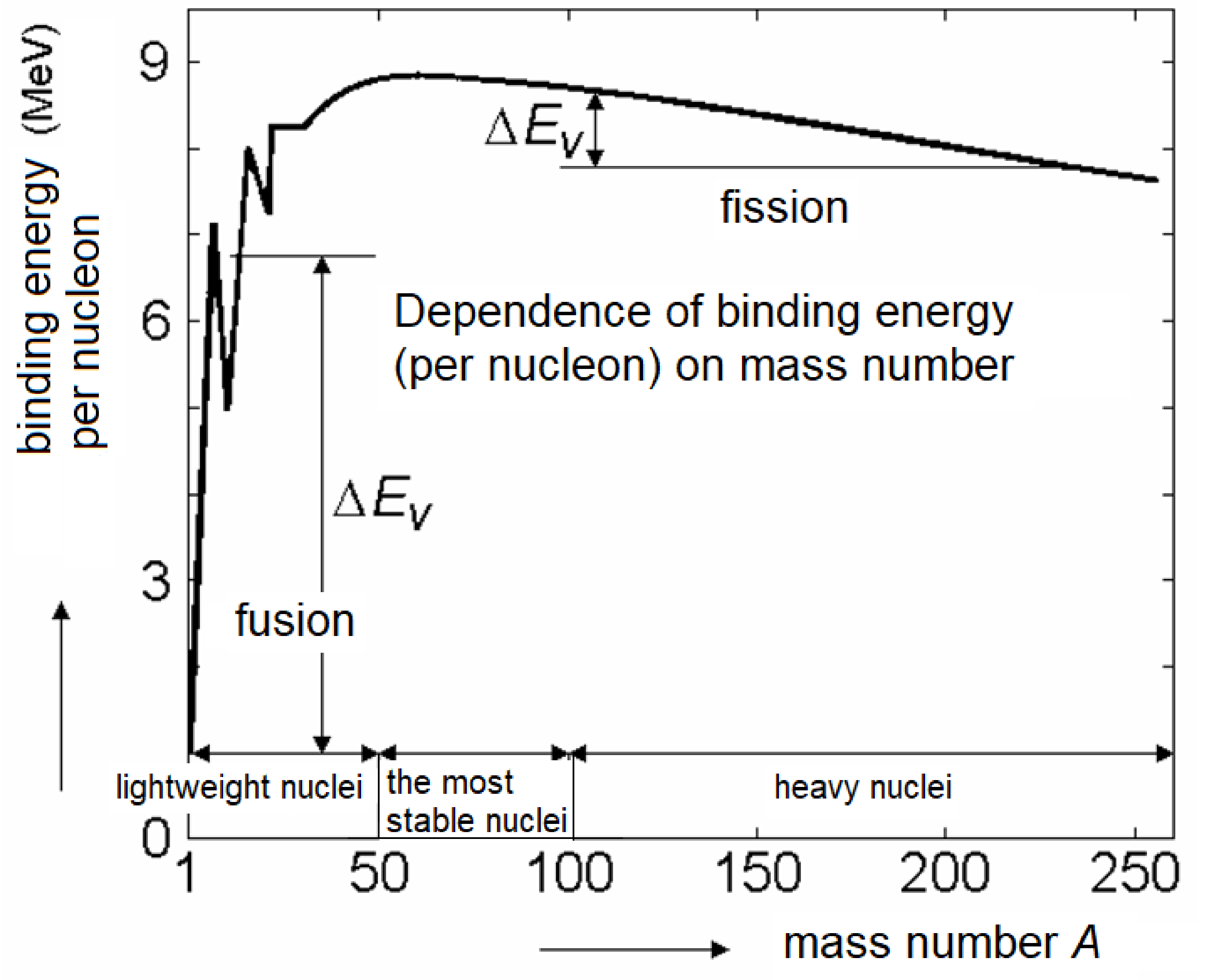
5) Fission of nuclei (n,f) **- nucleus usually split into two or three fragments *f* (fishion) due to neutron-nucleus interaction**

