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PART 6. X-ray

Study aid

For English-speaking students of medical, biomedical fields of study

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"Practical work. Medical physics. Part 6. X-ray" contains brief theory and descriptions of laboratory work. This book is for foreign students of medical specialties. For each work, a brief overview, installation manuals, step-by-step instructions, and a list of questions for self-study are provided.

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Contents

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We welcome any feedback from students and professors, especially concerning errors or deficiencies:

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Introduction

Nowadays making a correct diagnosis is often impossible without data obtained using non-invasive diagnostic methods. These include such methods as medical ultrasound (sonography), tomography (Magnetic Resonance Imaging – MRI, X-ray Computed Tomography – CT, Positron-Electron Tomography – PET), endoscopy, various methods of X-ray studies (radiography, fluoroscopy, mammography, CT, electroradiography, fluorography).

This manual discusses in detail the basic principles of X-rays, properties of X-ray and its applications in medicine. While reading the manual, students will gain an understanding of the X-rays interaction with matter, the process of X-ray irradiation and the formation of X-ray images. Students can study phenomena such as absorption, scattering, and refraction of X-rays as they interact with various materials. This can help to understand the principles of X-ray diagnostics and available data processing methods.

The main part of the manual contains a detailed presentation of the theoretical aspects of working with X-ray radiation. It discusses various methods of obtaining X-ray images. In addition, it describes the principles of operation of X-ray machines and methods for processing the resulting images. This will help students better understand how to apply their knowledge in practice and how to correctly interpret X-rays.

The final part of the manual contains theoretical questions and manuals for students' laboratory works. This will help them consolidate their acquired knowledge and test their competence in this area.

In general, this manual offers a complete and systematic approach to the study of X-ray radiation, which allows students and specialists to acquire the necessary knowledge to work with X-ray machines and intelligently analyze the resulting images.

BASIC THEORY

1. Basics of X-ray Physics

1.1. α, β, γ-radiation and X-ray

Alpha radiation (α) is a stream of helium nuclei ${}_{2}^{4}He$ or α-particles (helium atom with atomic mass number A = 4 and nuclear charge number Z = +2), emitted mainly by a natural radionuclide during radioactive alpha decay. These particles are formed during the decay of many radioactive substances (radium, uranium, thorium, polonium) and have a high ionizing ability [1].

The alpha decay scheme is shown below:

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

Where are:

- ${}_{Z}^{A}X$ is the parent nucleus (starting nucleus),
- A is the total number of nucleons (the number of neutrons plus the number of protons);
- Z is the total number of protons;
- ${}_{Z-2}^{A-4}Y$ is the daughter nucleus (ending nucleus);
- ${}_{2}^{4}\alpha$ is the released alpha particle;

Let's take a look for a few examples of alpha decay. There is a well-known example of the α-decay of Uranium, Radium and Polonium:

$$ {}_{92}^{238}U \rightarrow {}_{90}^{234}Th + {}_{2}^{4}He $$

$$ {}_{86}^{222}Rn \rightarrow {}_{84}^{218}Po + {}_{2}^{4}He \text{ and } {}_{84}^{218}Po \rightarrow {}_{82}^{214}Pb + {}_{2}^{4}He. $$

The energy of alpha particles is in the range of 4–7 MeV (Mega electron Volts). Alpha particle range of absorption:

- It reaches 8-10 cm in the air;

- It reaches several tens of micrometers in biological tissue.

Since the range of absorption for alpha particles in matter is small, and the energy is very high, the ionization density per unit length of absorption range is very high (up to 10 thousand pairs

of ions per 1 cm). Such particles, born during radioactive alpha decay, can be stopped even by a sheet of paper.

Beta radiation (β) is the flow of electrons e^- or positrons e^+ as a result of radioactive beta decay. Electrons e^- or positrons e^+ emitted by β-decay are also called beta particles. Beta particles have a mass equal to 1/1838 of the mass of a hydrogen atom and carry single negative (beta particle e^-) or positive (positron e^+) charges. Let's take a look deeper for mechanism of beta decay.

Beta decay occurs when there are an excess protons or neutrons in a parent nucleus and therefore nucleus cannot be stable because of this excess. To fix that one of the proton in parent nucleus is transformed into a neutron and vice versa. If a proton is converted to a neutron, it is known as β^+ decay. Similarly, if a neutron is converted to a proton, it is known as β^- decay. Due to the change in the nucleus, a beta particle is emitted. The beta particle is a high-speed electron when it is a β^- decay and a positron when it is a β^+ decay. It is determined that the β decay is always followed by the emission of a neutral particle – a neutrino $\boldsymbol{\nu}$ or antineutrino $\tilde{\boldsymbol{\nu}}$. This particle almost does not interact with matter. The energy released during β decay is distributed randomly between the β particle and the neutrino $\boldsymbol{\nu}$. Therefore, the energy spectrum of β radiation is continuous (Fig. 1) [2].

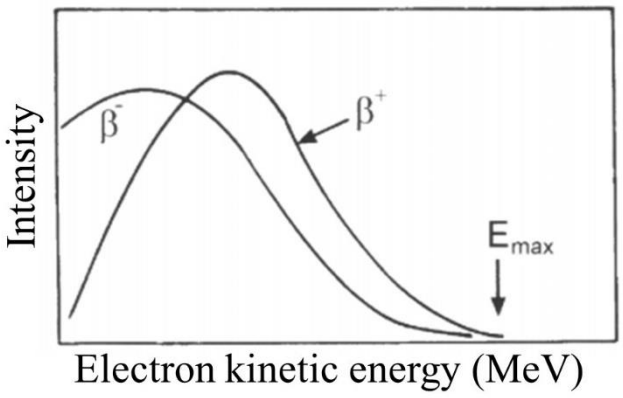

Fig. 1. The energy spectrum of β radiation

Beta-minus decay: In β^- decay, the weak interaction converts a parent nucleus into a nucleus with charge number Z increased by one, while emitting an electron e^- and an electron antineutrino $\bar{\nu}_e$. The β^- decay generally occurs in neutron-rich nuclei. In β^- decay the change in atomic configuration is:

$$^{A}_{Z}X \rightarrow {}_{Z+1}{}^{A}Y + {}_{-1}^{0}\beta + \tilde{\nu}.$$

Thus, an electron is formed due to the internuclear transformation of a neutron into a proton:

$$^{1}_{0}n \rightarrow {}_{+1}^{1}p + {}_{-1}^{0}\beta + \tilde{\nu}.$$

The example of electronic β^- decay is conversion of tritium to helium:

$$^{3}_{1}H \rightarrow {}^{3}_{2}He + {}_{-1}^{0}\beta + \tilde{\nu}.$$

Beta-plus decay*:* In this type of decay, a proton decay to form a neutron that leads to a decrease in the charge number Z. The nucleus loses a proton but gets a neutron as it expressed in the equation:

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

According to this scheme a positron is formed due to the internuclear transformation of a proton into a neutron:

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

The example of positron $\beta -$ decay is transformation of rubidium into krypton:

$$^{79}_{37}Rb \rightarrow {}^{79}_{36}Kr + {}_{+1}^{0}\beta + \nu.$$

However, this type of decay can happen only if the daughter nucleus is more stable than the parent nucleus. This difference goes into the conversion of a proton into a neutron, a positron and a neutrino. There is no increase in mass number because a proton and a neutron have the same mass.

Electron capture (K-capture): This is a process during which a nucleus captures one of its atomic electrons, resulting in the emission of a neutrino:

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

Where ν is neutrino. This process thereby changes a nuclear proton to a neutron and simultaneously causes the emission of an electron neutrino:

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

An example of electron capture is one of the decay modes of krypton into bromine:

$$_{36}^{81}Kr + _{-1}^{0}\beta \rightarrow _{35}^{81}Y + \nu.$$

And another example is conversion of beryllium to lithium:

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

The energy of beta radiation does not exceed a few MeV. Absorption range for beta particles:

–in the air is from 0.5 to 2 m;

–in living tissues – 2–3 cm.

The ionizing ability of beta particles is lower than of alpha particles (several tens of ion pairs per 1 cm of the path). To protect against beta particles with energies up to 1 MeV, an aluminum plate a few millimeters thick is sufficient.

Gamma radiation (γ) is photon radiation that occurs when the energy state of atomic nuclei changes, during nuclear transformations or during the annihilation of particles *(annihilation – lat. annihilatio – destruction; in physics, the reaction of the transformation of a particle and an antiparticle when they collide. The collision leads to formation of any other particles, which are different from the initial ones, for example, when an electron e- and a positron e+ collide, they disappear, turning into photons).*

Gamma radiation sources that are used in industry have energies from 0.01 to 3 MeV.

Gamma radiation has a high penetrating ability and low ionizing effect (low ionization density per unit length). For protection, heavy elements are effective – for instance, lead is used for protection.

X-ray radiation is also photon radiation, consisting of bremsstrahlung and (or) characteristic radiation that occurs in X-ray tubes, electron accelerators, with a photon energy of not more than 1 MeV.

X-ray radiation as well as gamma radiation has a high penetrating power and a low ionization density of the medium. X-rays and gamma rays do not differ in their nature and properties from each other. The only difference between them lies in the way they are produced: X-rays are usually obtained using an electronic apparatus, gamma rays are released during nuclear reactions or during the decay of many radioactive substances [2, 3].

1.2. X-ray

X-rays are electromagnetic radiation (waves) with a wavelength of 100 to 10^{-3} nm, a frequency of $3 \cdot 10^{16}$ to $3 \cdot 10^{19}$ Hz, and an energy of 10 eV to 250 keV (Fig. 2).

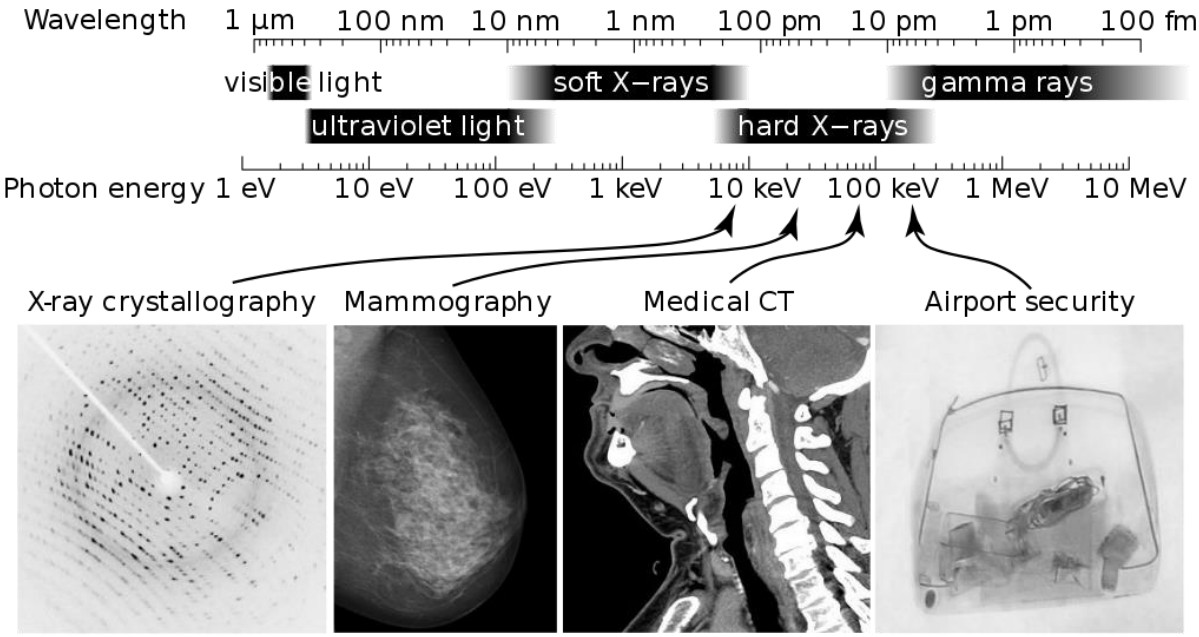

Fig. 2. X-ray spectrum with wavelength, photon energy and its applications [4]

The longest-wavelength X-ray radiation is covered by short-wavelength ultraviolet electromagnetic radiation. And short-wave X-ray radiation is covered by long-wave electromagnetic gamma radiation. According to the method of obtaining X-ray radiation is divided into bremsstrahlung and characteristic X-ray.

