Chapter 23. X-RAYS

X-rays are a form of electromagnetic radiation with a wavelength in the range of **80** to $\mathbf{10^{-5}}$ nanometers. They are longer than γ-rays but shorter than ultraviolet rays. If X-rays have short wavelength they are called **hard** X-rays. On the other hand, the long-wave radiation is classified as **soft** X-rays. X-rays is divided into **bremsstrahlung** and **characteristic** X-rays according to the mechanism of their formation.

In many languages, X-radiation is called Röntgen radiation, after Wilhelm Conrad Röntgen, who is credited as its discoverer, and who had named it X-radiation to signify an unknown type of radiation.

23.1. BREMSSTRAHLUNG X-RAYS

Bremsstrahlung X-rays («braking radiation» or «deceleration radiation») is electromagnetic radiation produced by the deceleration of a charged particle when deflected by another charged particle, typically an electron by an atomic nucleus. The moving particle loses kinetic energy, which is converted into a heat and a photon because energy is conserved. It is characterized by a continuous distribution of radiation (continuous spectrum) which becomes more intense and shifts toward higher frequencies when the energy of the bombarding electrons is increased.

In medicine X-rays is produced in a highly evacuated glass bulb, called an ***X-ray tube*** (fig. 23.1). It contains two electrodes — an anode made of molibdenun, tungsten, or another heavy metal of high melting point, and a cathode. When a high voltage is applied between the electrodes, streams of electrons (cathode rays) are accelerated from the cathode to the anode and produce X rays as they strike the anode. The focusing electrode directs

the electron beam towards the anode. Some part of the electron kinetic energy turns into the energy of X-rays. The other part of this energy passes into heat so the temperature of the anode rises. Therefore anode is kept cool by means of air, water or oil cooling arrangement.

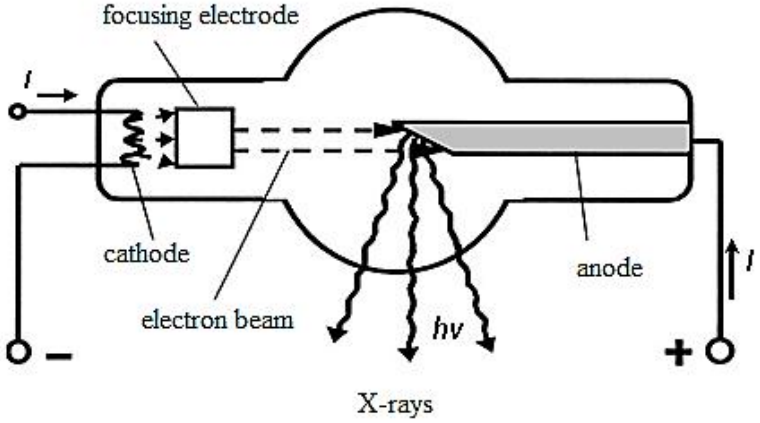

Fig. 23.1. X-Rays tube

The kinetic electron energy obtained in the electric field between the cathode and the anode can be written as:

$$\frac{mv^2}{2} = eU, \qquad (23.1)$$

where ***m*** is the mass of an electron, ***v*** is the velocity, ***e*** its charge, ***U*** is the applied electrical potential difference between the cathode and the anode.

When an electron hits the target its entire kinetic energy is converted into both photon energy ***hv*** and heat ***Q***:

$$eU = hn + Q. \qquad (23.2)$$

A relation between summands in right part of this equation (23.2) is random. Therefore the different frequencies are observed in the bremshtralung radiation spectrum. Bremsstrahlung X-rays has a continuous spectrum in which the intensity varies smoothly with wavelength. This spectrum has a definite short wavelength λ_{min} below which there is no radiation.

The ***minimum wavelength*** λ_{min} corresponds to maximum frequency n_{max}. If the magnitude of the voltage ***U*** is known the numerical value of λ_{min} can be calculated. Let's assume that $Q = 0$ (all kinetic electron energy turns into the radiation). Thus:

$$hn_{max} = \frac{hc}{\lambda_{min}} = eU \Rightarrow \lambda_{min} = \frac{hc}{eU}. \qquad (23.3)$$

where ***c*** is velocity of light.

Put the values of constants ***h***, ***c*** and ***e*** the minimum wavelength λ_{min} can be written:

$$\lambda_{min}(nm) = \frac{1{,}23}{U(kV)}. \qquad (23.4)$$

The curve of bremsstrahlung X-rays spectrum for each voltage starts at a particular minimum wavelength, rises rapidly to a maximum and drops gradually but indefinitely towards the longer wavelengths (fig. 23.2). Minimum wavelength λ_{min} depends on the tube voltage U. The higher voltage U the smaller value of the minimum wavelength λ_{min} (23.4).

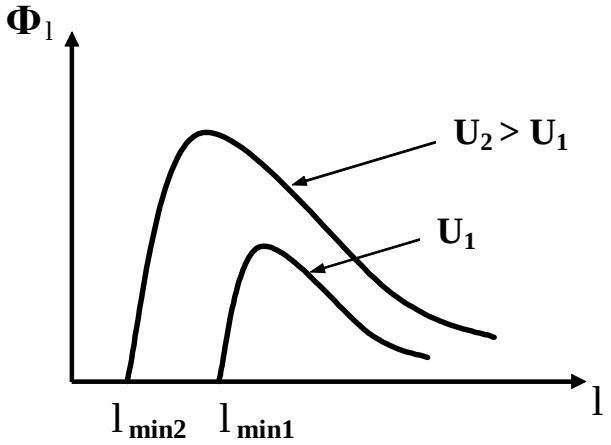

Fig. 23.2. The spectrum of the bremsstrahlung X-rays for different voltages U_1 and U_2 applied between cathode and anode

The spectrum of the bremsstrahlung X-rays is spectral distribution of a radiant flux, where the radiant flux Φ is determined by the number of light quanta falling on the surface in time unite.

A total radiant flux Φ of X-rays depends on current I and voltage U in the X-rays tube and determined by formula:

$$\Phi = k\, I\, U^2\, Z, \qquad (23.5)$$

where Z is the atomic number, k is the coefficient proportionality $k = 10^{-9}$ (V^{-1}).

As can see from fig 23.3 the λ_{min} is the same for different current values (I_1 and I_2) in the X-rays tube when U is constant. Therefore the radiant flux rises but the radiation hardness remains unchanged.

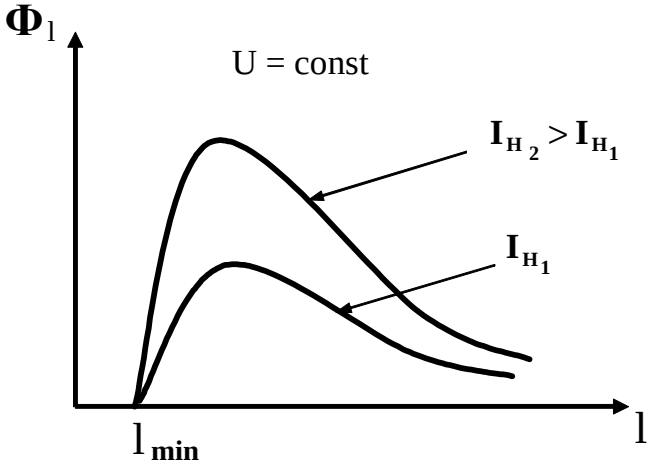

Fig. 23.3. The spectrum of the bremsstrahlung X-rays for different value of current in the X-rays tube

23.2. CHARACTERISTIC X-RAYS

If the bombarding electrons have sufficient energy, they can knock an electron out of an inner shell of the target metal atoms. Then electrons from higher states drop down to fill the vacancy, emitting x-ray photons with precise energies determined by the electron energy levels (fig. 23.4). These x-rays are called ***characteristic x-rays***.

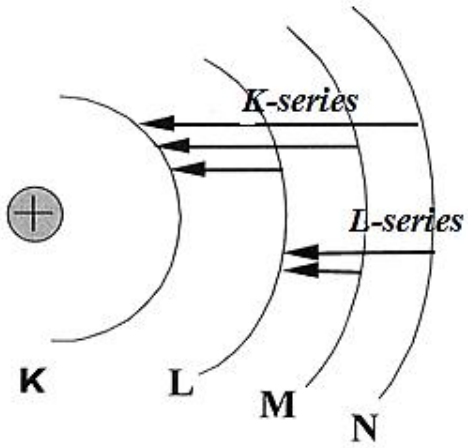

Fig. 23.4. Characteristic x-rays

This process produces an emission spectrum of X-rays at a few discrete frequencies, sometimes referred to as the spectral lines. The spectral lines generated depend on the target (anode) element used and thus are called characteristic lines. Usually these are transitions from upper shells into K shell (called K lines), into L shell (called L lines) and so on.

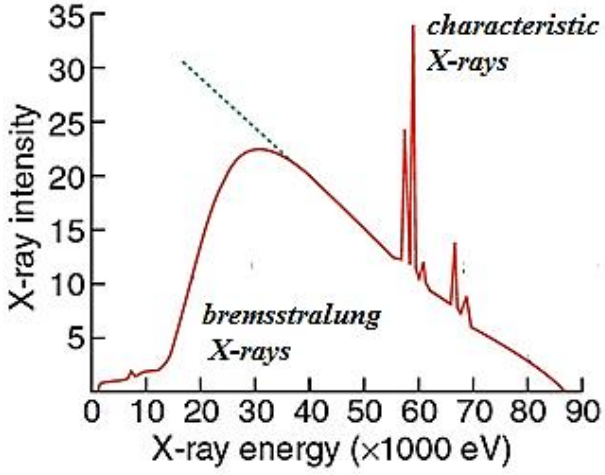

Fig. 23.5. X-rays spectrum

The frequency n of the characteristic X-rays rises as the atomic number Z increases. This relation is known as a ***Moseley Law***:

$$\sqrt{\nu} = A(Z - B), \qquad (23.6)$$

where A and B are constant.

23.3. INTERACTION BETWEEN X-RAY AND MATTER

Let's consider an interaction between quanta of X-rays and atoms and molecules of the matter. Obviously, the result of this interaction depends on the energy of the quantum. There are several different cases.

1. The quantum energy $\boldsymbol{hn}$ of X-rays is smaller than the energy of the atomic ionization $\boldsymbol{A_i}$ ($hn < A_i$). Such interaction is called a ***coherent scattering***. It is a process in which the photon is scattered on the entire atom. That is, the internal energy of the atom does not change. In this case the energy of the incident photon equals the energy of the scattered photon. Only soft X-ray experiences a coherent scattering (fig. 23.6, *a*). This is not an ionizing interaction.