- two to three neutrons are released from the nucleus during fission, i.e. more than the number of neutrons that entered the interaction - this is the basis of the chain reaction, e.g. in a nuclear reactor and in a nuclear explosion

- in the case of the isotopes ${}_{92}^{233}U$, ${}_{92}^{235}U$ **and** ${}_{94}^{239}Pu$ **fission occurs due to thermal neutrons; with energies of** $5 \cdot 10^{-3}$ **eV až** $5 \cdot 10^{-1}$ **eV**

Nuclear Physics

Release of nuclear energy



Nuclear Physics

- the nucleus has a mass less than the sum of the rest masses of all the nucleons that make up the nucleus

- energy can be released by combining light nuclei into heavier ones, which are in the region of the most stable nuclei, or by splitting heavy nuclei into lighter ones again in the region of the most stable nuclei - see Fig.

- fusion of light nuclei - thermonuclear reaction or nuclear fusion - takes place spontaneously in the nuclei of stars

- the mass of the Sun consists mainly of hydrogen nuclei and free electrons; a small fraction of helium nuclei and traces of lithium nuclei

- a high temperature of the order of 10^7 K is necessary for nuclear fusion, because the nuclei are positively charged and must have sufficient energy to overcome the repulsive electrostatic forces and come within the range of the nuclear forces, i.e. at a distance of 10^{-15} m

Nuclear Physics

Examples of some of the reactions taking place in the Sun's core and the amount of energy released:

$^{1}_{1}H + ^{1}_{1}H \rightarrow ^{2}_{1}D + e^{+} + \nu_e + \gamma$
$^{2}_{1}D + ^{1}_{1}H \rightarrow ^{3}_{2}He + \gamma$
$^{3}_{2}He + ^{1}_{1}H \rightarrow ^{4}_{3}Li + \gamma$
$^{2}_{1}D + ^{2}_{1}D \rightarrow ^{3}_{2}He + ^{1}_{0}n + 3{,}26\ MeV$
$^{2}_{1}D + ^{2}_{1}D \rightarrow ^{3}_{1}T + ^{1}_{1}H + 4{,}03\ MeV$
$^{2}_{1}D + ^{3}_{1}T \rightarrow ^{4}_{2}He + ^{1}_{0}n + 17{,}6\ MeV$
$^{2}_{1}D + ^{3}_{2}He \rightarrow ^{4}_{2}He + ^{1}_{1}H + 18{,}4\ MeV$
$^{6}_{3}Li + ^{2}_{1}D \rightarrow ^{4}_{2}He + ^{4}_{2}He + 22{,}4\ MeV$
$^{6}_{3}Li + ^{1}_{1}H \rightarrow ^{3}_{2}He + ^{4}_{2}He + 4{,}02\ MeV$
$^{7}_{3}Li + ^{2}_{1}D \rightarrow ^{4}_{2}He + ^{4}_{2}He + ^{1}_{0}n + 14{,}9\ MeV$
$^{7}_{3}Li + ^{1}_{1}H \rightarrow ^{4}_{2}He + ^{4}_{2}He + 17{,}3\ MeV$

Nuclear Physics

- artificially achieving nuclear fusion:

- uncontrolled reaction - by detonating a hydrogen bomb

- controlled reaction - in devices called tokamak

- the controlled reaction has not yet been technically mastered to the point where it can be used to produce energy

- fission of heavy nuclei:

- uncontrolled reaction - nuclear explosion

- controlled reaction - in fission nuclear reactors

- controlled fission chain reaction technically mastered since 1942 (first nuclear reactor in the USA)

- fission nuclear reactors - in nuclear power stations for power generation or as a source of neutrons for scientific research

Nuclear Physics

Ionizing radiation detection

- ionizing radiation detectors - designed to determine its basic physical characteristics

- based on interactions of ionising radiation with the material environment

- detectors: gas, scintillation and semiconductor

- the final output signal from these types of detectors is usually a voltage pulse after registering one particle, which is further processed and evaluated

- the amplitude of this pulse is often proportional to the energy of the registered particle