1.3. Soft and hard X-ray radiation

Soft X-ray radiation is characterized by the lowest radiation frequency (respectively, photon energy) and the longest wavelength. Hard X-ray radiation has the highest radiation frequency (respectively, photon energy) and the shortest wavelength. The conditional boundary between soft and hard X-rays on the wavelength scale is about 0.2 nm, which corresponds to photon energy of about 6 keV.

Soft X-ray radiation is used in the diagnosis of soft tissues and blood vessels in standard radiology methods.

In medical diagnostic applications, X-ray radiation with energies about 10 – 20 keV is commonly used. The low energy (soft) X-rays are unwanted, since they are totally absorbed by the body, increasing the radiation dose without contributing to the image. Hence, a thin metal sheet, often of aluminum, called an X-ray filter, is usually placed over the window of the X-ray tube, absorbing the low energy part of the spectrum. This is called hardening the beam since it shifts the center of the spectrum towards higher energy (or harder) X-rays.

Hard X-ray radiation is used to treat cancerous tumor, due to its ionizing effect, which destroys the tissue of a biological object [5].

1.4. X-ray tube

X-ray tube is an electrovacuum device that is used to generate X-rays. The main elements of an X-ray tube are the heated Cathode («-») and the Anode («+»). They are placed opposite each other inside

a glass flask, while all the air is pumped out of the flask. This is done in order to prevent the collision of electrons with air molecules and dust particles in the air, since such collisions will change the path of the electrons, therefore, the resulting image will be less clear (Fig. 3).

The cathode is a tungsten filament spiral. When the current is turned on (heating voltage U_h is applied to the filament), the temperature on the spiral increases, and the cathode begins to emit electrons (elementary particles with a negative charge). It turns out that the filament is surrounded by a cloud of these particles. Due to the high voltage potential difference between the cathode and the anode U_a, flow of these electrons is accelerated and moves towards the anode [6].

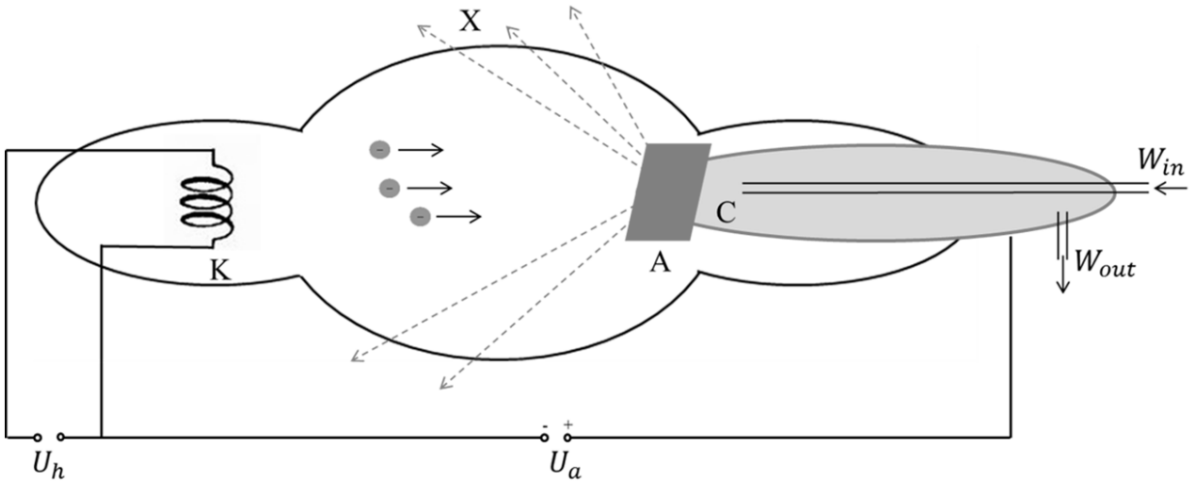

Fig. 3. Schematic of X-ray tube (hot cathode tube or Coolidge tube):
X are X-rays, K is filament or cathode (-), A is anode (+)
C is the cooling device, W_{in} is water inlet, W_{out} is water outlet,
U_a is the high voltage potential difference between cathode and anode,
U_h is filament/cathode heating voltage

When the electron beam hits the anode, it sharply slows down and dissipate, while losing most of the previously acquired energy – part of the kinetic energy of the electrons turns into heat (99%), another part of the energy goes to X-ray radiation (1%), which is called **Bremsstrahlung** (i.e. electromagnetic radiation produced by the de-

celeration of a charged particle after passing through the electric and magnetic fields of a nucleus). It should be noted that electron deceleration does not occur due to collision of electron with the atoms of the substance from which the anode is made, but deceleration occurs in anode atoms static field. Thus, we can say that the anode is the target material for electrons. The anode is made of materials that have a good heat storage capacity (for example, tungsten, copper). This is necessary so that, firstly, the heat is dissipated as quickly as possible and, secondly, the energy is most efficiently converted into X-ray beam.

There is the electron energy conversion to X-ray formula (1):

$$eU_a = hf_{max} = \frac{hc}{\lambda_{min}}. \quad (1)$$

Where are: elementary charge of electron $e = 1.602176634 \times 10^{-19}$ Coulombs, U_a is The high voltage potential difference between cathode and anode in Volts, Plank constant $h = 6.62607015 \times 10^{-34}$ J*s or J/Hz, f_{max} is frequency of emitted X-ray beam in Hz, speed of light $c = 3 \times 10^8$ m/s, λ_{min} is wavelength of emitted X-ray beam in meters.

The place on the anode where the electrons tend to hit is called the focal spot. The clarity of the image will depend on the size of the focal spot – the smaller this spot, the clearer the image will be. If the entire surface of the anode emits X-ray, the image will be blurred.

In order for the X-ray tube to last as long as possible and suffer less from high temperatures, a cooling system is necessary. Currently, this system is made of air, water or oil. In addition, X-ray tubes are equipped with a rotating anode with dual focus (large and small) [5].

1.5. The phenomenon of thermionic emission

At temperatures other than absolute zero, there are a number of electrons whose energy is sufficient to overcome the potential barrier (a region of space that separates two other regions with the same

or different potential energies) present at the metal boundary. As the temperature rises, the number of such electrons increases dramatically. Thus, **thermionic emission** is the emission of electrons by a heated metal.

Thermionic emission is the liberation of electrons from an electrode by virtue of its temperature (releasing of energy supplied by heat). This occurs because the thermal energy given to the charge carrier overcomes the work function of the material. The charge carriers can be electrons or ions, and in older literature are sometimes referred to as thermions. After emission, a charge that is equal in magnitude and opposite in sign to the total charge emitted is initially left behind in the emitting region. But if the emitter is connected to a battery, the charge left behind is neutralized by charge produced by the battery. As the emitted electrons move away from the emitter, the emitter will be in the same state as it was before emission [7].

1.6. The X-ray spectrum

The X-ray spectrum (Fig. 4) consists of a continuous spectrum caused by bremsstrahlung and characteristic lines (sharp peaks K_α and K_β) that arise due to the interactions of accelerated electrons with electrons of the inner K-shell of atoms.

The X-ray spectrum is a wide range of wavelengths of electromagnetic radiation that is obtained using conventional X-ray tubes. Two components are distinguished in this spectrum: bremsstrahlung and characteristic X-ray radiation [9].

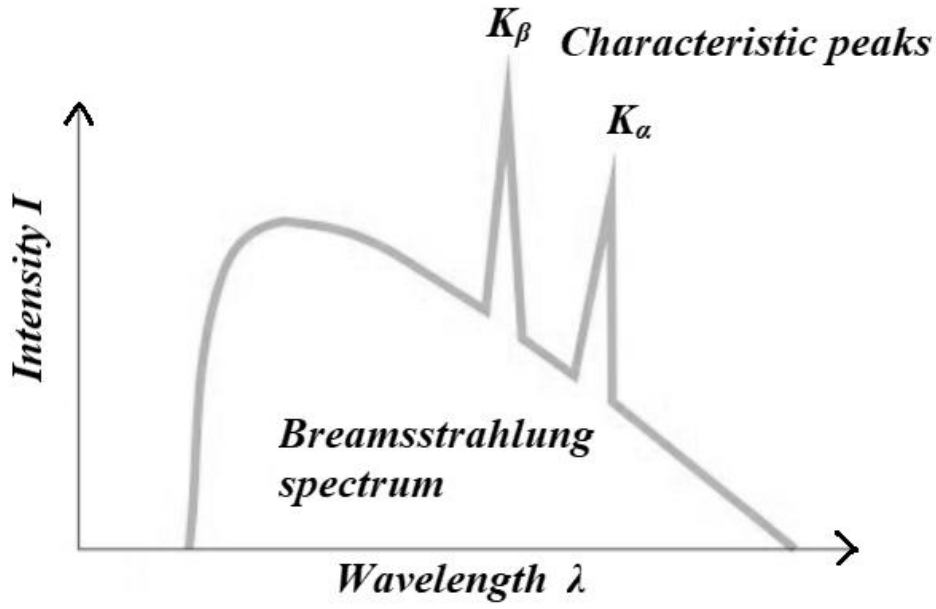

Fig. 4. The X-ray spectrum scheme. Intensity of signal I (W/m^2) is presented on vertical label. Wavelength of X-ray λ (nm) is presented on horizontal label [8]

Bremsstrahlung has a wide continuous spectrum, the appearance of which is caused by the deceleration of electrons on the substance from which the anode is made.

The bremsstrahlung flux Φ is calculated by the formula (2):

$$\Phi = kIU^2Z. \quad (2)$$

Where U and I are the high voltage potential difference between cathode and anode in Volts and the current in the X-ray tube in Amps, Z is the atomic number (nuclear charge number) of the anode substance, k = 10^{-9} Volt $^{-1}$ is the proportionality factor. The radiation flux is measured in Watts.

Another feature of the X-ray spectrum is the presence of distinct peaks of characteristic radiation, which arises due to the interactions of accelerated electrons with electrons of the inner K-shell of atom.

As we know, atoms consist of nuclei surrounded by electrons, the energy of which has discrete values. The energy levels of electrons are grouped into electron shells, which are denoted by the symbols K, L, M, etc. For instance when an accelerated electron hits with one

of the electrons located on the K-shell it knocks it out. The empty place is occupied by an electron from another L- or M- shell, which corresponds to a large energy. In this case, K_α radiation occurs, and in the second case, K_β radiation occurs of the characteristic spectrum.

Since the shell electrons have discrete energy values, the resulting X-ray photons also have a discrete spectrum. This corresponds to sharp peaks for certain wavelengths in X-ray spectrum, the specific values of which depend on the atomic number of the elements that make up the target material of anode [3].

1.7. The bremsstrahlung and characteristic X-ray radiation

When the current is turned on, the temperature on the cathode filament spiral increases, and the cathode begins to emit electrons; due to the potential difference between the cathode and the anode, this electron flow accelerates and moves towards the anode.

When the electron beam hits the anode, it sharply slow down and dissipate, while losing most of the previously acquired energy – part of the kinetic energy of the electrons turns into heat (99%), another part of the energy goes to X-ray radiation (1%), which is called **Bremsstrahlung** (i.e. electromagnetic radiation produced by the deceleration of a charged particle after passing through the electric and magnetic fields of a nucleus). It should be noted that electron deceleration does not occur due to collision of heated electron with the anode's atoms, but due to deceleration in anode atoms static field.

Characteristic X-rays is radiation that occurs when an electron passes from the outer shell to a vacancy located at the lower level of the atom. The energy of this radiation is equal to the difference between the energies of the outer and inner electron shells.

Characteristic X-rays radiation arises due to the fact that accelerated electrons penetrate deep into the atom and knock electrons out of the inner shells.

Electrons from upper levels move to free places and, as a result, photons of characteristic X-rays radiation are emitted with an energy hv equal to the difference in energies of the outer E_{outer} and inner E_{in} of electron shells (3):

$$hv = E_{outer} - E_{in}. \quad (3)$$

The scheme of the occurrence of characteristic X-ray radiation is shown in Fig. 5. There are characteristic lines K, L, M, etc., depending on which electron shell of the atom the transition to the vacancy occurred from. The names of these lines denote the electronic shells of the atom. Fig. 6 shows the energy scheme of the levels of the atom [3].