2. The quantum energy $\boldsymbol{hn}$ is slightly greater than the energy of the atomic ionization $\boldsymbol{A_i}$ ($hn \geq A_i$). In this case, the quantum energy $\boldsymbol{hn}$ is spent on atom ionization $\boldsymbol{A_i}$ and kinetic energy of electron $\frac{mv^2}{2}$:

$$h\nu = \frac{mv^2}{2} + A_i. \qquad (23.7)$$

This phenomenon is known as a photoelectric effect or ***photoeffect*** (fig. 23.6, *b*).

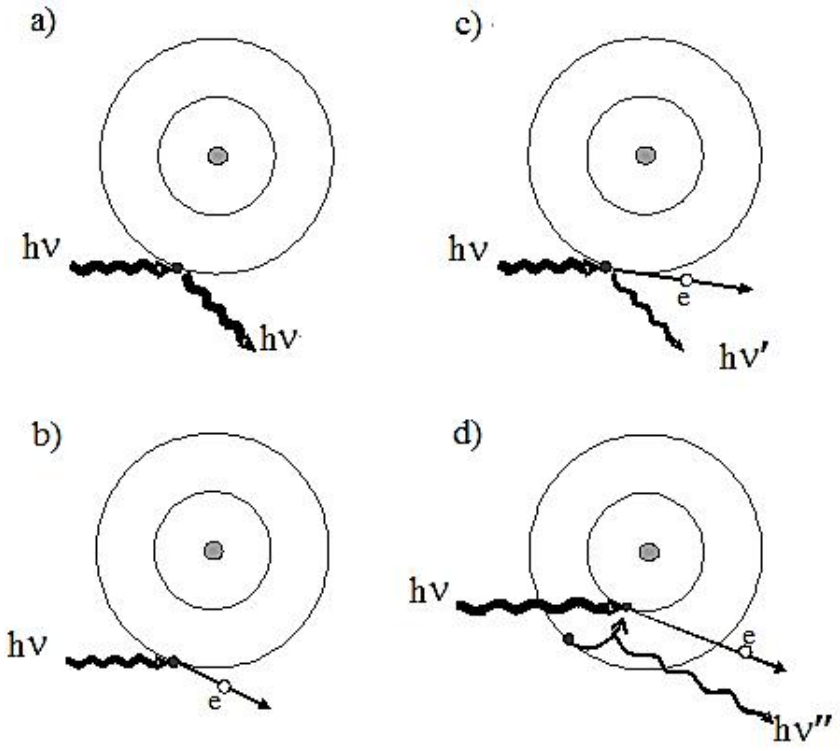

Fig. 23.6. Interaction between X-ray and matter

3. The quantum energy $\boldsymbol{h}$n is much greater than the energy of the atomic ionization $\boldsymbol{A_i}$ ($h\nu >> A_i$). A photon interacts with an electron, but in contrast to the photoelectric effect, only a part of the photon energy is transferred to the electron. The photon continues on its way, but with reduced energy $h\nu'$ (i. e.,

a lower frequency). This effect is called a ***Compton scattering*** or incoherent scattering (fig. 23.6, *c*). The electron is still emitted from its shell. In addition the electron obtains a kinetic energy $E_к$:

$$h\nu = A_i + h\nu' + E_к. \qquad (23.8)$$

If the electron is ejected from interior shells then the characteristic X-ray appears.

Secondary X-rays have energy $h\nu' > A_i$, and can produce the ionization of the matter again. Recoil electrons can also ionize adjacent atoms by means of a collision (fig. 23.6, *d*).

High-energy photons experience more Compton scattering than low energy photons. Unfortunately, Compton scattering is the major source of background noise in X-ray images. In addition, Compton scattering is the major source of tissue damage due to X-rays. For these reasons, this phenomenon X-rays is applied in medicine for damage cancer tumors.

23.4. ATTENUATION OF X-RAYS

When the X-rays pass through the matter, its intensity falls due to its absorption and scattering by the matter. The character of attenuation depends on the energy of X-rays, nature (i. e. wavelength) and thickness of matter. Let $\boldsymbol{I_0}$ be an initial intensity of X-rays incidents normally on a material and $\boldsymbol{I}$ be an intensity of the X-rays after traveling a distance $\boldsymbol{x}$ in the material (fig. 23.7). The attenuation of X-rays is described by the exponential law:

$$I = I_0\, e^{-\mu X}, \qquad (23.9)$$

where $\mu = \mu_{\text{absorption}} + \mu_{\text{scattering}}$ is the ***linear attenuation coefficient*** of material. It depends on material density ρ.

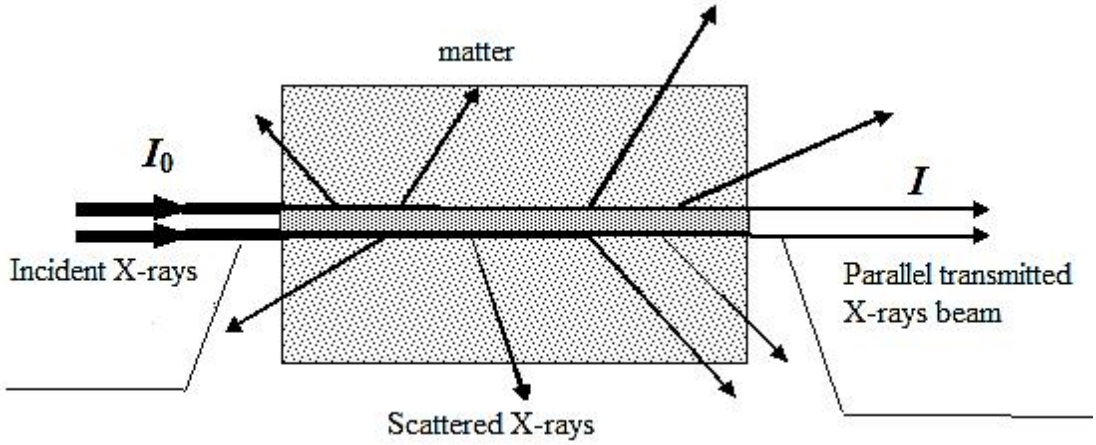

Fig. 23.7. Decrease in the intensity of X-ray through matter

A ***mass attenuation*** factor $\boldsymbol{\mu_m}$ is used also: $\mu_m = \mu/\rho$, this coefficient is independent on a density of material.

The beam of X-rays encloses quanta with different energy. They have different penetrating power. Therefore the coefficient μ in equation (23.9) is

constant only for monoenergetic X-ray photons. For X-rays with different photon energies the effective attenuation coefficient is used.

Let's estimate the penetrating power of X-rays. In practice a half-value layer is used, which is the thickness required to attenuate the beam intensity by 50 % (fig. 23.8). One can relate the half-value layer to the linear attenuation coefficient analytically. If in equation 23.9 $x = d_{1/2}$, then $I = I_0/2$:

$$I_0/2 = I_0 e^{-\mu d_{1/2}}$$

$$e^{+\mu d_{1/2}} = 2$$

$$\ln e^{+\mu d_{1/2}} = \ln 2$$

$$\mu d_{1/2} = \ln 2 = 0{,}69$$

Thus:
$$d_{1/2} = \frac{\ln 2}{\mu} = \frac{0{,}69}{\mu}. \qquad (23.10)$$

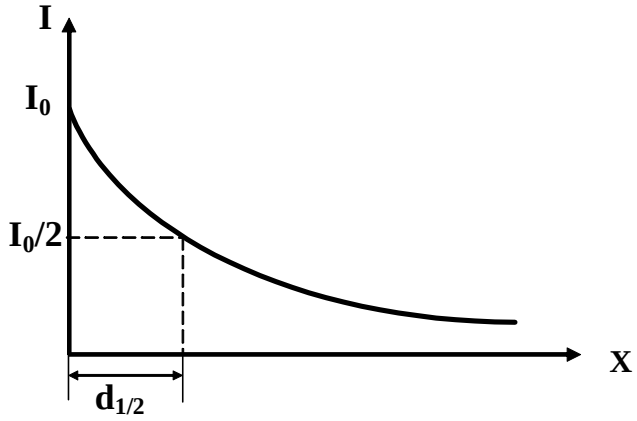

Fig. 23.8. Attenuation of X-rays passing through the matter

For example, the half-value layer for X-rays is equal 10 mm of water or 1 mm of aluminium when the applied in X-rays tube voltage ***U*** is 60 kV.

The half-value layer is a function of the energy of X-ray beam. Therefore a spectral composition of X-ray changes when the beam goes through the half-value layer. The radiation becomes harder because short rays have a big penetrating power. Soft X-rays are absorbed more strongly. This phenomenon is called «beam hardening».

23.5. PHYSICAL PRINCIPLES OF THE X-RAY DIAGNOSTICS

The mass attenuation coefficient μ_m of X-rays depends on the matter composition and the wavelength:

$$\mu_m = k \lambda^3 Z^3, \qquad (23.11)$$

where ***k*** is a coefficient of proportionality; ***Z*** is an atomic number of the material; l is a wavelength.

From equation 23.11 one can see that the mass attenuation coefficient μ_m is increases with the increasing of the atomic number ***Z*** and depends on the photon

energy. This is a basis of the medical X-rays diagnostics. The purpose of this diagnostic is to measure features of the internal anatomy of a patient through differences in the attenuation of X-rays passing through different parts of the body.

A simplified model of the human body consists of three different body tissues: fat, muscle, and bone. Air is also present in the lungs, sinuses and gastrointestinal tract. A ***contrast agent*** — a material with high ***Z*** number — may be used to accentuate the attenuation of X-rays in a particular region.

X-rays interact in fat and other soft tissues predominantly by photoelectric interactions. Low-energy X-rays are used to accentuate subtle differences in soft tissues (e. g., fat, mussels and other soft tissues) in applications such as breast imaging (mammography) where the object (the breast) provides little intrinsic contrast. When images of structures with high intrinsic contrast are desired (e. g., the chest where bone, soft tissue, and air are present), higher-energy X-rays are used. These X-rays suppress X-ray attenuation in bone which otherwise would create shadows in the image that could hide underlying soft-tissue pathology.