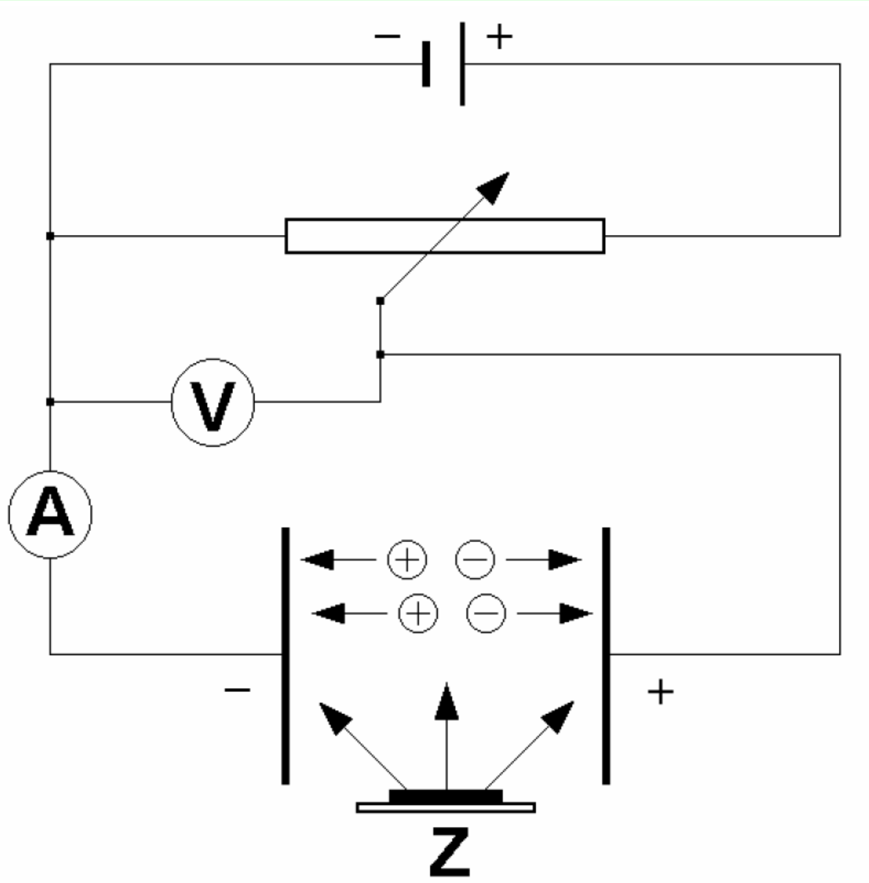
- the shape of the voltage pulse as a function of time is also important