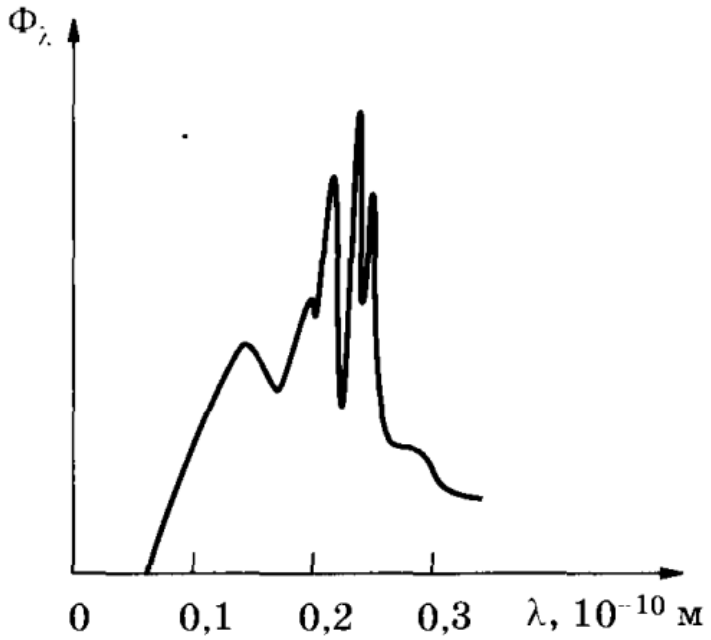

Fig. 5. Scheme of the occurrence of characteristic X-ray radiation [5]

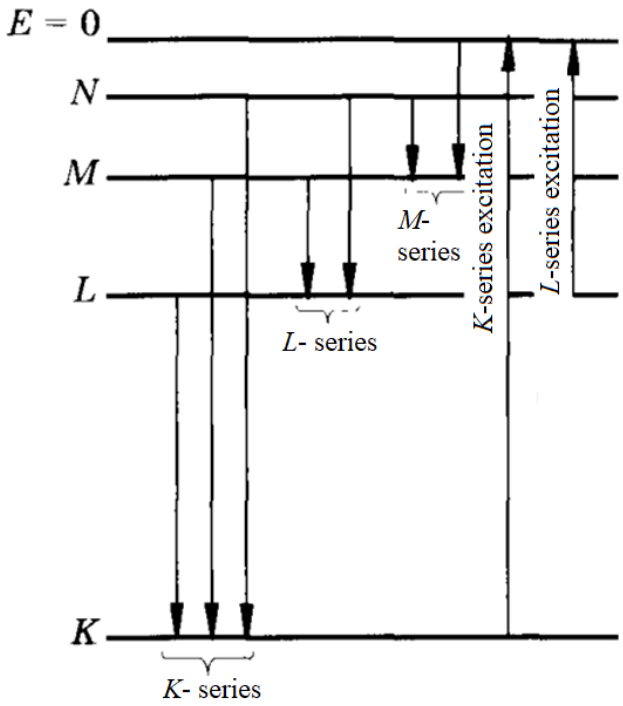

Fig. 6. Diagram of the energy levels of the atom [5]

1.8. Characteristic X-ray properties

- The characteristic X-ray spectrum of an atom does not depend on the chemical compound in which this atom is included. Thus, for example, the X-ray spectrum of the oxygen atom is the same for O, O_2, and H_2O, while the optical spectra of these compounds are essentially different.
- Characteristic X-ray radiation always occurs when there is free space in the inner shells of an atom, regardless of the reason that caused it. So, for example, characteristic radiation accompanies one of the types of radioactive decay, which consists in the capture of an electron from the inner shells by the nucleus.

1.9. Moseley's law

The characteristic X-ray spectra of different atoms are of the same type, since the inner layers of different atoms are the same

and differ only energetically. The energy difference is due to the different force impact from the nucleus that increases as the ordinal number of the element increases. Figure 7 shows experimental dependencies that illustrate Moseley's law.

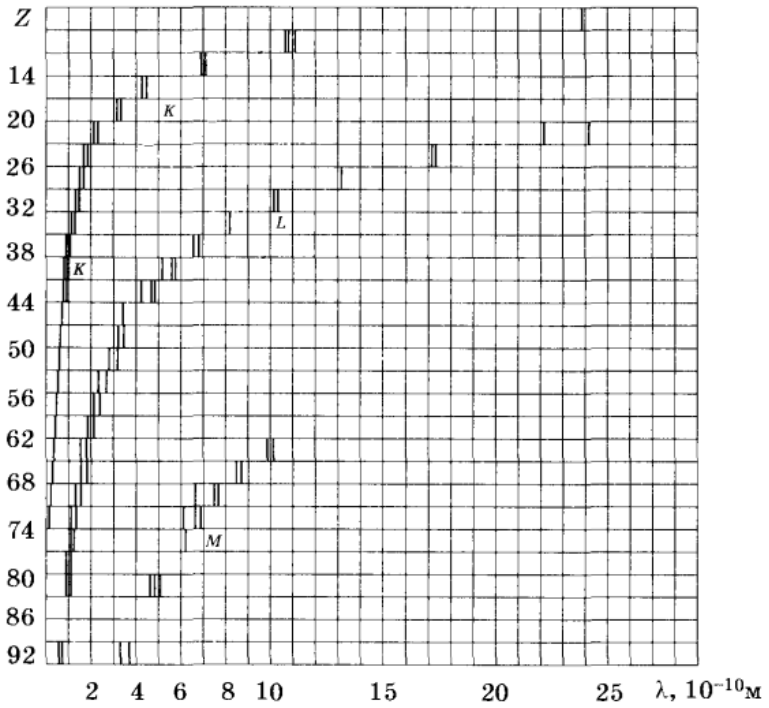

Fig. 7. Experimental dependence of the charge number of the element *Z*, for which the characteristic spectrum (*K*, *L*, *M* lines) is observed, on the obtained radiation wavelength λ in Angstroms (10^{-10} meters) [5]

Moseley's Law: The characteristic spectra shift towards higher frequencies ν (or shorter wavelengths λ) as the nuclear charge Z increases (4):

$$\nu = A(Z - B)^2. \quad (4)$$

Where *v* is the frequency of the observed characteristic line in Hertz; *Z* is the charge number; *A* and *B* are constants depending on the line type (*K*, *L*, etc.). The constant *A* is measured in Hertz. The constant *B* is a dimensionless quantity.

Moseley's law allows you to determine the charge number of the atom that emitted the characteristic radiation. According to the found frequency or the measured wavelength of the characteristic X-ray radiation by Moseley's law you can find the corresponding element from the periodic table [3, 5].

1.10. Ions and ionizing radiation

Ion is an atom or molecule that has an electrical charge. An electric charge in an ion arises due to an excess of electrons ("-" negatively charged ion) or a lack of electrons ("+" positively charged ion).

Ionizing radiation is any radiation whose interaction with the medium leads to the formation of different signs electric charges and is a stream of charged and (or) uncharged particles and forms ions of different signs when interacting with the medium. It can also be said that **ionizing radiation** is radiation that is created during radioactive decay, deceleration of charged particles in matter, nuclear transformations, and when interacting with the medium form ions of various signs.

2. Interaction of X-ray radiation with matter

The registration and use of X-ray radiation as well as its impact on biological objects, are determined by the primary processes of interaction of X-ray radiation (X-ray photon) with the electrons of atoms and molecules of matter. The primary processes of interaction mean the processes of scattering and absorption of X-rays by a substance. The photon energy hv and the ionization energy of the atom A_i determine these processes [5].

Depending on the ratio of the photon energy hv and the ionization energy A_i, there are three main processes that take place:

- **Coherent elastic scattering** (for $hv < A_i$)
- **Inelastic scattering** (**Compton scattering**) (for $hv \gg A_i$)
- **Photoelectric effect** (for $hv \geq A_i$)

Photon absorption plays the main role for low energies. The probability of the photoelectric effect decreases rapidly with increasing photon energy. As the X-ray energy increases, Compton scattering becomes the main mechanism of the interaction between photons and matter. If the value of the momentum transferred during the collision of a photon with an electron is small then the scattering of photons on atomic electrons occurs without loss of energy (Rayleigh or coherent elastic scattering).

Let's take a closer look at these processes.

2.1. Coherent elastic scattering

Coherent elastic scattering (**Rayleigh scattering**) is the scattering of long-wavelength X-ray radiation that occurs without changing the wavelength (Fig. 8). This scattering occurs if the ionization energy is greater than the photon energy: $A_I > hv$.

The ionization energy A_I is the energy required to remove internal electrons from an atom or molecule.

Fig. 8 illustrates the scheme of coherent elastic scattering occurrence. An incident photon, which has the energy hv, collides with an atom of matter. In the course of interaction between an atom of matter and an incident photon, a scattered photon with energy hv' is formed. The energy of the scattered photon is equal to the energy of the incident photon $hv' = hv$ in coherent elastic scattering. Rayleigh scattering occurs with the conservation of frequency and with a phase of scattered photon that differs by π from the phase of the incident photon.

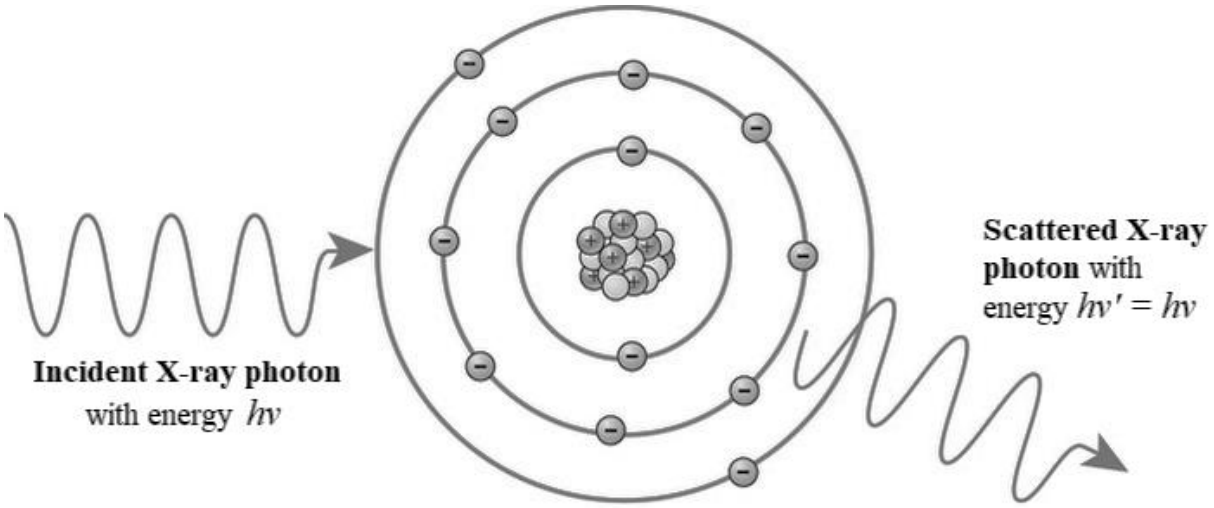

Fig. 8. Scheme of coherent elastic scattering [10]

2.2. Compton scattering

Inelastic scattering (**Compton scattering, Compton effect**) is the scattering of X-rays that occurs with wavelength change of scattered radiation (Fig. 9). Compton scattering appears if the ionization energy is less than the photon energy: $A_I < hv$.