In comparison with muscles and bones, fat has a higher concentration of hydrogen (~ 11 %) and carbon (~ 57 %) and a lower concentration of nitrogen (~ 1 %), oxygen (30 %) and high-Z trace elements (< 1 %). Hence, the effective atomic number of fat (Z_{eff} = 5,9 to 6,3) is less than that of soft tissues (Z_{eff} = 7,4) or bones (Z_{eff} = 11,6 to 13,8). Because of its lower Z_{eff}, low-energy photons are attenuated less rapidly in fat than in an equal mass of soft tissues or bones.

The effective atomic number and physical density are greater for bones than for soft tissues. Hence, X-rays are attenuated more rapidly in bone than in an equal volume (not necessarily mass) of soft tissue.

There are many X-ray based procedures used in medical diagnosis, for example, fluoroscopy, mammography, X-rays computer tomography. Spiral computer tomography provides images can be displayed in three dimensions. The X-rays tomography allows receiving a layerwise image when a difference between attenuation coefficients is equal 0,1 %.

***Questions*:**

1. Describe the bremsstrahlung X-rays appearence mechanism. Why does it have continuous spectrum? How to determine the minimum wavelength?
2. How to control the intensity and the hardness of radiation in the X-rays tube? Write the formula for bremsstrahlung X-rays radiant flux?
3. Compare the thermal radiation spectrum with the X-rays one. Discuss their similarity and differences.
4. Discuss the differences between the optical spectrum formation mechanisms and characteristic X-rays one.
5. Describe the interaction between X-rays and matter mechanisms. Why is the hard X-rays more harmful for an organism than the soft X-rays?
6. Write exponential law for X-rays attenuation in matter. What is the linear attenuation coefficient? Describe its relation with the half-value layer.
7. Compare the physical principles of ultrasound and X-rays one.

Chapter 24. RADIOACTIVITY

Radioactive decay is the process in which unstable atomic nucleus (called radionuclide) emits radiation in the form of particles and electromagnetic waves. This decay results in an atom of one type, called the parent nuclide transforming to an atom of a different type, called the daughter nuclide.

24.1. CHARACTERISTICS OF NUCLEUS

An atom consists of a positively charged nucleus surrounded by a cloud of negatively charged electrons. Nuclei consist of positively charged ***protons***, and electrically neutral ***neutrons*** held together by the so-called strong or nuclear force.

Let's point basic properties of the nuclear force. The nuclear force is related to a ***strong interaction***. At short distances, the nuclear force is stronger than the Coulomb force; it can overcome the Coulomb repulsion of protons inside the nucleus. It is a ***short-range force***, its range is limited to distances about 10^{-15} meters. The nuclear force is nearly independent of whether the nucleons are neutrons or protons. This property is called ***charge independence***. Every nucleon interacts with a limited number of adjacent nucleons (***property of saturation***).

The nuclear symbol is $^{A}_{Z}\mathbf{X}$. It consists of three parts: the symbol of the element ***X***, the atomic number of the element ***Z*** and the mass number of the specific isotope ***A***.

The number of protons in the nucleus, Z, is called the ***atomic number***. It determines the electric charge of nucleus and what chemical element the atom is. The number of neutrons in the nucleus is marked by ***N***. The given element can have many different isotopes, which differ from each other by the number of neutrons contained in the nuclei. The ***atomic mass number*** of the nucleus can be written as: $\boldsymbol{A = Z + N}$.

The sizes of nuclei grow through the periodic table. The nuclear radius ***R*** and the atomic mass number ***A*** are related by formula:

$$\boldsymbol{R = 1{,}5 \times 10^{-15} \times \sqrt[3]{A}\ (m).} \qquad (24.1)$$

The ***nuclear charge*** is equal to $\boldsymbol{q = Ze}$. ***Nuclear stability*** depends on the atomic number ***Z*** and on the number of neutrons ***N***. The light atomic nuclei contain practically as many neutrons as protons ($\boldsymbol{N/Z} = 1$). They are the most stable. In case $\boldsymbol{N/Z > 1{,}6}$ the atomic nuclei are unstable and undergo a radioactive disintegration.

The unit of energy commonly used in atomic and nuclear physics is the electron volt (eV):

$$1\ \text{eV} = 1{,}6 \cdot 10^{-19}\ \text{C} \cdot 1\text{V} = 1{,}6 \cdot 10^{-19}\ \text{J}.$$

Thus:

$$1\ \text{keV} = 1000\ \text{eV} = 1{,}6\cdot10^{-16}\ \text{J}$$
$$1\ \text{MeV} = 10^{6}\ \text{eV} = 1{,}6\cdot10^{-13}\ \text{J}.$$

24.2. MODES OF RADIOACTIVE DECAY

Unstable atoms undergo a radioactive decay in order to have a more stable configuration. For all types of radioactive decay conservation laws of mass number, electrical charge, total energy and impulse are performed.

Alpha-decay is a type of radioactive decay in which an atomic nucleus emits an alpha particle ${}^{4}_{2}\alpha$ (a helium nucleus ${}^{4}_{2}\text{He}$) and transforms into an atom with a mass number on **4** less and atomic number on **2** less.

Alpha-decay proceeds according to the following scheme:

$${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha + [\gamma]. \qquad (24.2)$$

As any type of decay, α-decay can be accompanied by the emission of γ-rays, for example:

$${}^{239}_{94}\text{Pu} \rightarrow {}^{235}_{92}U + {}^{4}_{2}\alpha + \gamma.$$

It often happens that the nuclei appeared as a result of radioactive transformation are also radioactive and decay. The new decay product may again be radioactive until stable nucleus is formed.

Beta-decay is accompanied by the interconversion between neutrons and protons inside a nucleus. There are three varieties of beta-decay:

1. ***Negative beta-decay.***

In negative beta-decay an unstable nucleus ejects from itself an energetic electron ${}^{0}_{-1}\beta$ and an antineutrino $\widetilde{{}^{0}_{0}\nu}$ (with no rest mass), and a neutron ${}^{1}_{0}n$ in the nucleus is converted into a proton:

$${}^{1}_{0}\text{n} \rightarrow {}^{1}_{1}p + {}^{0}_{-1}\beta + \widetilde{{}^{0}_{0}\nu}. \qquad (24.3)$$

Thus, negative beta decay results in a daughter nucleus, the proton number (the atomic number) of which is one more than its parent but the mass number (the total number of neutrons and protons) of which is the same ${}^{A}_{Z\text{-}1}Y$:

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{-1}\beta + \widetilde{{}^{0}_{0}\nu} + \gamma. \qquad (24.4)$$

Neutrino ${}^{0}_{0}\nu$ is an elementary particle that travels close to the speed of light, having no electric charge, little or no mass. It is able to pass through matter undisturbed and is thus extremely difficult to detect. The difference between neutrino ${}^{0}_{0}\nu$ and antineutrino $\widetilde{{}^{0}_{0}\nu}$ consists of the opposite direction of spins.

Energy emitted by the β-decay is distributed randomly between an electron and an antineutrino. Therefore the kinetic energy of emitted β-particles takes all possible values, from 0 to $E_{\max}$. Thus the kinetic energy of the β -particles has a continuous spectrum (fig. 24.1).

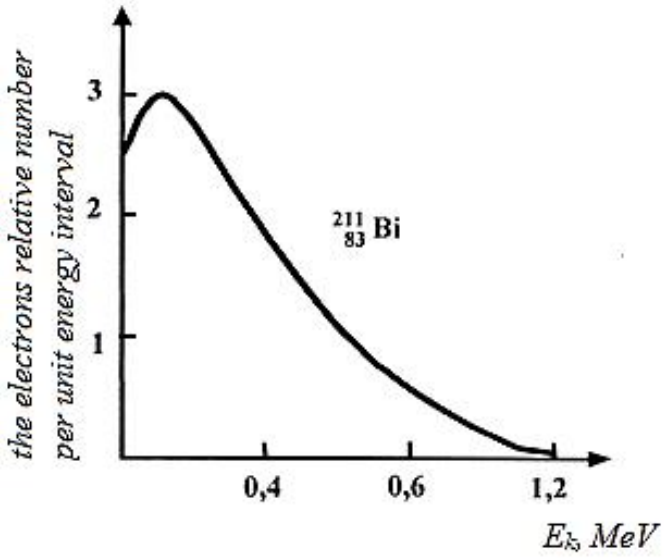

Fig. 24.1. β-particles kinetic energy spectrum

There are examples of the beta negative decay:

$$^{137}_{55}\text{Cs} \rightarrow {}^{137}_{56}\text{Ba} + {}^{0}_{-1}\beta + \widetilde{{}^{0}_{0}} + \gamma$$

$$^{131}_{53}\text{I} \rightarrow {}^{131}_{54}\text{Xe} + {}^{0}_{-1}\beta + \widetilde{{}^{0}_{0}\nu} + \gamma$$

$$^{90}_{38}\text{Sr} \rightarrow {}^{90}_{39}\text{Y} + {}^{0}_{-1}\beta + \widetilde{{}^{0}_{0}\nu}$$

$$^{90}_{39}\text{Y} \rightarrow {}^{90}_{40}\text{Zr} + {}^{0}_{-1}\beta + \widetilde{{}^{0}_{0}\nu}$$

2. ***Positive beta-decay***

In positive beta-decay a proton ${}^{1}_{1}p$ in the parent nucleus transforms into a neutron ${}^{1}_{1}n$ that remains in the daughter nucleus and ejects a ***positron*** ${}^{0}_{+1}\beta$, which is a positive particle like an ordinary electron in mass but of opposite charge, along with a neutrino ${}^{0}_{0}\nu$, which has no mass:

$$^{1}_{+1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}\beta + {}^{0}_{0}\nu. \qquad (24.5)$$

Thus, positive beta decay produces a daughter nucleus, the atomic number of which is one less than its parent and the mass number of which is the same:

$$^{A}_{Z}X \rightarrow {}_{Z-1}{}^{A}Y + {}^{0}_{+1}\beta + {}^{0}_{0}\nu. \qquad (24.6)$$

For example:

$$^{30}_{15}\text{P} \rightarrow {}^{30}_{14}\text{Si} + {}^{0}_{+1}\beta + {}^{0}_{0}\nu.$$

3. ***Electron capture***

In ***electron capture***, nucleus captures an electron located on inner atom orbit (fig. 24.2). The captured electron ${}^{0}_{-1}\beta$ combines with a nuclear proton ${}^{1}_{+1}p$ to produce a neutron ${}^{1}_{0}n$ and a neutrino ${}^{0}_{0}\nu$, which is ejected:

$$^{1}_{1}p + {}^{0}_{-1}\beta \rightarrow {}^{1}_{0}n + {}^{0}_{0}\nu. \qquad (24.7)$$