Nuclear Physics

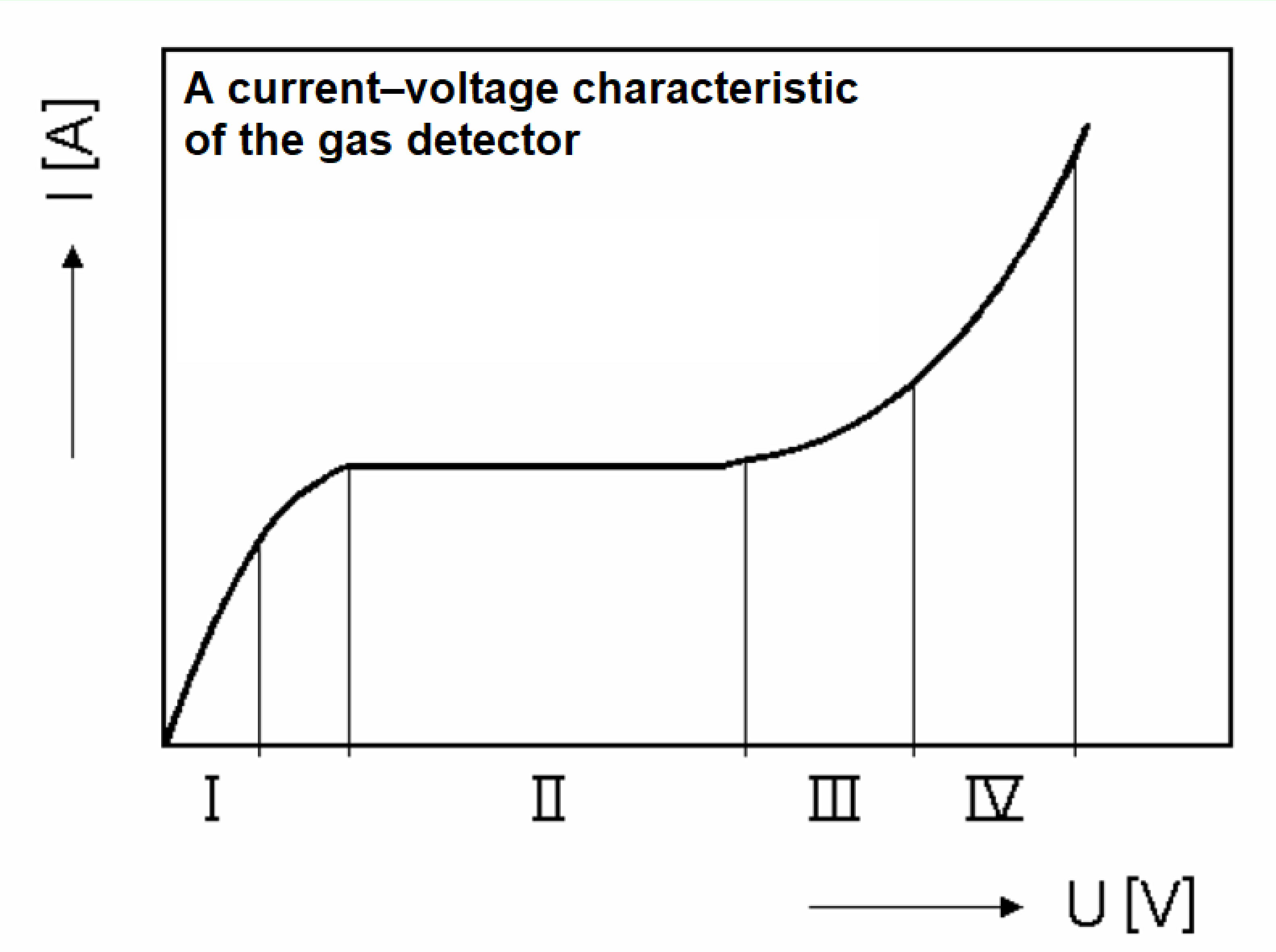
<u>Gas detectors</u>

***1) Ionization chambers*: based on the ability of ionizing radiation to ionize a gas**

- gas-filled chamber where two electrodes are placed:



Nuclear Physics



Nuclear Physics

- ionizing radiation passes through the gas detector ⇒ the gas is ionized ⇒ pairs of positively charged ions and negatively charged electrons are formed

- when there is a potential difference between the electrodes, positive ions move to the negative electrode and negative electrons move to the positive electrode ⇒ an electric current flows in a closed electrical circuit

- the speed at which electrons and ions move depends on the magnitude of the voltage between the electrodes

- at low voltage, the velocity of ions and electrons is relatively low and their recombination occurs before they reach the electrodes, since the probability of recombination increases as the mutual velocity of electrons and ions decreases

- with increasing voltage the current increases up to the so-called saturated current – in this region of the I-V characteristic all generated electrons reach the electrodes, therefore the current cannot increase with increasing voltage

Nuclear Physics

Gas amplification:

- at high voltages the electrons gain such energy when accelerated in an electric field that they ionize other gas atoms (secondary ionization), so that the current between the electrodes avalanches

2) Proportional computers**: their geometrical arrangement similar to that of ionisation chambers**

- they work in the region of proportionality III - see figure - here the impact ionization starts to appear, i.e. the electrons between two collisions gain energy in the electric field sufficient for further ionization of the gas

Nuclear Physics

***3) Geiger-Müller computers*: their arrangement similar to that of ionisation chambers or proportional computers**

- they operate in the Geiger region IV of the I-V characteristic - see Fig.