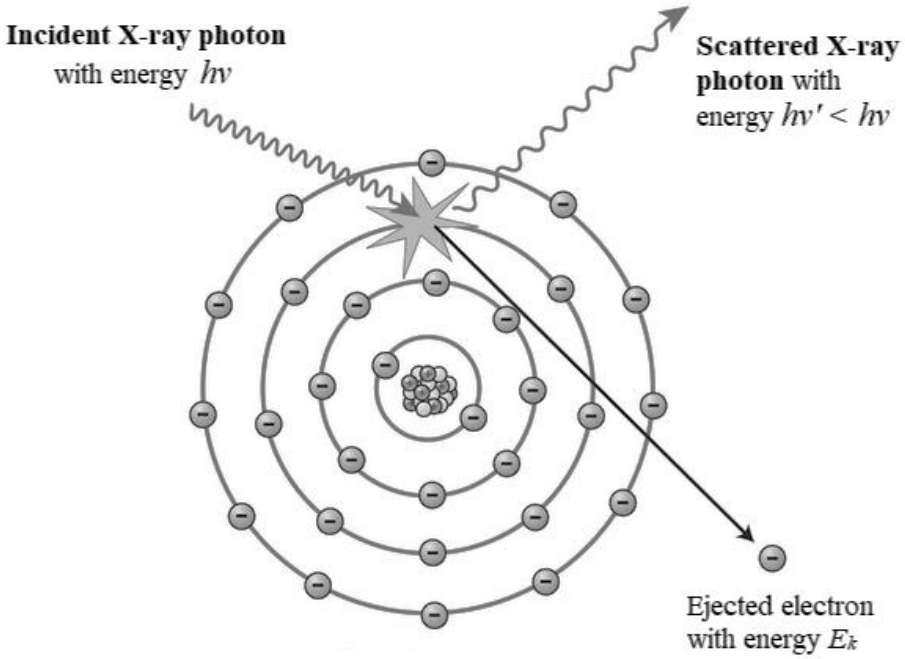

Fig. 9. Scheme of inelastic scattering [10]

Let's explain Compton scattering. When interacting with an atom the energy $h\nu$ of the incident photon (denoted as the primary photon in Fig. 9) is spent on the formation of a new scattered X-ray photon with energy $h\nu'$ (denoted as the scattered photon in Fig. 9) and on the detachment of the electron from the atom (ionization energy A_I) with the kinetic energy E_k imparted to the electron. Thus, the ionization of an atom or molecule occurs.

We can write the law of conservation of energy for the Compton effect in the following form (5):

$$h\nu = h\nu' + E_k + A_I. \quad (5)$$

If we take into account that the Compton effect usually occurs on free electrons, then the energy of the incident photon $h\nu$ is much higher than the ionization energy of the atom A_I: $h\nu \gg A_I$. The equation describing the law of conservation of energy in the system can be rewritten as follows (6):

$$h\nu \approx h\nu' + E_k. \quad (6)$$

2.3. Photoelectric effect

Photoelectric effect is the release of electrons that are in a substance in a bound state, under the influence of photons (Fig. 10).

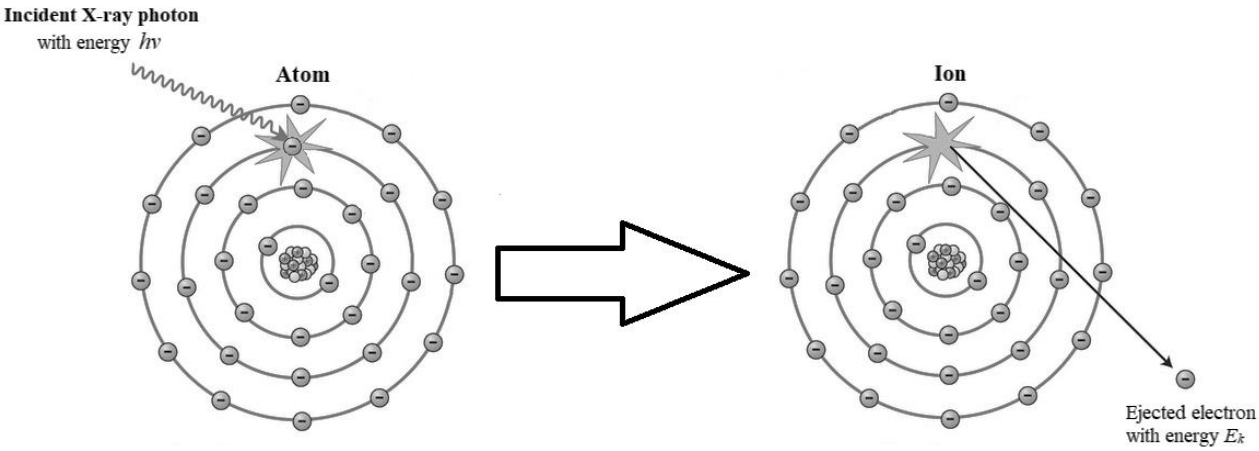

Fig.10. Scheme of the Photoelectric effect [10]

Under the Photoelectric effect we denote the process that an atom absorbs an incident photon hv and after emits an electron. In this case, the incident photon interacts with the electron bound in the atom (inner electron) and transfers its energy to it. The electron receives kinetic energy E_k and leaves the atom. In this case, one of the electron shells of the atom becomes free (a vacancy is formed) and the atom remains in an excited state. Thus, the ionization of the atom occurs (the ionization energy A_I is imparted to the atom). The law of conservation of energy in the photoelectric effect can be represented as (7):

$$hv = E_k + A_I. \quad (7)$$

Since in this process almost all of the photon energy is spent on ionization of the atom, the law of conservation of energy can be rewritten in the following form (8):

$$hv \approx A_I. \quad (8)$$

Compton scattering and the photoelectric effect can be accompanied by characteristic X-ray radiation since the formed vacancies are filled with electrons from the outer shells of the atom after the knocking out of internal electrons [11].

2.4. Absorption of X-rays in a medium

X-rays are absorbed to some extent by all substances through which they pass. The fraction of ray energy absorbed in a substance depends on the thickness of the absorbing layer, the nature of the substance, and the wavelength of the X-rays. X-rays lose part of their energy when passing through matter due to several processes: the conversion of photon energy into other types of energy, which is called true absorption, and a change in the direction of their propagation, i.e. scattering. The X-rays absorption law in matter can be obtained under the assumption that the fraction of the energy of X-rays absorbed when they pass through a sufficiently thin layer of matter is proportional to the thickness of this layer. In this case, the coefficient of proportionality is the so-called absorption coefficient μ, which depends on the atomic number of the substance Z and the radiation wavelength. There are also mass and linear radiation absorption coefficients.

Absorption of X-ray in a medium law (8):

$$\Phi = \Phi_0 e^{-\mu x} \quad or \; I = I_0 e^{-\mu x}. \tag{8}$$

Where μ is the linear absorption coefficient in m^{-1}, x is the penetration depth in m, Φ_0 is the X-ray flux incident on the medium in Watts (W), Φ is the X-ray flux after medium absorption in W. I_0 is the intensity of the X-ray radiation incident on the medium in W/m^2, I is the intensity of the X-ray radiation after absorption by the medium in W/m^2.

Half-value layer (HVL) or half-value thickness $d_{1/2}$ is the thickness of the substance at which the intensity of the incident radiation (or the flux of transmitted radiation Φ_0 to $\Phi_0/2$) is reduced by one half. $d_{1/2}$ is measured in units of length (meters, millimeters, etc.).

An illustration of finding the half-value thickness $d_{1/2}$ for the substance is in Fig. 11.

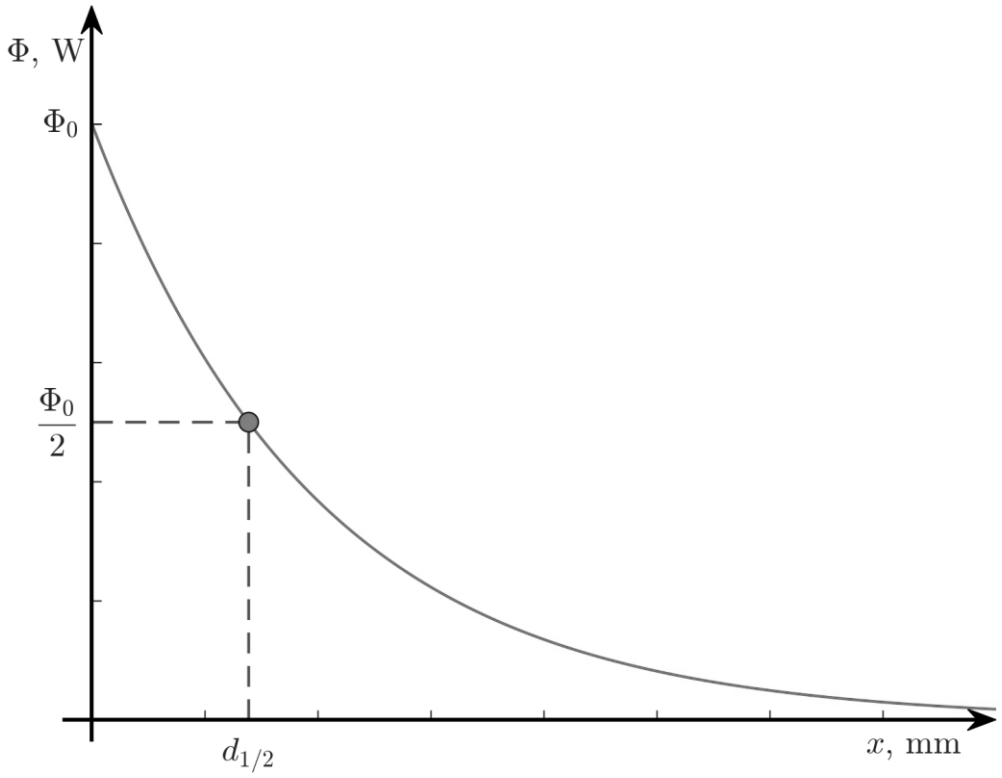

Fig. 11. Absorption of X-ray flux in a medium law. The thickness of the substance x in mm is plotted along the horizontal axis. The vertical axis shows the flux of transmitted radiation Φ in Watts. The HVL $d_{1/2}$ is located on the graph by the value of the initial flow divided by two and then finding the corresponding coordinate on the horizontal axis

The HVL $d_{1/2}$ is used to evaluate the penetrating power of the X-rays. The HVL $d_{1/2}$ depends both on the properties of the irradiated substance (density ρ and atomic number Z) and on the hardness of the incident X-ray radiation (value of wavelength λ). Here down below is a derivation of HVL $d_{1/2}$ from the linear absorption factor μ.

Let us write down the absorption of X-ray flux law at the value of penetration depth $x = d_{1/2}$. Then the flux of transmitted radiation should be equal to $\Phi = \Phi_0$ *(9)*:

$$\frac{\Phi_0}{2} = \Phi_0 e^{-\mu d_{\frac{1}{2}}} \rightarrow \frac{1}{2} = e^{-\mu d_{\frac{1}{2}}} \rightarrow e^{\mu d_{\frac{1}{2}}} = 2 \rightarrow \mu d_{\frac{1}{2}} = \ln 2 = 0.69. \quad (9)$$

Thus, the dependence of the HVL of the substance is inversely proportional to the linear absorption coefficient of the substance (10):

$$d_{1/2} = \frac{ln2}{\mu} = \frac{0.69}{\mu} \text{ or } d_{1/2} \approx \frac{1}{\rho\lambda^3 Z^3}. \quad (10)$$

2.5. Linear and mass absorption coefficients

The process of radiation attenuation can be depicted schematically as in Fig. 12.

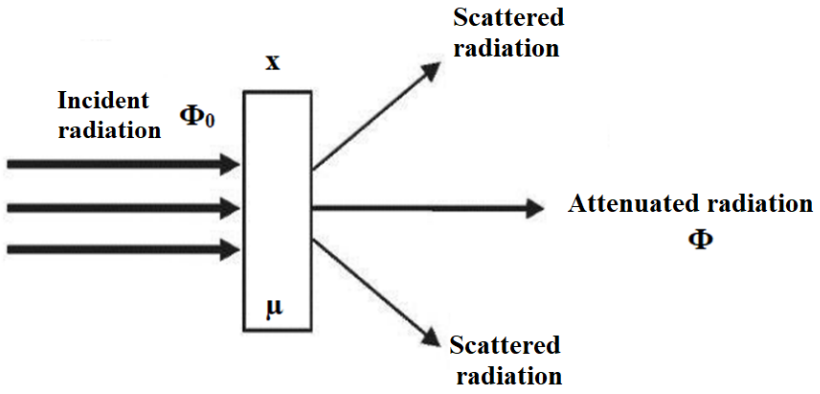

Fig. 12. Scheme of the X-ray flux absorption during interaction with the substance [5]

The linear absorption coefficient *μ* (linear attenuation coefficient**)** is a parameter characterizing the attenuation of the incident X-ray flux (intensity) of radiation per unit of layer thickness, which depends on the density of the substance ρ, the atomic number Z of this substance and the wavelength of the incident X-ray radiation λ (11):

$$\mu = \rho k \lambda^3 Z. \quad (11)$$

Where μ is the linear absorption coefficient in m^{-1}, ρ is the density of the substance in kg/m^3, k is the proportionality factor in W^{-1}, λ is the wavelength in m, Z is the dimensionless atomic number.