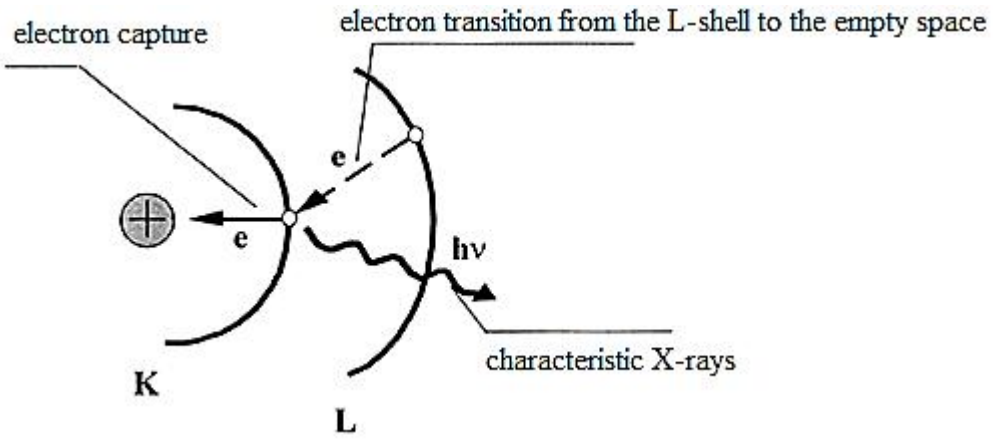

Fig. 24.2. Electron capture

As in positron emission, the nuclear positive charge and hence the atomic number decreases by one unit, and the mass number remains the same. Electron capture is accompanied by the following electron transitions to empty spaces with characteristic X-rays producing. An example of electron capture is the transformation of beryllium ${}^{7}_{4}\mathrm{Be}$ into lithium ${}^{7}_{3}\mathrm{Li}$:

$$ {}^{7}_{4}\mathrm{Be} + {}^{0}_{-1}\beta \rightarrow {}^{7}_{3}\mathrm{Li} + {}^{0}_{0}\nu. $$

24.3. NUCLEAR REACTIONS

A ***nuclear reaction*** is a process in which two nuclei or nuclear particles collide to produce particles different from the initial particles.

The first nuclear reaction was carried by Ernest Rutherford, who bombarded nitrogen ${}^{14}_{7}\mathrm{N}$ with alpha particles ${}^{4}_{2}\alpha$:

$$ {}^{14}_{7}\mathrm{N} + {}^{4}_{2}\alpha \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{P}. $$

It is necessary to accelerate elementary particles up to high energy for this process. Then a charged particle can overcome the electrostatic repulsion force of nuclear protons.

Another method of the nuclear reaction realization is ***neutron activation***. A stable nucleus ${}^{\mathrm{A}}_{\mathrm{Z}}X$ absorbs a neutron ${}^{1}_{0}n$ and changes into a radionuclide ${}^{\mathrm{A+1}}_{\mathrm{Z}}X$ of this element:

$$ {}^{A}_{Z}X + {}^{1}_{0}n \rightarrow {}^{A+1}_{Z}X. \qquad (24.8) $$

It is possible to obtain radioactive cobalt by this way:

$$ {}^{59}_{27}\mathrm{Co} + {}^{1}_{0}n \rightarrow {}^{60}_{27}\mathrm{Co}. $$

Radioactive cobalt ${}^{59}_{27}\mathrm{Co}$ is subjected to electron decay:

$$ {}^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + {}^{0}_{-1}\beta + \widetilde{{}^{0}_{0}\nu} + \gamma. $$

Gamma-radiation which appears in this reaction is used in radiotherapy for the destruction of malignant tumors.

Moderated neutrons are more useful for nuclear reactions because fast neutrons can experience elastic collisions with a nucleus and scatter.

24.4. RADIOACTIVE DECAY LAW

Following to the ***radioactive decay Law*** one can say that the number of undecayed nuclei ***N*** decreases exponentially with time ***t***:

$$N = N_0\, e^{-\lambda t}, \qquad (24.9)$$

where **λ** is a constant characteristic of the given radioactive substance and known as the ***decay constant***, N_0 is the initial number of undecayed nuclei at the time $t = 0$.

The time during which a half of the initial number of nuclei N_0 decays is called the ***half-life T***. It is determined by the condition:

$$\frac{1}{2}N_0 = N_0\, e^{-\lambda T} \Rightarrow 2 = e^{-\lambda T}.$$

Finally:
$$T = \frac{\ln 2}{\lambda} \approx \frac{0{,}69}{\lambda}. \qquad (24.10)$$

The half-life time can be determined from fig. 24.3:

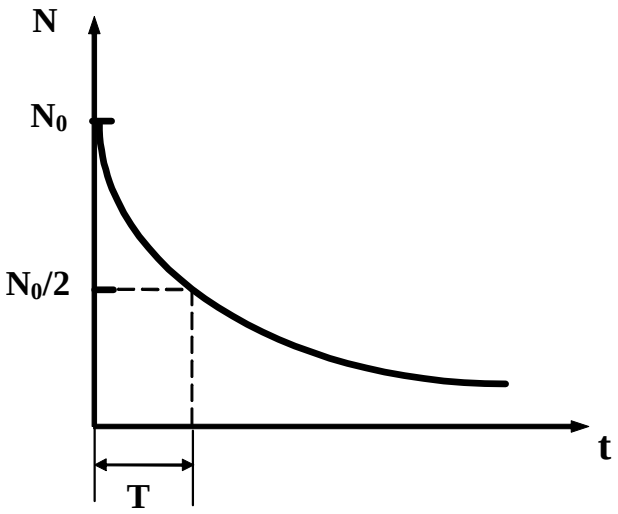

Fig. 24.3. Dependence of the number of undecayed nuclei ***N*** on time ***t***

The time during during which the number of undecayed nuclei decrease in ***e*** time is called ***mean lifetime***. There is following relation between **τ**, **λ** and ***T***:

$$\tau = \frac{1}{\lambda} = \frac{T}{0{,}69}. \qquad (24.11)$$

24.5. RADIOACTIVE SUBSTANCE ACTIVITY

The ***activity*** of a radioactive preparation ***A*** is defined as a number of disintegrations per unite time. On other words the ***activity A(t)*** is the number of radioactive transformations per second:

$$A = -\frac{dN}{dt}. \qquad (24.12)$$

Let's put (24.9) in (24.12) and differentiate with respect to time:

$$A = -\frac{dN}{dt} = \lambda N = \lambda (N_0 \cdot e^{-\lambda t}) = A_0 e^{-\lambda t}. \quad (24.13)$$

Then:

$$A = \lambda N = 0{,}69\frac{N}{T}. \quad (24.14)$$

The SI unit of activity ***A*** is the ***becquerel*** (Bq): 1 Bq = 1 transformations· s^{-1}.

Another unit of activity is the ***curie*** (Ci): 1 Ci = 3,7 · 10^{10} Bq. One curie is defined to be equal to the disintegration rate of 1 gm of ^{226}Ra, or 3,7 · 10^{10} disintegrations per second (d/s).

Activity ***A*** decreases with time exponentially:

$$A = A_0\, e^{-\lambda t}. \quad (24.15)$$

Let's relate the activity ***A*** with radionuclide mass ***m***. The number of undecayed nuclei ***N*** is determined as:

$$N = \frac{m}{m_N},$$

where ***m*** is a nuclei mass, m_N is one nucleus mass.

The one nucleus mass m_N can be found from following formula:

$$m_N = \frac{M}{N_A},$$

where ***M*** is an atomic mass, N_A is Avogadro constant.

$$A = \frac{0{,}69 \cdot N}{T} = \frac{0{,}69 \cdot m \cdot N_A}{TM} = \frac{0{,}69 \cdot 6{,}02 \cdot 10^{23} \cdot m}{TM} = 4{,}17 \cdot 10^{23}\frac{m}{TM}. \quad (24.16)$$

The activity of substance depends on its mass, thus the ***unit-mass activity*** A_m is used for determination of the object radiation pollution. The unit-mass activity is measured in Bq/kg or Ci/kg. It is determined as $A_m = \frac{A}{m}$.

The concentration of radionuclides in liquid or in gas is characterized by the ***specific volume activity*** A_v (unit is Bq/m^3, Bq/l, Ci/l). It is determined by the formula: $A_V = \frac{A}{V}$.

The ***specific surface activity*** A_s (Bq/m^2, Ci/m^2) characterizes the radioactive surface pollution and is determined by the formula: $A_S = \frac{A}{S}$.

24.6. INTERACTION OF THE IONIZING RADIATION WITH THE MATTER

Ionizing radiation produces ions during the interaction with atoms in the matter. There are several types of ionizing radiation. Alpha-particles $^4_2\alpha$, beta-particles $^0_{-1}\beta$, $^0_{+1}\beta$, neutrons $^1_0 n$ and protons $^1_1 p$ are examples of particulate

ionizing radiation. Gamma-rays and X-rays are electromagnetic ionizing radiation.

24.6.1. Characteristics of the radiation-matter interaction

Three important parameters associated with the passing of charged particles through matter:

Linear specific ionization is the total number of ion pairs ***dn*** produced per length unit ***dl*** of the path of the incident radiation: ***i = dn/dl*** (fig. 24.4). Specific ionization increases with decreasing energy of the charged particle because of the increased probability of interaction at low energies.

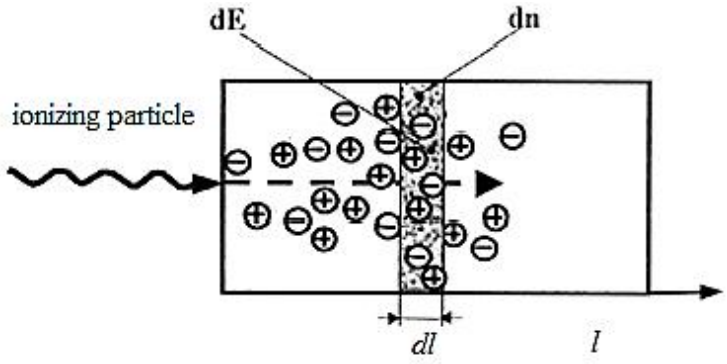

Fig. 24.4. Ion formation under ionizing radiation in the matter

Linear energy transfer (LET) is the amount of energy deposited per length unit of the path by the radiation: ***LET = dE/dl***. Electromagnetic radiation and β-particles have low LETs. In contrast, heavy particles (α-particles, neutrons and protons) lose energy very rapidly, producing many ionizations in a short distance, and thus they have high LETs.