- coaxial electrode arrangement

- the pressure of the gaseous charge is usually less than 10^5 Pa

- to increase the efficiency of the detector, small amounts of organic substances such as alcohol, ethylene, trimethylboron are usually added to the gas filling

- the voltage on the electrodes of the GM computer is set below the value causing a independent discharge

- when ionizing particles pass through, the gas becomes conductive, an dependent discharge is produced and a current flows through the circuit

- voltage rises on the resistor connected in series $\Rightarrow$ across the electrodes of the GM tube the voltage drops and then the discharge is extinguished

- the electronics counts the number of pulses, i.e. the number of particles that have passed through the tube

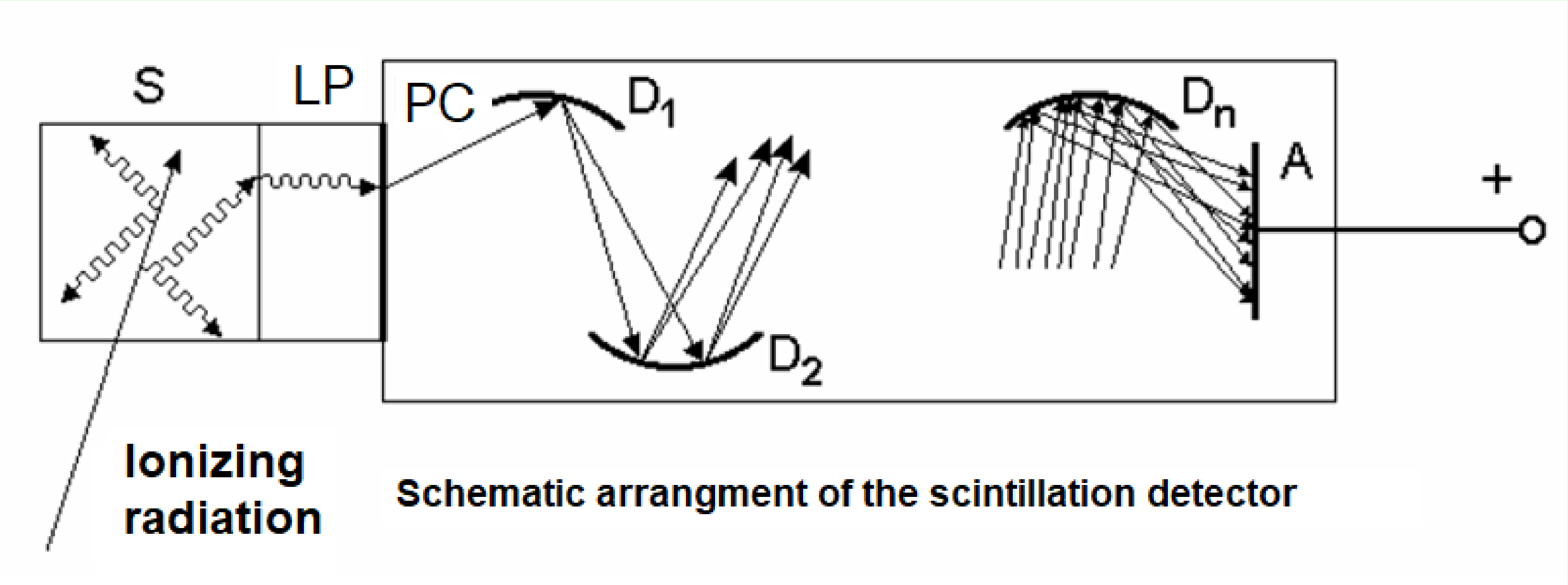
Nuclear Physics

Scintillation computers

- detection of ionizing radiation by scintillation detectors is one of the oldest methods

- principle of the method - charged particles can produce short flashes of visible or ultraviolet light in some substances

Nuclear Physics



- a particle of ionizing radiation penetrates the scintillation substance S and causes light flashes

- the resulting photons after passing through the scintillator are led through the LP light pipe to the photocathode of the PC photomultiplier