The linear absorption coefficient takes into account the contribution of the processes of absorption μ_a (contribution of the photoelectric effect μ_p) and scattering μ_s (contribution of coherent scattering μ_{cs} and incoherent scattering μ_{ics}) (12):

$$\mu = \mu_a + \mu_s = \mu_p + \mu_{cs} + \mu_{ics}. \quad (12)$$

In addition to the linear absorption coefficient, the mass absorption coefficient is often used in practice, since the mass absorption coefficient is a constant value for a given substance and does not depend on its state of aggregation or density of a substance.

The mass absorption coefficient μ_m is a parameter that characterizes the attenuation of the incident X-ray flux (intensity) of radiation per unit of layer thickness when passing through 1 gram of a substance. The mass coefficient does not depend on the density of the substance ρ and is determined only by the atomic number Z of this material (compound) and the X-ray wavelength λ (13):

$$\mu_m = k\lambda^3 Z^3. \quad (13)$$

The mass and linear absorption coefficients are related as (14):

$$\mu_m = \mu / \rho. \quad (14)$$

Based on the dependences of the absorption coefficients μ and μ_m on the parameters λ and Z, we can conclude that:

- Short-wavelength X-rays are absorbed much less than long-wavelength X-rays, since there is a dependence of the absorption coefficient on the wavelength to the third power: μ, $\mu_m \sim \lambda^3$.
- Elements with a lower value Z absorb X-rays much weaker than elements with a higher value Z, since there is a dependence of the absorption coefficient on the atomic number of material to the third power: μ, $\mu_m \sim Z^3$.

2.6. Detecting of X-ray

X-ray detector is a device for detecting and determining the intensity of X-rays. There are many types of X-ray detectors, differing in principle of operation and technical characteristics.

The principle of detecting and determining the intensity of the X-ray flux is based on the absorption of an X-ray photon in the sensitive material of the detector and the conversion of the absorbed energy into a signal or image, which can be interpreted as a quantity related to the number of absorbed photons. There are two main methods for registration X-rays: the photographic methods and the electronic methods (Fig. 13).

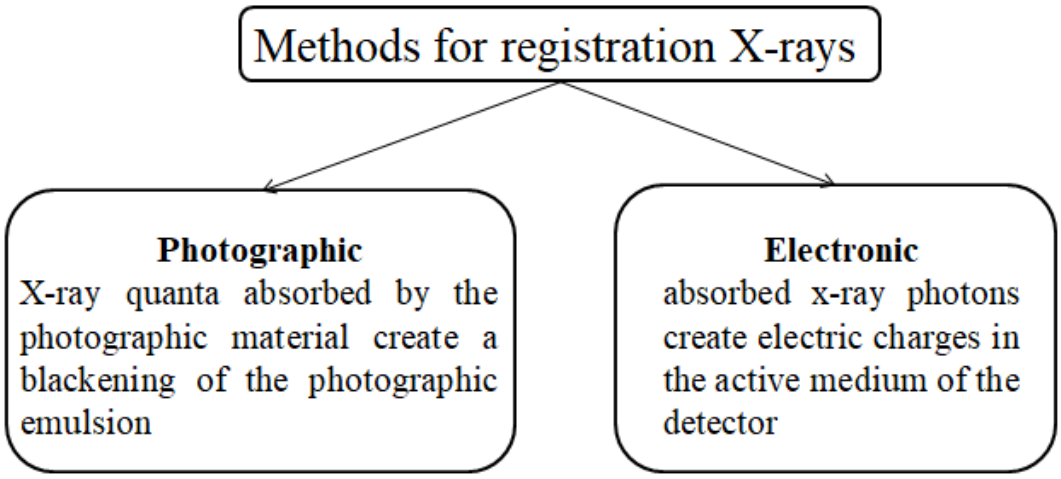

Fig. 13. Methods for registration X-rays

Photographic methods of registration of X-rays are based on the fact that X-ray quanta absorbed by the photographic material create a blackening of the photographic emulsion. The density of blackening can be compared with the intensity of X-rays. At present, this method is rarely used. The devices that are used for this method are called imaging detectors.

Electronic methods (dose measurement devices) for detecting X-rays are based on the fact that absorbed X-ray photons create

electric charges in the active medium of the detector. These charges can be measured and recalculated in the intensity of the photon flux. The most interesting among electronic detectors are proportional counters (they operate in the mode of counting individual quanta) and ionization chambers (allow you to measure powerful integral photon fluxes). The detectors used for this method are called dose measurement devices [12].

3. Dosimetry

Dosimetry (Radiation dosimetry) is a section of applied nuclear physics that studies ionizing radiation, physical quantities that characterize the radiation field or the interaction of radiation with object (usually the human body), as well as the principles and methods for determining these quantities [13].

3.1. Absorbed dose

Absorbed dose (***D***) is the ratio of the average energy transferred by ionizing radiation to a substance in an elementary volume per mass of the substance in this volume. The unit of absorbed dose in the SI system is Gray [Gy] or Joule per kg (the non-systemic unit is rad, 1 rad = 10^{-2} Gy. Rad is defined as the dose of absorption of any ionizing radiation, which is accompanied by the release of 100 erg of energy in 1 g of absorbing material (1 rad = 100 erg / g)) (15).

$$D = \frac{E}{m}. \quad (15)$$

Where E is the energy absorbed by the substance in Joule, m is the mass of the substance in kg.

3.2. Equivalent dose

Equivalent dose (***H***) - the value necessary to assess the effect of radiation on living organisms. It is derived from the physical quantity – absorbed dose D for organ (radiation type R) and tissue T, but also takes into account the biological effectiveness of the radiation, which is dependent on the radiation type and energy. The SI unit of equivalent dose H_T is Sievert [Sv] (16).

$$H_T = \sum_R D_{T,R} * w_R. \quad (16)$$

Where $D_{T,R}$ is the absorbed dose in Gy, ω_R is the radiation weighting factor with no unit. The unit of equivalent dose is [J ⁄ kg] or Sievert [Sv].

1 Sv is equal to the equivalent dose at which the dose of absorbed gamma radiation is 1 Gy. The value of the equivalent dose determines the degree of danger of the radiation dose for a living organism.

It is customary in dosimetry to compare the biological effects of different radiations with the corresponding effects caused by X-rays and gamma rays.

The coefficient ω_R is the **radiation weighting factor** showing how many times the effectiveness of the biological action of this type of radiation is greater than X-ray or gamma radiation, with the same dose of radiation in tissues. This coefficient ω_R depends on the type of particle, on the energy of the particle. It has no units of measurement.

The value ω_R for β-, γ-, X-rays is 1. For α-radiation it is 20.

3.3. Effective dose

The effective dose (***E***) is the amount of ionizing radiation used as a measure for the risk of long-term irradiation consequences to the entire human body and its individual organs, taking into account the occurrence of long-term adverse effects of radiation in them. SI unit is Sievert [Sv].

The effective dose is equal to the equivalent dose that creates the same risk of adverse effects in case of uniform exposure. In case of non-uniform exposure, the effective dose is equal to the product of the equivalent dose (H) and the tissue weighting factor (W_T) (17). It is impossible to measure the effective dose of radiation to the whole body therefore it can only be calculated as sum of effective doses that obtained different organs and tissues by exposure. It is calculated as the sum of the products of equivalent doses (H) in individual organs

and tissues and the corresponding values of the weighting factor (W_T) indicated in Table 1.

$$E = \sum_T H_T * W_T = \sum_{T,R} W_T * W_R * D_{T,R}. \quad (17)$$

Where H_T is the equivalent dose in an organ or tissue in Sv, W_T is the weighting factor for the corresponding organ or tissue with no unit.

Weighting factor for tissues and organs when calculating the effective dose ($\boldsymbol{W_T}$) are equivalent dose multipliers in organs and tissues used in radiation protection to take into account the different sensitivity of different organs and tissues in the occurrence of stochastic effects of radiation [5].

Table 1

Some W_T weighting factors for tissues and organs when calculating the effective dose

Name of an organ or a tissue	$\boldsymbol{W_T}$
Gonads	0.2
Bone marrow (red)	0.12
Colon	0.12
Lungs	0.12
Stomach	0.12
Bladder	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01

According the *International Commission on Radiological Protection* (ICRP) system of radiological protection depending on the type of medical imaging, the effective dose is calculated as follows according to the Table 2[14]:

Table 2

The effective dose obtained by patient depending on the type of medical imaging

Target organs	**Exam type**	**Effective dose in adults**
CT of the head	Single series	2 mSv
Chest	CT of the chest	7 mSv
Heart	Coronary CT angiography	12 mSv
Abdominal	CT of abdomen and pelvis	10 mSv
Spine	Spine X-ray	1.5 mSv
Mammography		0.4 mSv

3.4. Exposure dose

Exposure dose (***X***) is a measure of air ionization by x-rays and gamma rays. The unit of exposure dose in the SI system is Coulomb/kg [C/kg] (non-systemic unit is roentgen R). 1 R = 2.57976×10^{-4}C/kg. The radiation dose created by X-ray or gamma radiation is measured in roentgens; for all other types of ionizing radiation, this dose is measured in the physical equivalent of a roentgen. One unit of X-ray or gamma radiation corresponds to radiation, which in 1 ml (1 cm) of dry air (weighing 0.001293 g) at a pressure of 760 mm Hg at a temperature of 0 °C causes ionization equal to 2.083×10^{9} pairs of ions (i.e. about 2 billion) [A1].

To evaluate the biological activity of neutrons that corresponds to a neutron flux with a biological effect equivalent to that of 1 R gamma radiation the unit is used called the biological equivalent of a roentgen or the roentgen equivalent man [rem] that is non SI unit (18).

$$X = \frac{D}{f}. \tag{18}$$

Where *D* is the absorbed dose, *f* is the transition coefficient depending on the irradiated substance and photon energy.

3.5. Limit dose

The limit dose is the amount of annual effective or equivalent dose to an organ or tissue that must not be exceeded under normal operating conditions. Compliance with the annual dose limit prevents the occurrence of deterministic effects (i.e., injuries that increase in probability and severity with increasing radiation dose and for which there is a dose threshold), and the possibility of stochastic effects (i.e., harmful biological effects of radiation that do not have a dose threshold occurrence, the probability of occurrence of which is proportional to the dose and for which the severity of the manifestation does not depend on the dose) remains at the same time at an acceptable level [15].

Dose limits in Russia:

The allowable effective dose per year is 1 mSv for the civilian population.

There are *group A* and *group B* among the personnel (population) according Russian official SanPiN (Sanitary Norms and Rules) classification [16]. In terms of X-ray safety *group A* personnel includes persons who work directly with the radiation source. For *group A* personnel the permissible effective dose is on average 20 mSv per year for any consecutive 5 years. In this case, the annual exposure rate should not exceed 50 mSv.

Group B personnel include persons who do not directly work with the radiation source but are exposed to them according to X-ray safety term. For the working personnel of *group B* the permissible effective dose is on average 5 mSv per year for any consecutive 5 years. In this case, the annual exposure rate should not exceed 12.5 mSv.

Dose limits according the ICRP

Categories of exposure and exposure situations are used to consider how best to approach radiological protection in different circumstances according the International Commission on Radiological Protection (ICRP) [14].

Exposure Categories are: occupational, public, and medical:

- **Occupational Exposure** is exposure of workers incurred as a result of their work.
- **Public Exposure** is exposure of members of the public other than occupational and medical exposures, and not including the normal local natural background radiation.
- **Medical Exposure** is exposure of patients as part of their diagnosis or treatment, volunteers helping in the support and comfort of patients, and volunteers in biomedical research.

Exposure Situations are: planned, existing, and emergency:

- **Planned Exposure Situations** are situations where radiological protection can be planned in advance, and exposures can be reasonably predicted.
- **Existing Exposure Situations** are situations that already exist when a decision on control has to be taken.
- **Emergency Exposure Situations** are unexpected situations that may require urgent protective actions.

Categories and Situations are considered together to help guide the best approach to radiological protection in a particular circumstance is presented in Table 3a [17].