Mean linear range of a charged particle is an average distance which the particle passes before its energy will be equal to the mean particles energy in this matter.

Let's consider features of the interaction with matter for different particles.

24.6.2. Features of the interaction of different particles with matter

Alpha-particles ${}^{4}_{2}\alpha$ are easily absorbed by materials because of their charge and large mass, and can travel only a few centimeters in air and in biological tissues — 10–100 μm. They can be absorbed by paper or the outer layers of the human skin and that is why they are not generally dangerous to life unless the source is ingested or inhaled. However, if alpha-radiation does enter the body, it is the most destructive form of ionizing radiation due to high LET. Exposure of alpha-particles produces atoms excitation, ionization, characteristics X-rays appearance, nuclear reactions.

Beta-particles ${}^{0}_{-1}\beta$, ${}^{0}_{+1}\beta$ have an electrical charge and mass less than alpha-particle charge. Beta particles are much more penetrating than alpha particles,

but they have smaller ionizing power. Very high energy beta particles can penetrate to a depth of about a centimeter in tissue. Eye and skin damage is possible if the source is strong. They are, however, relatively easy to deal with by shielding. Exposure of beta-particles produces ionization and bremsstrahlung X-rays appearance.

Gamma-rays are a form of electromagnetic radiation of the highest frequency and energy, and also the shortest wavelength (below about 10^{-5} nanometer), within the electromagnetic spectrum. A high-energy gamma photon passing near a nucleus sometimes produces an electron and positron pair. Gamma-ray photons lose energy by being scattered from free electrons (Compton effect) or are completely absorbed by ejecting electrons from atoms (photoelectric effect). Thus the photoeffect and incoherent scattering (Compton effect) are the main mechanisms of interaction gamma-rays with matter. Gamma radiation frequently accompanies alpha and beta emissions. Gamma-rays have high penetrating power, they can pass tens and hundreds of meters in air and a few meters in soft tissues. Gamma-rays are much more penetrating than alpha-particles and beta- particles (fig. 24.5).

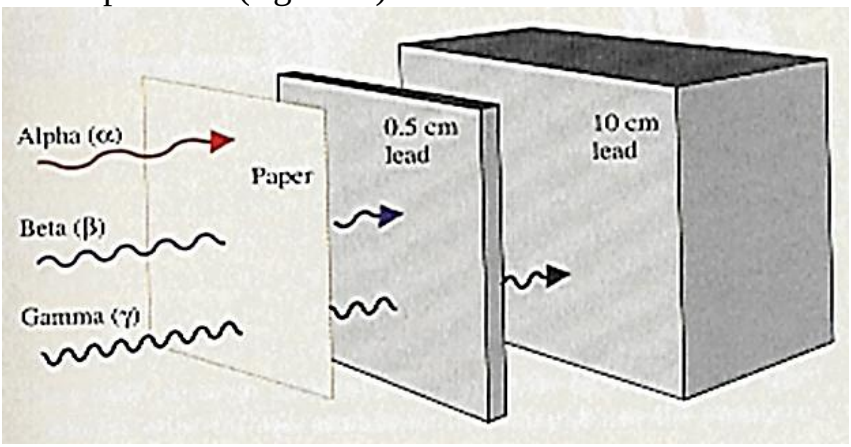

Fig. 24.5. Penetrating power of α-, β- and γ-radiation

Neutrons. Since free neutrons are electrically neutral, they pass free through the electrical fields within atoms and so constitute a penetrating form of radiation, interacting with matter almost exclusively through collisions with atomic nuclei. The way in which neutrons interact with matter depends on their energies. Neutrons will have a low probability of interaction because of the small size of the nucleus in relation to the atom, and could thus travel considerable distances in matter.

24.7. PRINCIPLES OF RADIONUCLIDE DIAGNOSTICS METHODS

Radionuclide diagnostics is based on the radionuclides incorporation in biological tissue. Incorporated radionuclides are the γ-ray source which is registered by special detectors.

Let us specify physical properties of radiopharmaceuticals. The half-life must be short enough so that a reasonable fraction of the radioactive decays take place during the diagnostic procedure; any decays taking place later give a patient a dose that has no benefit. (This requirement can be diminished if the biological excretion is rapid.) On the other hand, the lifetime must be long enough so that the radiopharmaceutical can be prepared and delivered to a patient. For the diagnostic work, the decay scheme should minimize the amount of radiation which provides a dose to the patient but never reaches the detector. The ideal source then is a γ source, which means that the nucleus is in an excited state (an isomer). Such states are usually very short-lived. If the decay is a β^- or β^+ decay, the product has different chemical properties from the parent and may be taken up selectively by a different organ. If it is also radioactive, it can confuse a diagnosis and give an undesirable dose to the other organ. It is necessary to remove the radioactive isotope from stable isotopes of the same element, because the chemicals are usually toxic.

Methods of the radionuclide diagnostics may be divided into two general types: gamma-scintigraphy and quantitative scintigraphy.

Gamma scintigraphy is a radiographic image techniques for visualizing the distribution of an injected radionuclide within the given organ as a means of studying of the anatomic structure of an organ via the introduction of an appropriate short lived gamma emitting radioisotope. The observed distribution can then be correlated with the rate and extent of drug absorption.

Different types of radionuclides tend to concentrate in different organs or tissues. So, the radionuclide used depends on which part of the body is to be scanned. For example, for scanning the thyroid gland radioactive iodine is used. Active parts of the tissue will emit more gamma-rays than less active or inactive parts. The gamma-rays which are emitted from inside the body are detected by the gamma-camera, are converted into an electrical signal, and sent to a computer. The computer builds a picture by converting the differing intensities of radioactivity emitted into different colours or shades of grey (fig. 24.6).

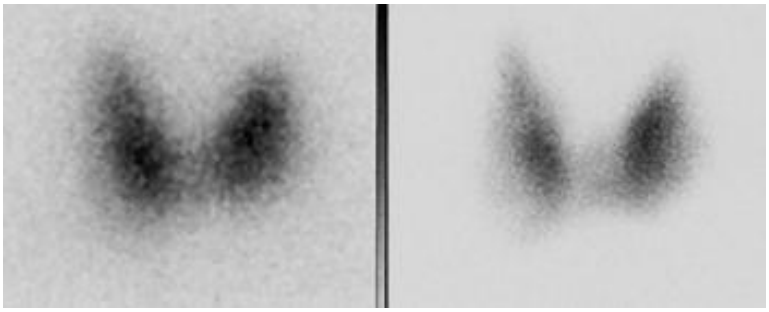

Fig. 24.6. Different types of thyroid scintigraphy

Radiography (quantitative scintigraphy) is a quantitative assay techniques for measuring the absorption and retention of a radionuclide within an organ as a means of studying the metabolism of the organ. It is displayed on

the dependence of gamma-ray intensity on time. This investigation allows conclude about the blood flow, work of liver, kidneys, and lungs.

Let's consider radiographic study of kidneys (fig. 24.7). The analysis data supplies detailed information about a kidney activity. It allows to find out a disturbance of an internal process (a rising branch) or an elimination process (a descending branch). One can perform this measurement for each kidney and make a comparative assessment their work.

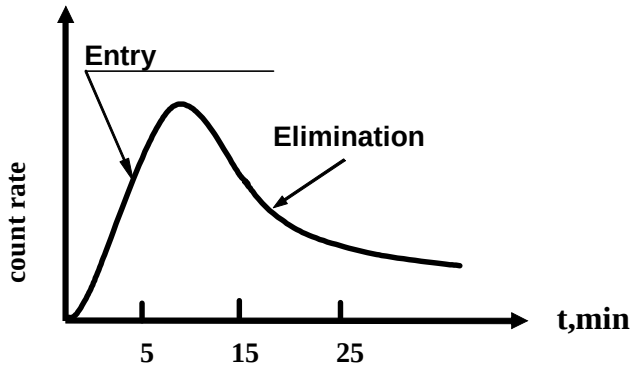

Fig. 24.7. The radiographic study of kidneys

24.8. PHYSICAL BASICS OF THE RADIATION THERAPY

Radiation therapy makes use of ionizing radiation, deep tissue-penetrating rays which can react physically and chemically with diseased cells to destroy them. Radiation therapy is used for cancer and for blood disorders such as leukemia.

Radiation may be injected to the body by implanting radioactive substances into the tumors or by exposing the body to external sources of high-energy rays that penetrate internally. Both methods have shown good results in the treatment or arrest of cancerous growths; the type of treatment used depends largely on the size of the tumor, its location.

The purpose of such radiation therapy is to destroy cancerous cells with minimal damage to normal healthy tissue or systemic involvement. Let's consider features of different rays for radiation therapy. ***X-rays*** are applied for the irradiation of superficial tumors. The intensity of X-ray decrease sharply as depth increases (fig. 24.8, dotted line).

Gamma-rays have deep penetration and cause a minimum of surface-tissue irradiation. It allows to destroy deeply located tumors. Also it decreases damage to the skin and healthy tissues. Gamma radiation from $^{60}_{27}\mathrm{Co}$ has been usually used in cancer therapy.

Electron beams with energy about 25 MeV produce a maximum ionization at depth of 1–3 cm. They are used for irradiation of not deeply situated tumors.

Protons, due to their relatively big size, scatter less easily in the tissue. The beam stays focused on the tumor shape without much lateral damage to

the surrounding tissues. All the protons of the given energy pass a certain distance; no proton penetrates beyond that distance. Furthermore, the dosage to tissue is maximum just over the last few millimeters of the particle range. This depth depends on the energy to which the particles were accelerated by the proton accelerator. Therefore it is possible to focus the cell damage due to the proton beam at the very depth in the tissues (11–14 sm) where the tumor is situated; the tissues situated before this area receive some reduced dose, and the tissues situated after the peak receive none.