- photons induce a photoelectric effect on the photocathode

- electrons released from the photocathode fall on the electrodes in the photomultiplier - dynodes D, where the incident electron causes the emission of several other electrons

Nuclear Physics

- there are several dynodes in the photomultiplier according to the required amplification

- from the last dynode the electrons are led to the anode A, to which the capacitor C is connected via the grounding resistor R, where the passage of the ionizing particle through the scintillator results in a voltage pulse

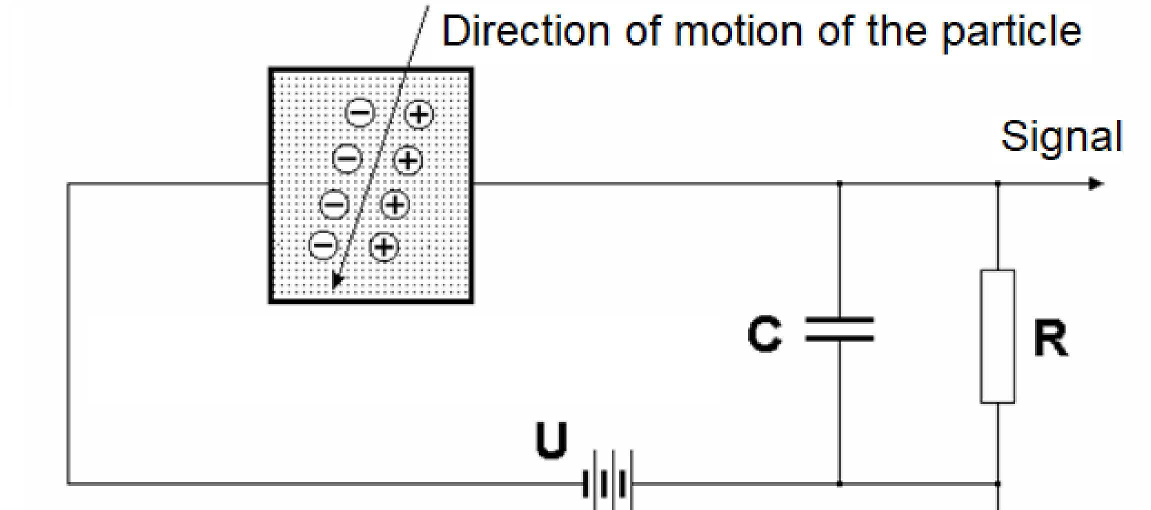
Nuclear Physics

<u>Semiconductor detectors</u>

- in semiconductor materials, electron-hole pairs are generated by the impact of an ionizing particle

- voltage applied to the detector causes electrons to flow to the positive electrode and holes to flow to the negative electrode

- the impact of the particle appears as a voltage pulse on a resistor connected in series - see Fig.



Schematic of the ionizing radiation detection arrangement radiation with a semiconductor detector

Nuclear Physics

<u>Radioactive emitters</u>

<u>Basic quantities characterizing the emitter</u>

- radioactive substances are widely used in physical research and other fields of science and technology - e.g. in medical applications

- each emitter is characterized by the type of transformation that occurs in its nuclei (alpha transformation, beta transformation, gamma-ray emission, neutron emission)

- the conversion occurs with a certain probability, i.e. with a certain half-life $T_{1/2}$, which is a constant for a given emitter

- activity characterises the amount and rate of radioactiv transformations:

$A = \frac{\mathrm{d}N}{\mathrm{d}t}$**, i.e. the fraction of the mean number of dN of spontaneous nuclear transformations from a given energy state in a given amount of radionuclide over a time interval dt and the length of this interval dt**

Nuclear Physics

- the unit of activity is the becquerel (Bq) of dimension s^{-1}

- to assess the effects of radiation on substances and living organisms, the quantity dose (absorbed dose) D, unit gray (Gy), dimension,

is used $m^2.s^{-2}$:

$D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m}$ **, where $\mathrm{d}\bar{\varepsilon}$ is the mean communicated energy, i.e. the energy imparted by ionising radiation to a substance of mass d*m* at a given location**