Table 3a

Exposure Categories and Situations by the ICRP

	Occupational Exposure	**Public Exposure**	**Medical Exposure**
Planned Exposure Situation	e.g. working in a hospital, uranium mine, or nuclear power plant	e.g. visiting a hospital, living near a nuclear power plant	e.g. getting an X-ray, CT scan, or radiation treatment
Existing Exposure Situation	e.g. aircrew and astronauts exposed to cosmic radiation	e.g. radon gas in the home	n/a
Emergency Exposure Situation	e.g. in the immediate response to an accident	e.g. during a major accident	n/a

Information on recommended dose limits for the public according the ICRP is presented in Table 3b [17].

Table 3b

Dose Limits Recommended by the ICRP

Type of Dose limit	**Limit on Dose from Occupational Exposure**	**Limit on Dose from Public Exposure**
Effective Dose	20 mSv per year, averaged over defined periods of 5 years, with no single year exceeding 50 mSv	1 mSv in a year *In special circumstances, a higher value could be allowed in a single year, provided that the average over 5 years does not exceed 1 mSv per year*
Equivalent Dose to the Lens of the Eye	20 mSv per year, averaged over defined periods of 5 years, with no single year exceeding 50 mSv	15 mSv in a year
Equivalent Dose to the Skin *Averaged over 1 cm^2 of skin regardless of the area exposed*	500 mSv in a year	50 mSv in a year
Equivalent Dose to the Hands and Feet	500 mSv in a year	-

3.6. Natural background radiation

Background radiation is the background created by natural radioactive sources. These sources include: cosmic rays, the radioactivity of water and subsoil, the radioactivity of the nuclei that make up the human body. This background is approximately equal to the equivalent dose of 125 mrem (100 rem = 1 Sv).

3.7. Protection against ionizing radiation

It is necessary to protect personnel from harmful effects when working with any sources of ionizing radiation. There are three types of protection:

- **time protection** means that person should be under the influence of ionizing radiation a minimum amount of time;

- **distance protection** means to minimize harm from ionizing radiation person should be at the maximum distance from the radiation source;

- **material protection** means that substances have different ability to absorb different types of ionizing radiation. A person can use some materials as a shield against radiation sources (Fig.14).

As mentioned above, a sheet of paper or a layer of air a few cm thick is sufficient to protect against **α-radiation**.

Glass a few cm thick or aluminum plates are sufficient to protect against **β-radiation**.

It is necessary to use heavy metals (for example, tungsten, lead) to protect against **γ-radiation, X-rays**.

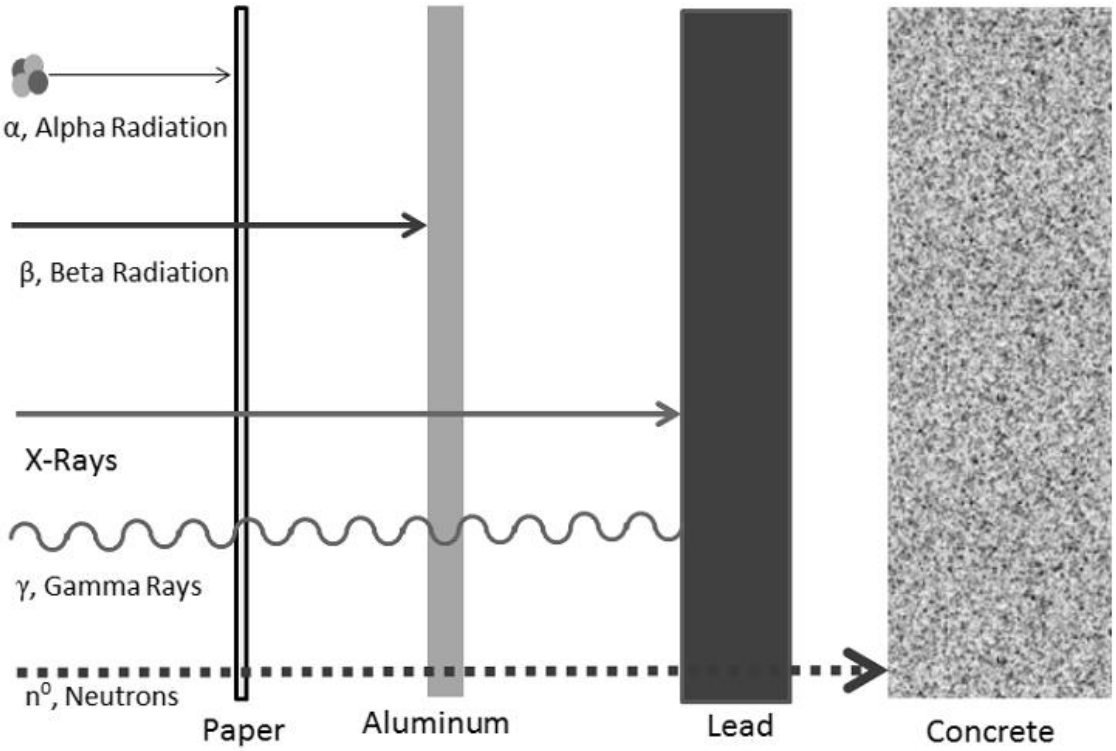

Fig. 14. Different penetration levels of different products of decay, with gamma being one of the most highly penetrating and alpha being one of the least penetrating

4. The effect of X-rays for a living things

Due to the fact that X-ray radiation can penetrate quite deeply into the human body, it leads to a negative effect on cells and organs. There are several ways that X-rays affect the body (Fig.15) [5,18,19]:

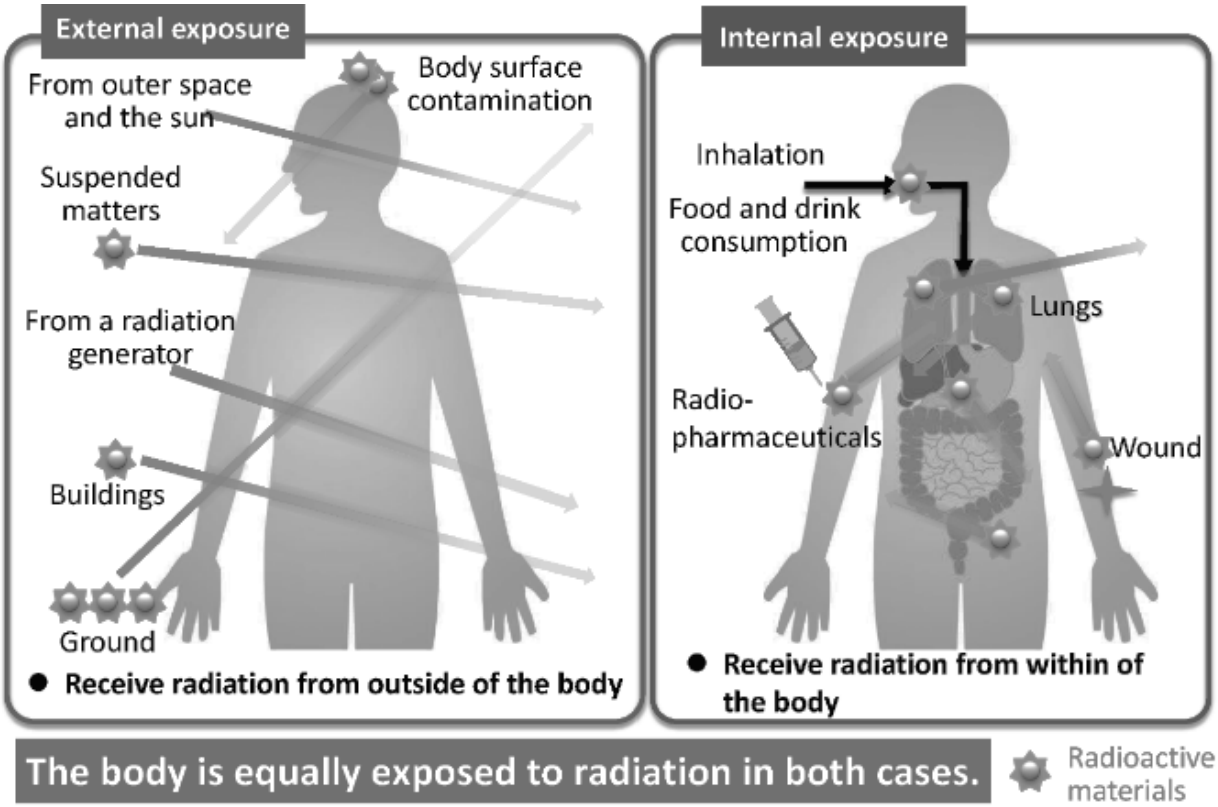

Fig. 15. External exposure and internal exposure illustrations [20]

1. **External Exposure** is an exposure comes from a source that is outside the body.

2. **Internal Exposure** is an exposure occurs when a radioactive substance enters the body, for example, with food, water, dust particles that enter the respiratory tract, through damaged skin, or by absorption through healthy skin.

The impact of X-ray radiation on a living organism is that changes in various biochemical processes occur in the body, as a result

of which the structural elements of cells and tissues are disrupted, leading to:

1. Damage to amino acids, polypeptide and hydrogen bonds in proteins. As a result there is the loss of biological functions;

2. In nucleic acids, changes in individual structures (nucleotides) and the helical structure. As a result there is gene and chromosomal mutations occur;

3. In lipids, peroxidation of unsaturated fatty acids is observed. As a result there is the formation of aldehydes, ketones and alcohols.

Radiation sickness is a disease resulting from exposure to various types of ionizing radiation. Depending on the nature of the effects of radiation, acute radiation syndrome and chronic radiation syndrome can be distinguished.

Acute Radiation Syndrome (ARS) is a disease caused by a single or prolonged (relatively short period of time, for example, several days) exposure most part of the body or its entire surface to ionizing radiation of a fairly high power (1 Gy (100 rad) or more).

Main clinical syndromes:

- hematological;
- hemorrhagic;
- damage to the gastrointestinal tract;
- damage to the endocrine system;
- damage to the nervous system.

Depending on the radiation dose there are the following severity degrees of damage:

- **I** degree (mild injury) from 1 to 2 Gy (100–200 rad);
- **II** degree (moderate injury) from 2 to 4 Gy (200–400 rad);
- **III** degree (severe injury) from 4 to 6 Gy (400–600 rad);
- **IV** degree (very severe injury) over 6 Gy (from 600 rad).

Chronic Radiation Syndrome (CRS) is a chronic disease that develops as a result of prolonged (often repeated) exposure to ionizing radiation in relatively small doses (but exceeding the maximum

allowable). In other words, one of the main conditions for the occurrence of CRS is overexposure that is absorption by the body tissues of an exorbitant total dose, which causes such changes in the tissues that cannot be quickly and completely compensated. The main clinical syndromes are similar to those seen in ARS.

The limiting total doses are:

- with a single irradiation is 0.5 Gy (50 rad),
- with repeated irradiation is 1 Gy (100 rad),
- per quarter is 2 Gy (200 rad),
- per year is 3 Gy (300 rad).

If we are talking about production activities, then within 2–3 years, a value lying in the range of 1.2–1.8 Gy (120–180 rad) should be considered.

Depending on the severity of clinical manifestations, CRS is divided into the following degrees of severity:

- **I** degree (mild);
- **II** degree (moderate);
- **III** degree (severe).

4.1. Direct and indirect effects of ionizing radiation on the body. Water radiolysis

Water radiolysis is the decay of water molecule (H_2O) under the impact of radiation into hydrogen (H) and hydroxyl (OH) radical, followed by the formation of molecular hydrogen and hydrogen peroxide.

It is known that when radiation passes through a substance, ions and excited molecules are formed. In case of water (19):

$$H_2O \rightarrow H_2O^+ + \text{e}. \qquad (19)$$

The H_2O^+ ion that appears and the free electron very quickly, within a time measured for a tiny fractions of a second, react with water molecules (20), (21):

$$H_2O^+ + H_2O \rightarrow H_3O^+ + OH, \quad (20)$$

$$e + H_2O \rightarrow H_2O^- \rightarrow H + OH^-. \quad (21)$$

Thus, as a result of the transformation of initially unstable ions, H and OH radicals and new ions stable in water are formed: hydroxonium ions H_3O^+ and hydroxyl OH^-. Atomic hydrogen and hydroxyl radical are unstable, their lifetime does not exceed millionths of a second. During this time, the H and OH radicals moving in water have time to interact (22), (23).

$$H + H \rightarrow H_2, \; OH + H \rightarrow H_2O, \quad (22)$$

$$HO + OH \rightarrow H_2O_2. \quad (23)$$

As a result of these reactions, water is formed again and new already stable compounds appear: molecular hydrogen and hydrogen peroxide. They are usually called molecular products of water radiolysis, in contrast to the unstable radical products H and OH.