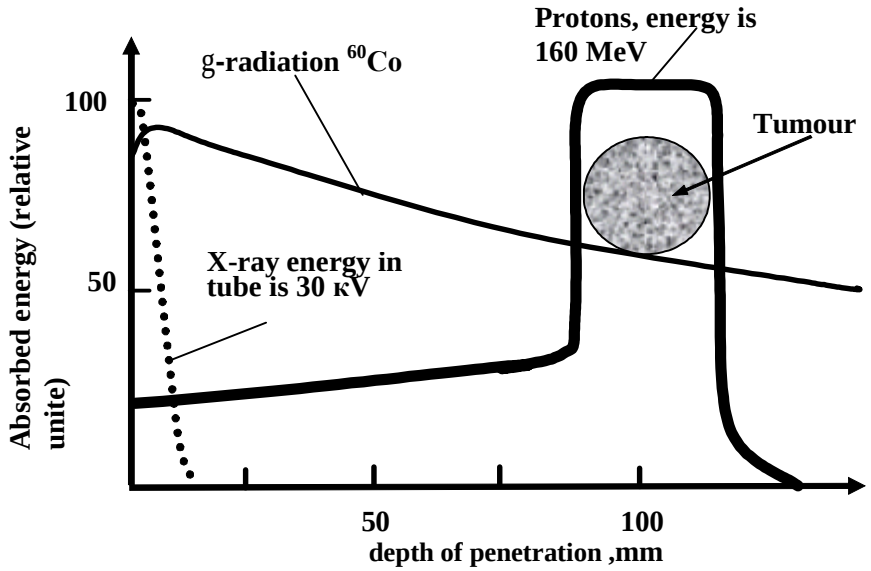

Fig. 24.8. Depth of penetration for different types of radiation

Alpha-particles because of small linear range in matter may be used via the contact with on organism or on introducing it inside. A radon therapy is a characteristic example of it. Radon water is used for action on the skin (radon bath), the digestive apparatus (drinking), the respiratory apparatus (inhalations).

***Questions*:**

1. Specify atomic nucleus characteristics.
2. What are the basic properties of the nuclear forces?
3. Describe modes of radioactive decay.
4. Explain why some radionuclides decay is accompanied by emitting γ- radiation?
5. Give β-particles kinetic energy spectrum and explain the spectrum.
6. Derive Radioactive decay Law. What are decay constant, half-life, mean lifetime? Describe relation between them.
7. What is the activity of a radioactive substance? What are the units of activity? Give the relationship between units.
8. What is the changing of the activity with time? How does activity depend on radionuclide mass?
9. Describe the characteristics of ionizing radiation interaction with the matter. What feature for α- and β,-particles and γ-radiation interaction with the matter are observed?
10. Explain principles of radionuclide diagnostics methods.
11. What are the physical basics of the radiation therapy? Describe the features of the action of α- and β,-particles, γ-radiation, neutrons and protons on the living organism.

Chapter 25. RADIATION DOSIMETRY

Ionizing radiations are generally characterized by their ability to excite and ionize atoms of matter with which they interact. The primary goal of radiation dosimetry is a quantitative estimation of the energy absorption in tissue and estimation of the biological effects.

25.1. RADIATION DOSES

25.1.1. Exposure dose

Exposure dose X is a measure of radiation based on the ability to produce air ionization:

$$X = \frac{dQ}{dm}, \tag{25.1}$$

where ***dQ*** is a total ions charge, ***dm*** is an air mass.

If the charge ***Q*** distributes uniformly in the air mass ***m*** the exposure dose ***X*** can be written as:

$$X = \frac{Q}{m}. \tag{25.2}$$

The exposure dose is used only for air and only for X-rays or γ-rays and characterizes the environment ionization by electromagnetic radiation measure.

In SI the exposure dose is measured in C/kg. The off-system unit of ***X*** is roentgen (R). It is an X-ray dose or an γ-rays dose which action produces $2{,}08\times10^9$ ion pairs in 1 sm^3 (0,001293 g) of air under favorable condition.

1 R = $2{,}58\cdot10^{-4}$ C/kg or 1 C/kg = 3876 R.

Exposure dose rate is determined as a derivative of the exposure dose ***X*** according to time ***t***:

$$\dot{X} = \frac{dX}{dt}. \tag{25.3}$$

If the exposure dose rate is obtained during time ***t*** the mean exposure dose rate can be determined as:

$$\dot{X} = \frac{X}{t}. \tag{25.3a}$$

The exposure dose rate is measured in 1A/kg.

25.1.2. Absorbed dose

Absorbed dose D is a measure of the energy deposited in a medium by ionizing radiation per unit mass (i. e., energy per gram). Chemical and biological changes in the tissue exposed to ionizing radiation depend upon the energy absorbed in the tissue from the radiation. Absorbed dose ***D*** delivered to a small mass ***m*** in kilograms is: $D = \frac{dE}{dm}$

or

$$\boldsymbol{D = \frac{E}{m}}, \tag{25.4}$$

where $\boldsymbol{E}$ is the absorbed energy in a medium from any type of ionizing radiation.

The quantity of absorbed dose described in SI units of gray. One ***gray*** (Gy) represents the dose corresponding to absorption of one joule of energy per kilogram of absorbing material:

1 Gy = 1 J/kg.

The traditional unit of the absorbed dose is ***rad***: 1 Gy = 100 rad.

Note that the absorbed dose is not a good indicator of the likely biological effect. For example, 1 Gy of alpha-radiation would be much more biologically damaging than 1 Gy of gamma-radiation.

The ***absorbed dose rate*** is described similarly to the exposure dose rate:

$$\dot{D} = \frac{dD}{dt}$$

or for constant dose:

$$\dot{D} = \frac{D}{t} \tag{25.5}$$

and it is measured in Gy/s, rad/s and subunits.

For external irradiation the absorbed dose is proportional to the exposure dose:

$$\boldsymbol{D = f X}, \tag{25.6}$$

where f is a coefficient which depends on the irradiated material structure and photons energy.

Let us evaluate this coefficient for the air. If the exposure dose is equal to 1 R for 1 kg of air then $2{,}08 \cdot 10^9$ ion pairs are generated in 1 sm^3 ($1{,}29 \cdot 10^{-6}$ kg) of air. It is necessary to spend the energy equal to 34 eV = $34 \cdot 1{,}6 \cdot 10^{-19}$ J for one pair ions production. Then the absorbed dose $\boldsymbol{D}$ is equal to:

$$D = \frac{E}{m} = \frac{34 \cdot 1{,}6 \cdot 10^{-19} \cdot 2{,}08 \cdot 10^9}{1{,}29 \cdot 10^{-6}} = 88 \cdot 10^{-4}\,\text{Gy} = 0{,}88\,\text{rad}.$$

Therefore in exposure dose of X = 1 R the absorbed dose $\boldsymbol{D}$ will be 0,88 rad/R. Consequently coefficient for air $\boldsymbol{f}$ is equal to 0,88 rad/R for air, for water and soft tissue — f = 1,0 rad/R. For bone tissue this coefficient $\boldsymbol{f}$ depends on photon energy and it takes on the value from 1 to 0,45 rad/R, decreasing with the quantum energy increase.

25.1.3. Equivalent dose

The same absorbed dose delivered by different types of radiation may result in different degrees of biological damage to body tissues. When radiation is absorbed by biological material, the energy is deposited along the tracks of charged particles in a pattern that is characteristic of the radiation type involved.

After the exposure to X-rays or gamma-rays, the ionization density would be quite low. After the exposure to neutrons, protons, or alpha-particles, the ionization along the tracks would occur much more frequently, producing a much denser pattern of ionizations. These differences in density of ionizations are the major reason that neutrons, protons, and alpha particles produce more biological effects per unit of the absorbed radiation dose than do more sparsely ionizing radiations such as X-rays, gamma-rays, or electrons.

The ***relative biological effectiveness (RBE)*** for the given test radiation is calculated as a ratio of absorbed dose of a reference radiation, usually X-rays 180–200 kV energy, to test radiation dose producing the same biological effect. Thus, for the same biological endpoint:

$$\text{RBE} = \frac{\text{Absorbed dose of X-rays (180–200 keV) to cause an biological effect}}{\text{Absorbe dose of comparison radiation needed to cause same effect}}. \quad (25.7)$$

For example, the 20 rad of X-rays cause the same effect as 1 rad of α-particles, the RBE for α-particles is 20.

In dosimetry the RBE is represented in radiobiological standarization and regulatory law by the ***quality factor k***. This factor is selected for the type and energy of the radiation incident on the body, or in the case of sources within the body, emitted by the source. The value of k is ***k* = 1** for X-rays, gamma-rays and beta-particles, but it is higher for protons, neutrons ***k* = 10** for energy 0,1–10 MeV, alpha particles ***k* = 20** for energy less than 10 MeV.

The ***equivalent dose*** is a computed average measure of the radiation absorbed by a fixed mass of biological tissue that attempts to account for the different biological damage potential of different types of ionizing radiation. The equivalent dose is more biologically significant than the absorbed dose for assessing the health risk of radiation exposure.

The equivalent dose is calculated by multiplying absorbed dose by the appropriate quality factor:

$$H = kD, \quad (25.8)$$

where ***D*** is the absorbed dose in grays.

The SI units of the equivalent dose is Sieverts (Sv). One ***sievert*** is generally defined as the amount of radiation roughly equivalent in biologic effectiveness to one gray (or 100 rads) of gamma radiation: 1 Sv = 1 J/kg. The sievert is inconveniently large for various applications, and so the millisievert (mSv), which equals to 0,001 sievert, is frequently used instead. Conventional unit, Röntgen equivalent man -***rem*** is also used: 100 rem = 1 sievert.

Equivalent dose rate (H) — is known as a derivative of the exposure dose according to time:

$$\dot{H} = \frac{dH}{dt}. \quad (25.9)$$

If the equivalent dose doesn't depend on time, the equivalent dose rate is given as:

$$\dot{H} = \frac{H}{t}. \qquad (25.9a)$$

The units of the equivalent dose rate are Sv/s, mZv/hr, rem/s etc.

25.1.4. Effective equivalent dose

Effective equivalent dose estimates the damage of the certain equivalent dose has been delivered to some target organs. The effective equivalent dose is the sum of the products of the equivalent dose to various organs or tissues $\boldsymbol{H_i}$ and the weighting factors $\boldsymbol{w_i}$ applicable to each of the body organs or tissues that are irradiated:

$$H_{eff} = \sum_i w_i H_i. \qquad (25.10)$$

The tissue ***weighting factor*** or coefficient of radiation risk $\boldsymbol{w_i}$ is the radiation detriment of the damage to the whole body during constant irradiation. By definition, the sum of $\boldsymbol{w_i}$ over all organs is equal to one: $\sum_i w_i = 1$.