- batch power input: $\dot{D} = \frac{\mathrm{d}D}{\mathrm{d}t}$ (unit $Gy.s^{-1}$, dimension is $m^2.s^{-3}$),

i.e. the ratio of the dose increment d*D* over the time interval d*t* and this interval d*t*

Nuclear Physics

- the biological effect of ionising radiation depends not only on the absorbed radiation dose but also on the type of radiation

- for radiation protection purposes, it is therefore necessary to introduce a quantity that takes into account the different biological efficiencies of different types of radiation

- X-rays with an energy of 200 keV are usually used as a reference radiation source

- the biological effectiveness of the radiation relative to the effectiveness of the reference source - the quality factor *Q* - characterises the severity of the biological effects of a particular type of radiation

Nuclear Physics

- *Q*-factor values for selected radiation types:

radiation *X*, γ, β^-, β^+ 1

particles α 20

thermal neutrons 2,3

neutrons with unknown energy spectrum ………............ 10

- dose equivalent *H* - characterises the biological effects of radiation (already considering different types of radiation):

$H = D.Q.N$ (unit Sievert - Sv),

where *D* - absorbed dose (Gy),

Q - quality factor (dimensionless number),

N - modifying factor, usually equal to one

Nuclear Physics

Radioactive emitters

1) Alpha emitters **- either as natural radionuclides or can be prepared artificially by nuclear reactions**

- one of the advantages - a huge range of half-lives with relatively small differences in the energy of the emitted particles :

Examples: ^{212}Po **- alpha particles energy 8,78 MeV, half-life 3,04.10^{-7} s, vs.** ^{232}Th **- alpha particles energy 3,98 MeV, half-life 1,39.10^{10} years**

- another advantage - line energy spectrum of emitted particles - energy values determined with an accuracy of about 0.1%, i.e. units of keV

- high accuracy in determining energy values and small natural width of peaks in the spectrum ⇒ use of alpha emitters for energy calibration and determination of detector energy resolution

Nuclear Physics

<u>2) Beta emitters</u> **- emit electrons or positrons**

- emitters β^- - the emitted electrons are of natural origin or artificially prepared by nuclear reactions

- emitters β^+ - emitted positrons are not found in nature, they can only be prepared artificially by nuclear reactions in accelerators or nuclear reactors

- for both electron and positron emission: the greater the energy released during the transformation, the shorter the beta conversion half-life

- shortest half-lives in beta conversion in the order of 10^{-2} s - to that corresponds the energy of about 10 MeV released during the conversion

- the energy spectrum of beta radiation is continuous, the characteristic quantity is the maximum energy in the spectrum

Nuclear Physics

- the resulting nucleus is usually in an excited state after beta conversion $\Rightarrow$ virtually simultaneously with the emission of electrons or positrons, gamma rays are emitted

- when the beta-emitter is a positron source, photons with an energy of 0.511 MeV are additionally produced in the material of the emitter or pad due to the annihilation of positrons with electrons

3) Radioactive gamma radiation sources **- usually radionuclides undergoing beta conversion**

- the advantage is the possibility of achieving high activity

- the energy of emitted gamma radiation for different radionuclides is in the intervalfrom a few keV up to 20 MeV

Nuclear Physics

4) Sources of neutrons **– those sources involving nuclear reactions of the type (α, *n*) or (γ, *n*) using a radioactive emitter as a source of alpha particles or gamma radiation**

- use of e.g. highly probable reaction: $^{9}_{4}Be + ^{4}_{2}He \rightarrow ^{12}_{6}C + ^{1}_{0}n$

- for reactions of type (α, *n*), either ^{210}Po **or** ^{226}Ra **is used as a source of alpha particles from radioactive emitters**

- for reactions of type (γ, *n*) nuclides nuclei can be used as radioactive emitters $^{9}_{4}Be$ **and** $^{2}_{1}H$

- the largest neutron fluxes nuclear reactors provide - up to 10^{18} neutrons per second with energies from 10^{-3} eV up to 20 MeV emerge from the entire surface of the reactor core