The processes occurring during the radiolysis of water can be represented as a chain of successive transformations:

Water == > ions (H_2O^+, e) == > radicals (H and OH) == > molecular products (H_2, H_2O_2).

Molecular products upon irradiation of very pure water accumulate in a very low concentration that is no more than ten thousandths of a percent of the amount of the original substance. The reason for this is the destruction of the resulting compounds by H and OH radicals (24), (25).

$$H_2O_2 + H \rightarrow H_2O + OH \quad (24)$$

$$H_2 + OH \rightarrow H_2O + H \quad (25)$$

So the radicals, generating molecular products, also destroy them. There is a cycle: water == > products of radiolysis == > water.

4.2. Protein damage

The products of water radiolysis, reactive oxygen species and organic radicals are capable of changing the structure of biologically

significant macromolecules with a violation of their biological function. The processes occurring in proteins, DNA and phospholipids are important for further life of irradiated cell. The structure of proteins is disturbed (breaks of disulfide bridges, hydrogen bonds, peptide chains, oxidation of sulfhydryl groups, etc.). As a result, the secondary and tertiary structure of proteins changes, which leads to a violation of their biological properties, including enzymatic activity. Radiation damage to DNA manifests itself in the form of violations of the structure of nitrogenous bases, the appearance of DNA breaks, DNA-DNA and DNA-protein cross-links, and violations of DNA complexes with other molecules. The role of the "oxygen effect" is significant in DNA damage. The number of DNA base damage increases by more than 3 times in the presence of oxygen. As a result, the genetic apparatus of the cell is damaged [21].

4.3. Lipid peroxidation

Lipid peroxidation is a chain reaction of sequential oxidation of fatty acids or their residues in other lipids, which occurs mainly under the influence of radioactive radiation (Fig. 16). The consequence is the formation of free radicals. It is the process in which free radicals "steal" electrons from the lipids in cell membranes, resulting in cell damage. This process occurs in the body constantly, but it is physiologically balanced. However, with a large increase in the production of free radicals due to the failure of antioxidant protection or prooxidant effects, oxidative stress develops, which is accompanied by damage to lipids, proteins, and DNA. The chemical products of this oxidation are known as lipid peroxides or **lipid oxidation products** (LOPs).

The danger for the body lies in the fact that free radicals accelerate the aging of the body, lead to inflammatory processes in all tissues (including the nervous system and brain cells) and break the functions of body system.

Substrates of lipid peroxidation processes in cell membranes are polyunsaturated fatty acids (PUFA) (for example, arachidonic acid, AA or ARA). Oxygen radicals take away hydrogen H from the groups – CH_2 – of a polyunsaturated fatty acid, located next to the double bond. This is energetically more favorable for them, since the unpaired electron is delocalized between three carbon atoms. A fatty acid radical is formed, which easily attaches O_2 and turns into a fatty acid peroxide radical. This radical can take hydrogen from another fatty acid molecule. A chain reaction ensues. Peroxides readily decompose to form aldehydes by breaking the carbon-carbon bond adjacent to the peroxide group in the fatty acid. This is energetically more favorable, since these aldehydes have a system of conjugated double bonds (C = C, C = O).

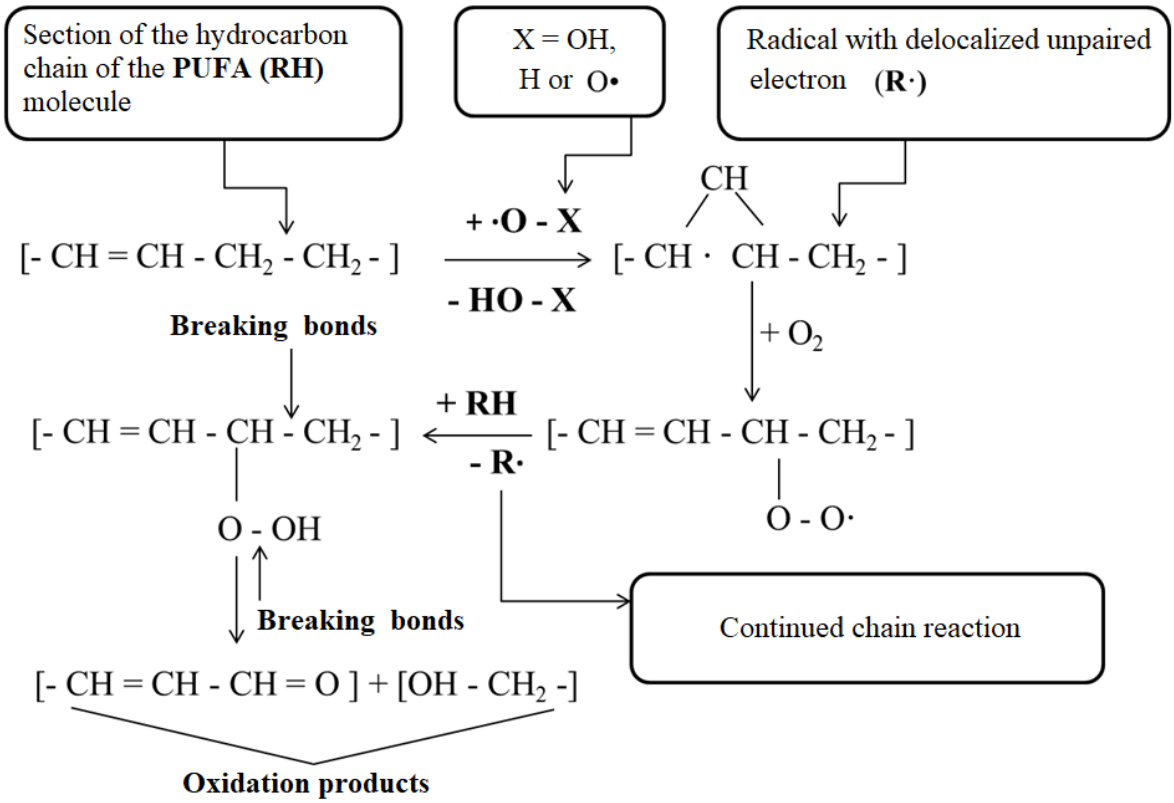

Fig. 16. Mechanism of lipid peroxidation

5. X-ray diagnostics or Radiography. Mass absorption coefficient

X-ray diagnostics (Radiography) is a method of obtaining images of internal organs by using X-rays. When a human body is illuminated with X-rays, a shadow image of organs located in the path of X-rays is observed on a picture or on a monitor.

This method is based on the difference in the absorption of X-rays by different substances. The image of the organs in the picture is obtained due to the different mass absorption coefficient μ_m of X-rays by the substance. Substances with a high μ_m absorb more incident radiation and are indicated in the image in white, while substances with a small μ_m absorb radiation less and therefore are indicated by a darker color in the image.

Photons of non-hard X-ray radiation with an energy of about 60–120 keV are used for X-ray diagnostics. The interaction of non-hard X-ray radiation with matter at reduced energies is determined mainly by the photoelectric effect. The mass absorption coefficient is also mainly determined by the photoelectric effect and is equal to $\mu_m = k\lambda^3 Z^3$. The value of μ_m is proportional to the third power of the wavelength λ^3, therefore, hard radiation with a short wavelength has a greater penetrating power when passing through matter.

The absorption of X-rays is almost independent of the compound in which the atom is present in the substance. Therefore, the calculation of the mass absorption coefficient of a molecule μ_{mABC}, consisting of atoms A, B and C, is determined by the total atomic number of all atoms Z_{ABC} of this molecule by next formula (26):

$$\mu_{mABC} = k\lambda^3 Z_{ABC}{}^3 = k\lambda^3 (Z_A{}^3 + Z_B{}^3 + Z_C{}^3). \quad (26)$$

The absorption of X-rays by soft tissues, which are mostly consist of water, will be determined by the mass absorption coefficient of water H_2O. For hard tissues, the absorption of X-ray radiation will be determined by the mass absorption coefficient of calcium phosphate $Ca_3(PO_4)_2$, since this is the main element in the composition

of bone tissue. The charge atomic numbers for the basic atoms that make up soft and hard tissue are presented in the following Table 4.

Table 4

Atomic number Z for different chemical elements

Chemical element		**Atomic (Charge) number Z**
Hydrogen	H	1
Oxygen	O	8
Phosphorus	P	15
Calcium	Ca	20

Why are images of bones clearly visible on X-ray diagram, but images of soft tissues are almost invisible in X-ray diagram? To answer this question by using the data of the table of charge numbers, we compare the mass absorption coefficients of bone μ_{mb} $Ca_3(PO_4)_2$ and water μ_{mw} H_2O by next formula:

The mass absorption coefficient for water μ_{mw}:

$$\mu_{mw} = k\lambda^3 Z_{H2O}{}^3 = k\lambda^3(2*Z_H{}^3 + Z_O{}^3) = k\lambda^3(2*1^3 + 8^3) = 514\, k\lambda^3.$$

The mass absorption coefficient for bone μ_{mb}:

$$\mu_{mb} = k\lambda^3 Z_{Ca3(PO4)2}{}^3 = k\lambda^3(3*Z_{Ca}{}^3 + 2*Z_P{}^3 + 8*Z_O{}^3) =$$
$$= k\lambda^3(3*20^3 + 2*15^3 + 8*8^3) = 34846\, k\lambda^3.$$

Let's compare μ_{mb} and μ_{mw}:

$$\frac{\mu_{mb}}{\mu_{mw}} = \frac{34846k\lambda^3}{514k\lambda^3} = \frac{34846}{514} \approx 68.$$

From a comparison of the mass absorption coefficients μ_{mb} and μ_{mw}, we found that μ_{mb} is 68 times greater than μ_{mw}. Therefore, when passing through hard tissue, X-rays are attenuated 68 times more than when passing through soft tissue. That is why, in X-ray diagnostics, bone images are clearly visible against the background of soft tissue

images due to a significant difference in the ability to attenuate transmitted X-rays.

5.1. Contrast agents for X-ray diagnostics

Changes in the structure of soft tissue differ much less than in hard tissue, since μ_m almost do not differ for different parts of it. Therefore, in order to create a clearly distinguishable picture on an X-ray, a contrast agents (radiopaque substance) is injected into the desired tissue before the examination, which greatly attenuates the transmitted X-ray radiation in the desired tissue. Thus, the contrast agent increases μ_m for the tissue where it was injected, compared to neighboring tissues, and due to this, a contrast image of the tissue under study appears against the background of other tissues.

Compounds that are not toxic to the body are used as contrast agents for X-ray diagnostics that containing chemical elements with a larger charge number Z, since $\mu_m \sim Z^3$. During X-ray diagnostics of the gastrointestinal tract, the patient is given a drug based on barium sulfate BaSO with a charge number $Z_{Ba} = 56$, which is in the form of a creamy mass that fills the stomach and intestines. Iodine compounds I with a charge number $Z_I = 53$ that non-toxic to the body are used when diagnosing the vascular bed.

5.2. Methods of X-ray diagnostics

In the modern sense, there are the following main types of X-ray diagnostics: **fluoroscopy (radioscopy)** and **radiography**. The methods are based on the attenuation of X-rays. The difference between the methods is only in how the result of the passage of X-rays through the human body is presented. Both methods have both advantages and disadvantages.

Fluoroscopy (radioscopy) is method based on the translucence of an object with X-rays, when the resulting image is formed on a fluorescent screen in real time. The brightness of the resulting image is low, and therefore carry out this procedure in a darkened room. Since the procedure takes place in real time, the patient and the doctor are exposed to a large radiation exposure compared to other methods of X-ray diagnostics. The doctor must wear a special protective lead gown before the procedure to reduce exposure to X-rays. The main advantage of this method is that we get a dynamic picture of what is happening inside the patient. Figure 17 is an illustration of a chest fluoroscopic X-ray procedure [22-24].