For example, if human lungs are exposed to the equivalent dose 1 Sv the probability of developing radiation-induced cancer is $P_1 = 2 \cdot 10^{-3}$. If the whole body were to receive the equivalent dose of 1 Sv, the probability of radiation induced cancer is $P_0 = 1{,}65 \cdot 10^{-2}$. The weighting factor w_l for lungs is:

$$w = \frac{P}{P_0} = \frac{2 \cdot 10^{-3}}{1{,}65 \cdot 10^{-2}} \approx 0{,}12.$$

The table 25.1 shows w_i permissible to each target organ:

Table 25.1

Organ	$\boldsymbol{w_i}$
Gonads	0,25
Breast	0,15
Red bone marrow	0,12
Lungs	0,12
Thyroid gland	0,03
Bone surfaces	0,03
Remainder	0,30

25.1.5. Collective effective dose

The equivalent dose $\boldsymbol{H}$ characterizes the consequences of radiation exposure for a particular organ, while the effective equivalent dose $\boldsymbol{H_{eff}}$ — for the whole organism. To estimate radiation effects on a large group of people the collective effective dose $\boldsymbol{S}$ is used.

The ***collective effective dose S*** is a measure of the total amount of the individual effective doses $H_{i\,eff}$ multiplied by the size of the exposed population:

$$S = \sum_i H_{i\,eff}\ N_i, \qquad (25.11)$$

where N_i is the total number of individuals in the given group.

It is used to predict the magnitude of stochastic effects of radiation on the population. The collective dose is usually measured in units of ***person-sieverts*** or man-sieverts.

25.2. IONIZING RADIATION DETECTORS

The ***ionizing radiation detector*** is a device that is sensitive to radiation and can produce a response signal suitable for measurement or analysis. There are different detector types which are based on the effects of interaction between radiation and matter.

Trace detectors help to define a particle trajectory and its track length in the matter. A ***Wilson cloud chamber*** consists essentially of a closed container filled with a supersaturated vapor, e. g., water in the air. When ionizing radiation passes through the vapor, it leaves a trail of charged particles (ions) that serve as condensation centers for the vapor, which condenses around them. Thus the path of the radiation is indicated by tracks of tiny liquid droplets in the supersaturated vapor.

The tracks of alpha and beta particles have distinctive shapes (for example, alpha particle's track is broad and straight, while that of an electron is thinner and shows more evidence of deflection). When a vertical magnetic field is applied, positively and negatively charged particles curve in the opposite directions.

One of the disadvantages of the cloud chamber is the relatively low density of the gas, which limits the number of interactions between ionizing radiation and molecules of the gas. For this reason physicists have developed other particle detectors, notably the bubble chamber. In the ***bubble chamber*** (fig. 25.1) the particle track is formed in the result of boiling a superheated liquid along the particle trajectory. As charged particles move through the liquid, they knock electrons out of the atoms of the liquid, creating ions. If the liquid is close to its boiling point, the first bubbles are formed around these ions. The observable tracks can be photographed and analyzed to measure the behavior of the charged particles.

In the basic type of an ionization detector a number and characteristics of an electric beam produced in the gas by the radiation are measured. For example, ***Geiger counters*** are widely used to indicate the presence and intensity of nuclear radiations. When a fast-moving charged particle traverses a Geiger counter, an electrical impulse is produced and can be counted.

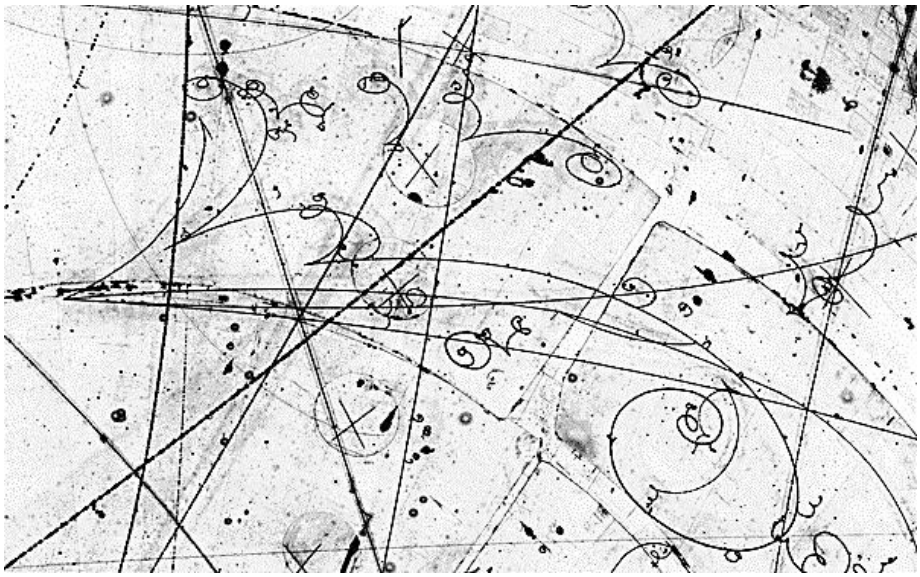

Fig. 25.1. A bubble chamber tracks of some particles

A Geiger counter consists of a gas between two electrodes (fig. 25.2). One electrode, usually cylindrical and hollow, is the cathode. The other electrode, stretched along the axis of the cylinder, is the anode. A potential of about 1000 volts is placed on the wire. As particles enter the tube, they create a large avalanche of ionization in the gas, which then discharges, creating a brief electric pulse. The tube produces the same large output pulse for virtually every charged particle that passes through the gas and so it is useful for detecting individual particles. It can therefore indicate lower levels of radiation than is possible in comparison with other types of detectors.

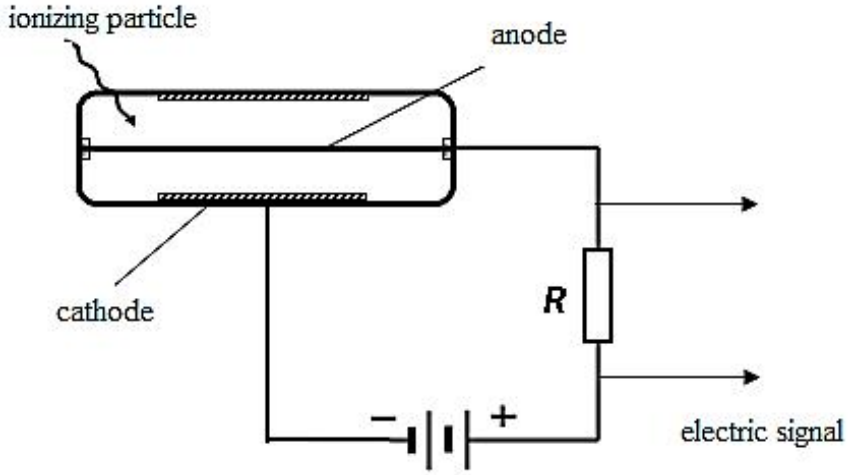

Fig. 25.2. Geiger counter

The degree of ionization per volume unit is measured by ionization detectors. X-rays and gamma-rays have a great track length in the gas they rarely cause ionization. Mainly they knock electrons out of tube wall atoms which get into gas and ionize it.

Scintillation detector or a scintillation counter (fig. 25.3) also measures ionizing radiation. The sensor, called a scintillator, consists of a transparent crystal, plastic, or organic liquid that fluoresces when struck by ionizing radiation. A sensitive photomultiplier measures the light from the crystal. It is attached to an electronic amplifier and other electronic equipment to count and possibly quantify the amplitude of the signals produced by the photomultiplier. In order to direct as much as possible of the light flash to the photosensitive surface, reflecting material is placed between the scintillator and the inside surface of the container.

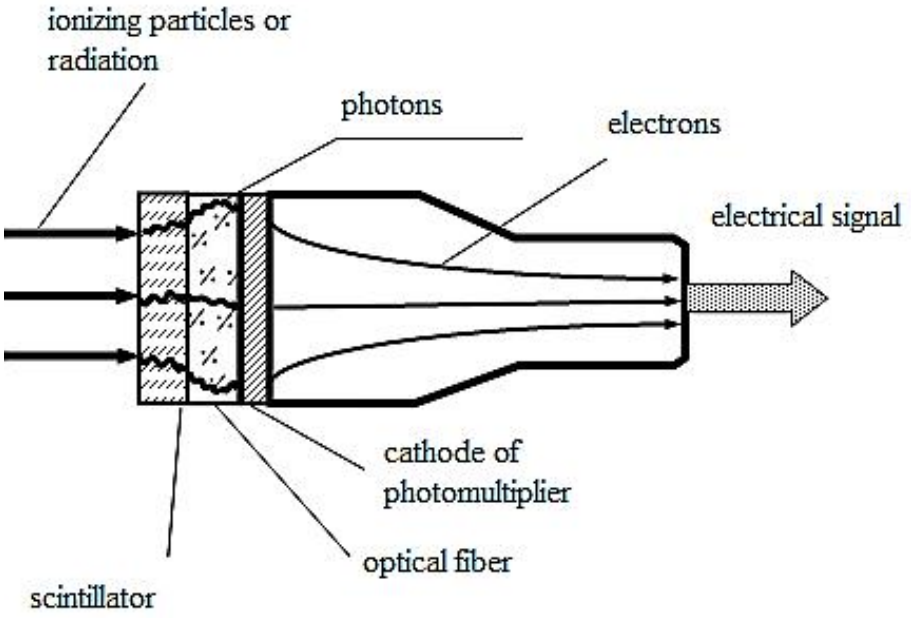

Fig. 25.3. Scintillation detector

A charged particle, moving through the scintillator, loses energy and leaves a trail of ions and excited atoms and molecules. Rapid interatomic or intermolecular transfer of electronic excitation energy follows, leading eventually to a burst of luminescence characteristic of the scintillator material. When a particle stops in the scintillator, the integral of the resulting light output, called the scintillation response, provides a measure of the particle energy, and can be calibrated by reference to particle sources of the energy. Scintillation counters may be used to detect the various types of radioactivity (alpha, beta, and gamma rays), cosmic rays, and various elementary particles.

The registration of α-particles is most difficult due to their short path in matter. Alpha-radiation may be registered only from a thin surface layer so special preparation of patterns is necessary. Beta-particles have a longer path in matter so their detection is slightly simplier. The registration of γ-rays is the simpliest due to their long path in matter. They may be registered even from a deep-seated object layer (fig. 25.4).

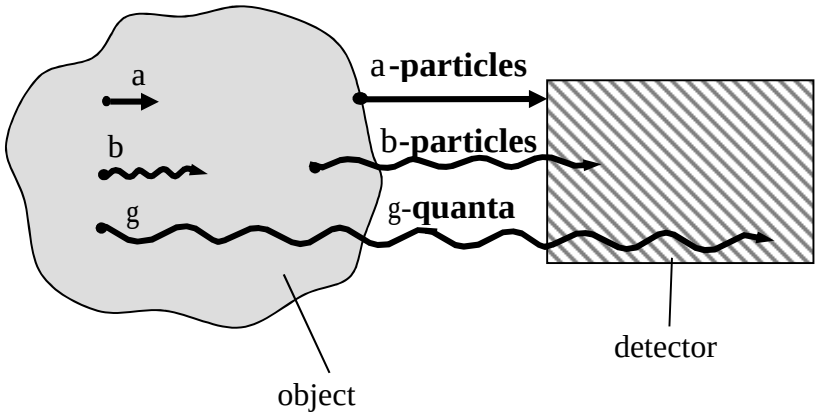

Fig. 25.4. The detection features of different particles

25.3. RADIATION MONITORING INSTRUMENTS

Radiation monitoring instruments are devices for the radiation doses or activity measurement. They are divided into dosimeters and radiometers.

A ***dosimeter*** is a device used to measure an individual's exposure to a dangerous environment, particularly when the hazard is cumulative over long intervals of time. A dosimeter consists of a detector and an electronic measuring device, which transform a detector signal into a form useful for registration.

Let us consider a dosimeter is based on ionization camera use. The ionization camera is filled with air under atmospheric or low pressure. Its active volume is V. The ionization chamber consists of two electrodes (fig. 25.5). Before using these electrodes are filled with a potential difference U_1 and obtain a charge q_1.

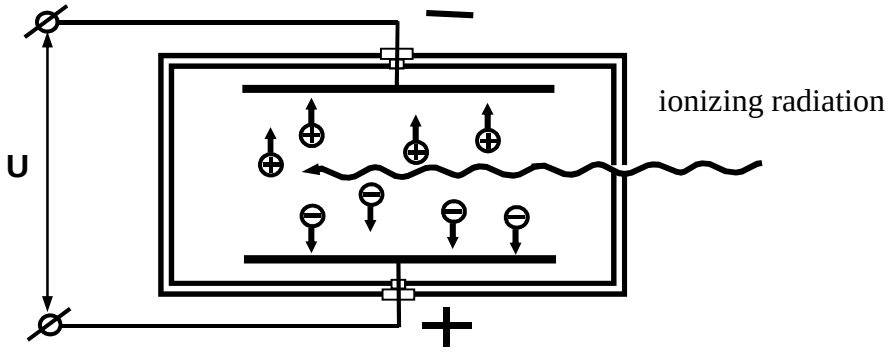

Fig. 25.5. Ionization chamber

When ionizing radiation penetrates the gas in the camera this radiation liberates electrons from the gas atoms leaving positively charged ions. The current begins to flow in a camera as soon as the electrons and ions begin to separate under the influence of the applied electric field. Therefore the potential difference decreases from the initial value U_1 to U_2, and the charge decrease from q_1 to q_2. Their changes are related in the following formula:

$$q_1 - q_2 = \Delta q = C(U_1 - U_2).$$

where C is electrocapasity.

Therefore the exposure dose is equal to:

$$X = \frac{\Delta q}{m} = \frac{C(U_1 - U_2)}{\rho \cdot V} = k(U_1 - U_2) = k\,\Delta U,$$

where ***V*** is a camera volume, ***m*** is air mass, r is the air density. Constants in this formula may be joined in coefficient ***k*** in this formula. This coefficient is determined under device calibration.

An individual radiation dosimeter is a pen-like device that measures the cumulative dose of radiation received by the device. It is usually clipped to somebody clothing to measure his actual exposure to radiation.

Exposure rate measure is based on the current determination in the detector:

$$\dot{X} = \frac{dX}{dt} = \frac{dQ}{dt \cdot m} = \frac{I}{m}.$$

Exposure rate measuring instruments are usually calibrated in mR/hr or μR/s.

So dosimeters help to measure the exposure dose in the air and to control γ-rays and X-rays background level. They can not be used to control radiation pollution degree of foodstuffs and the human organism.

A ***radiometer*** is a device for activity measurement. The activity is determined as the number of decay events per time unit. Therefore, radiometers count electrical pulse caused by particles hitting on the detector per time unit.

Let us consider one of the methods for determining a specific volume or mass activity. A radiometer detector and the tested specimen are placed into the lead-wall camera to minimize the influence of the natural radiation background. It is necessary to improve the measurement accuracy. At first initial background activity (without the test specimen) is measured. Let N_1 be the impulse count of background activity in time t_1. Then a measuring cell is filled up with the tested product. Let a detector indicate the impulse count N_2 in time t_2. Then a specific activity is calculated by the formula:

$$A_v = \frac{N_2/t_2 - N_1/t_1}{P},$$

where coefficient ***P*** take into account a specimen volume and radiometer sensivity to different radiation types.

The determination of radioactive substance content in the human organism is a very important task. The internal irradiation radiometry is the most effective for gamma-emitting radionuclides. A special apparatus for internal the radiation dose consist of a steel protective room, a scintillation counter set, a recording system and a chair for a patient. A multichannel analyzer registers gamma-quanta and determines radionuclide type and the concentration of in the organism.

25.4. BACKGROUND RADIATION

Background radiation is the ionizing radiation emitted from a variety of natural and artificial radiation sources. Some of this radiation is man-made, such as radiation used in medical applications and some is «natural». Natural sources include cosmic rays, terrestrial, and internal. Man-made radiation includes medical X-rays, medical nuclear procedures, consumer products, industrial sources, and some miscellaneous sources of radiation. The actual background encountered by each individual varies significantly, depending upon where he lives, the food that is consumed, the radon levels in the house, and so on.

Cosmic rays have always bombarded the earth. A typical person receives 0,31 mSv per year from cosmic rays. The earth's atmosphere provides some shielding from cosmic rays. This shield is reduced at greater heights, and the cosmic ray dose is increased. Inhabitants at heights of 1600 meters receive 0,50 mSv/yr from cosmic rays, while those at the heights of 3200 meters receive 1,25 mSv. The effective equivalent dose, received by a person living at a sea level in the result of cosmic rays equals about 0,31 mSv per year.

Cosmic rays may broadly be divided into two categories, primary and secondary. The cosmic rays that arise in extrasolar astrophysical sources are primary cosmic rays; these primary cosmic rays can interact with interstellar matter to create secondary cosmic rays. The secondary cosmic rays reach the ground surface and contain all known elementary particles. The sun also emits low energy cosmic rays associated with solar flares. The exact composition of primary cosmic rays, outside the Earth's atmosphere, is dependent on which part of the energy spectrum is observed. However, in general, almost 90 % of all the incoming cosmic rays are protons, about 9 % are helium nuclei (alpha-particles) and about 1 % are electrons.

Terrestrial background originates from radioisotopes that are found everywhere in our surroundings. All elements found in nature have radioactive isotopes, many of which are also present in the environment. The exact composition of soil influences the local terrestrial background, because the minerals present determine which elements are most abundant. Terrestrial background sources are categorized as «primordial» if their half-lives are the same order of magnitude as the presumed lifetime of the earth ($4{,}5 \cdot 10^9$ years). That is, these sources were present when the earth was formed and there is no way to replenish them in nature. Two isotopes of uranium, ^{238}U and ^{235}U, and one of thorium ^{232}T, give rise to three different decay series. In each of these series, the radioactive nuclide decays to another stable isotope of bismuth or lead. Seventeen other nuclides are primordial, but are not part of a decay series. Of these nonseries radionuclides, ^{40}K and ^{87}Rb make the greatest contribution to the background dose so the dose accrue 0,65 mSv per year. The mean background exposure dose rate for Belarus in normal stage is 10–12 μR/h.

Internal background is the dose imposed by the isotopes contained in our bodies. A small percentage of the potassium in the human body is ^{40}K. This radioactive nuclide emits both locally absorbed beta radiation and more penetrating gamma radiation. Similarly, ^{14}C, which comprises a small percentage of the carbon atoms found in organic molecules throughout our bodies, contributes to the total dose of 1,35 mSv/yr from internal background.

Radon, as part of the ^{238}U decay series, is significant because it is an alpha emitter that exists as an inert gas. Since it is inert, radon generated by decay of ^{226}Ra at some depth in the soil does not bind chemically with other elements. Instead, it percolates up to the surface to escape into the atmosphere. Being heavier than most constituents of the atmosphere, it tends to remain at lower elevations. Although minable deposits of uranium ore are primarily associated with granite rock formations, uranium is found everywhere in the earth's crust. Ninety-nine percent of the uranium found in nature is ^{238}U. Thus, the air we breathe anywhere on earth contains some amount of radon.

Radon itself is not particularly hazardous, when inhaled, because it does not react and in most cases is simply exhaled. A more significant concern is that two of the decay products of radon (^{218}Po and ^{214}Po), delivered to the air by decaying radon, are not inert. These products adhere to dust particles in the air, which may then be inhaled into the lung. Therefore the natural source dose is equal to 2,0 mSv per year.

Various human activities add to the annual radiation background. At first it is diagnostic radiology (0,39 mSv). Radiation received by patients in radiation therapy is not counted in man-made background, because the intention is to track radiation doses that are associated only with stochastic effects.

Various consumer products emit small amounts of radiation. Some examples include exit signs that contain ^{3}H, a low-energy beta emitter, and smoke detectors that contain ^{241}Am, an alpha emitter. Luminous dials on watches, clocks, and instruments contained ^{3}H and ^{147}Pm, both of which are low-energy beta emitters. The low-energy beta particles emitted by these substances are absorbed in the instrument components and provide negligible amounts of the radiation dose to their owners. Increasingly, liquid crystal displays and light-emitting diodes are replacing the use of radioactive materials in luminous displays. Collectively, consumer products are estimated to contribute approximately 0,1 Sv to the yearly dose from man-made background radiation.

***Questions*:**

1. What is the exposure dose? What are the units of the exposure dose? Give the relationship between units.

1. What is the absorbed dose and the absorbed dose rate? What are the units of the absorbed dose?

2. Calculate a coefficient which connects on the exposure dose and the absorbed dose for the air.

3. Give a definition of the relative biological effectiveness. What does the equivalent dose mean? What are the units of the equivalent dose?

4. Write formula for the effective equivalent dose. What does this dose characterize?

5. What is the collective effective dose?

6. Why is alpha-particles registration more difficult than a gamma-rays registration?

7. What is the difference between a dosimeter and a radiometer?

8. What does a background radiation consist of?