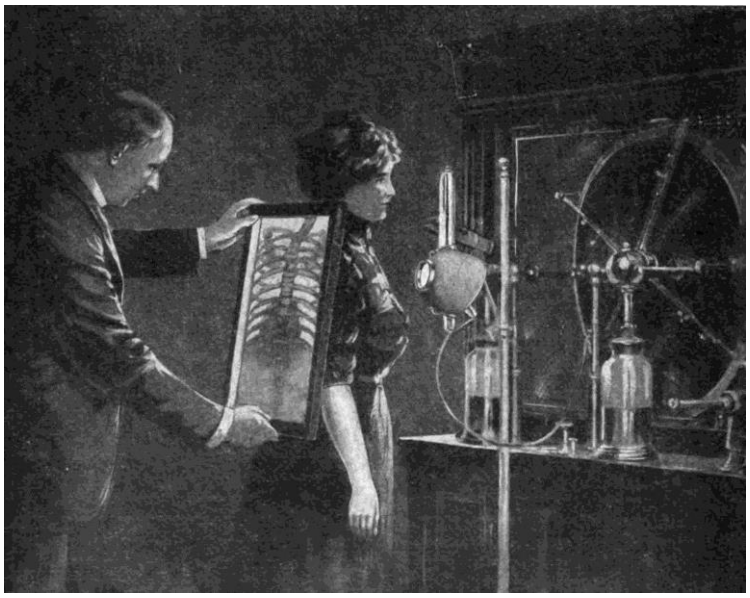

Fig. 17. Chest fluoroscopic X-ray using a hand-held fluorescent screen, 1909. No radiation protection is used as the dangers of X-rays were not yet recognized [25]

The X-ray tube is positioned behind the patient during fluoroscopy. A fluorescent screen is placed in front of the patient. There is a shadow image appears on the screen. It is necessary to choose the appropriate radiation hardness for fluoroscopy of certain parts of the body in order to pass radiation through the studied soft tissues,

but be sufficiently absorbed by dense (hard) tissues. If this condition is not complete then a uniform shadow will appear on the screen and it will not be possible to distinguish structures.

It has become possible to get rid of some of the shortcomings of fluoroscopy with the advent of digital devices in our lives. The modern version of fluoroscopy is telefluoroscopy. X-ray image amplifiers are used in this method. The amplifier perceives the weak glow of the X-ray screen after amplifies it and transmits it to the TV screen. As a result, the radiation load on the doctor has sharply decreased, the brightness of the image has increased, and it has become possible to record the results of the examination on video. An example of a modern telefluoroscopy procedure is shown in Figure 18.

Fig. 18. Telefluoroscopy of a patient. The figure shows the device-fluoroscope, inside which the patient is placed. The operator-doctor is dressed in a protective gown and is located next to the fluoroscope [26]

Radiography is method based on the transmission of an object with X-rays, when the resulting image is formed on a special photographic film that is sensitive to X-rays. The procedure for obtaining an image of the passage of X-rays through a patient on film takes a fraction of a second (exposure time). Pictures are taken in two mutually

perpendicular projections (direct and lateral). The image becomes visible after photo processing. The finished dried image is viewed in transmitted light. At the same time, details are satisfactorily visible, the contrasts of which differ by 1-2%. Since the time of exposure to X-ray radiation on the patient takes only a few seconds, the radiation exposure for the patient is hundreds of times less than with fluoroscopy. The main advantages of this method are that we obtain a high-resolution image and expose the patient to X-ray radiation for a short time.

Radiography X-ray methods include methods of fluorography, electroradiography, angiography and CT.

Fluorography is a radiographic method for obtaining images of the organs of the chest, mammary glands, and the skeletal system on a small-format fluorescent film or fluorescent screen. The image arises due to the passage of X-rays through a person and their uneven absorption by human organs and tissues, due to different μ_m for tissues. Fluorography is widely used in the mass survey of the population. The image obtained during the fluorography procedure is called a fluorogram. If pathological changes are found on the fluorogram then the patient is prescribed a more detailed examination.

Electroradiography is a method of radiography in which an X-ray image is obtained on a charged semiconductor plate and then transferred to plain paper. The image carrier is an electrostatically charged layer of amorphous selenium.

Significant advantages of the method are cost-effectiveness and speed of image acquisition: a dry image is obtained in 2–3 minutes (an X-ray image of the object of study on plain paper). The disadvantages of the method include a relatively higher radiation dose during the study and the unreliability of the existing equipment. The most expedient is the use of electroradiography in trauma centers.

The process of electroradiography consists of 5 stages. The first is the application of a positive electrostatic charge to the selenium

plate, as a result of which it becomes sensitive to X-rays. The second stage is X-ray photography of the object under study, in which a selenium plate is used instead of an X-ray film. Under the influence of X-ray radiation passing through the object under study, the electric potential on the surface of the plate changes (the positive charge decreases) and a latent electrostatic image is created. The third stage is image processing. The plate is pollinated with black powder after negatively charged particles of the powder settle on the surface of the plate due to the positive charge remaining on it. The fourth stage is the transfer of the powder image from the plate to paper by contact method. The fifth step is the fixation of the image. All stages, except for the X-ray itself, are carried out using an electrographic apparatus, consisting of a technological unit (for charging the plates and transferring the image from them to paper) and a fixing unit.

Electroradiography has a number of important differences from radiography. In particular, during electroradiography, the so-called edge effect is noted that is a more intense deposition of powder at the border of areas with different potentials, which ensures the clarity of the contours of the shadow, high contrast and some increase in the image. All this creates the impression of volumetric details and increases the diagnostic capabilities of the method. In the study of soft tissues, it is possible to obtain an image of the skin, subcutaneous tissue, muscles, ligaments, which makes it possible to identify foci of inflammation, hemorrhage, and cysts. The method allows you to simultaneously obtain an image of tissues that differ in density and thickness. So, when examining joints, along with the articular ends of the bones, elements of the ligamentous apparatus, tendons, and muscles are determined. An example of the picture obtained during electroradiography is shown in Figure 19.

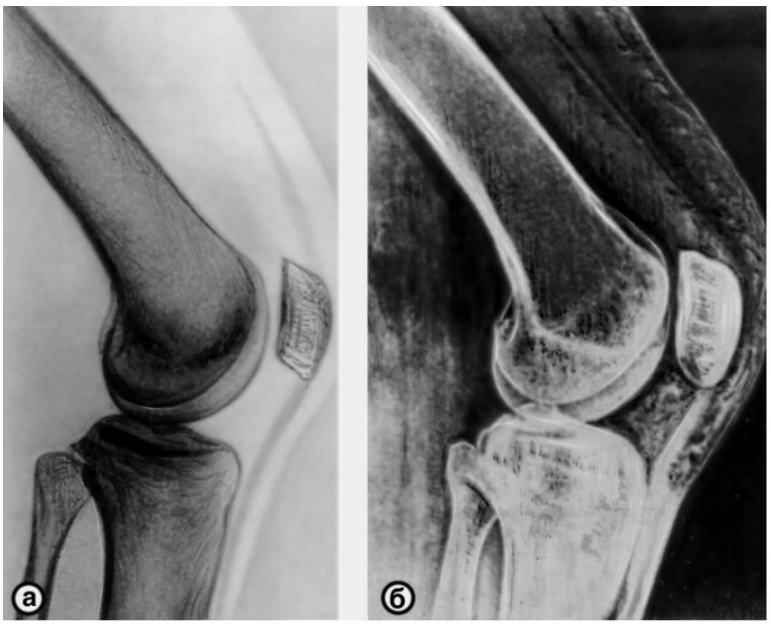

Fig. 19. Radiogram (a) and Electroradiogram (b) of a normal knee joint (lateral view) [27]

Angiography is a fluoroscopic and radiographic method for examining the patient's blood vessels with the introduction of a special contrast agent with a high μ_m relative to other tissues. A contrast agent is injected into the vein through a catheter, after which a powerful X-ray machine takes a series of images following each other in a fraction of a second. Iodine compounds I are used as contrast agents for blood vessels. An example of the obtained angiogram of the renal arteries is shown in Figure 20.

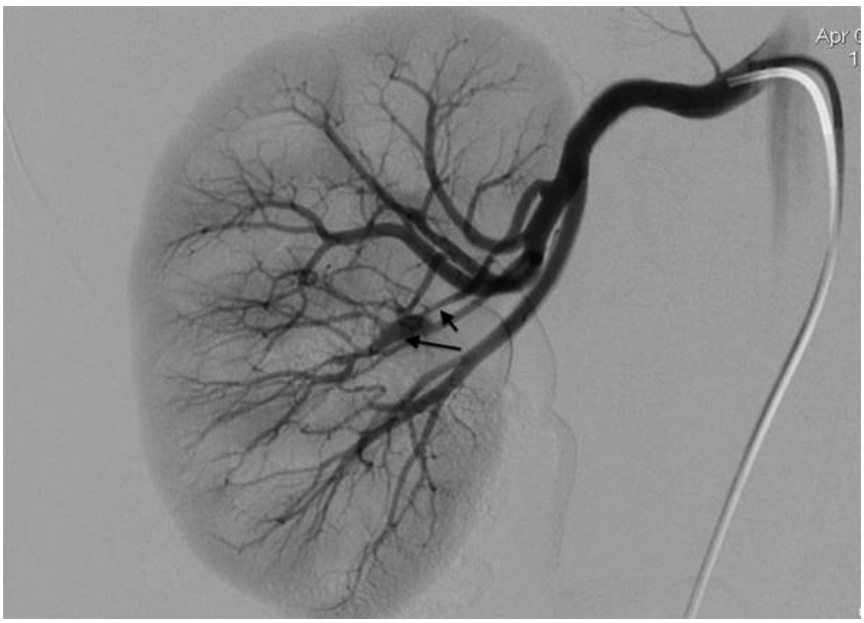

Fig. 20. Angiography of the renal arteries. You can get information about the shape, diameter and presence of narrowing of the renal arteries from this image [28]

X-ray computed tomography (**CT or XCT**) is type of X-ray examination allows you to get an image of a flat section of the body with a thickness of several mm. In this case, the given section is repeatedly illuminated at different angles with the fixation of each individual image in the computer's memory. Then a computer reconstruction is carried out, the result of which is the image of the scanned layer.

Computed tomography makes it possible to distinguish elements with a density difference between them up to 1%. Conventional radiography allows you to capture a minimum difference in density between adjacent areas of 10-20%. An example of an X-ray tomogram and a method for obtaining it is shown in Figure 21.

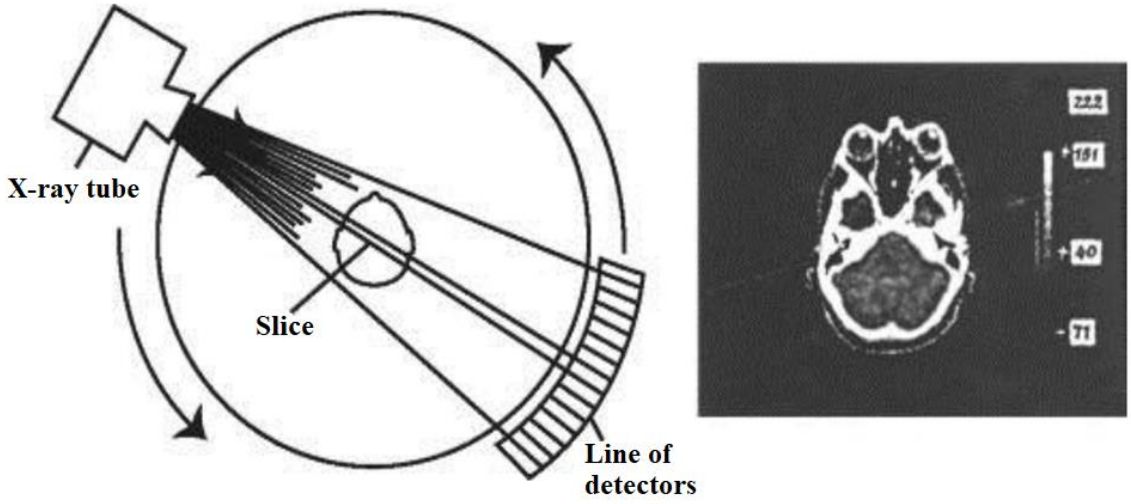

Fig. 21. Scanning scheme of computed tomography and tomogram of the head in cross section at eye level [29]

5.3. Disadvantages of conventional radiography techniques

The main disadvantage of conventional radiography methods is that conventional methods are inferior in information content to more high-tech studies such as computed tomography (CT) and magnetic resonance imaging (MRI). If X-rays show the superposition of anatomical structures on top of each other, then on the other hand CT and MRI make it possible to obtain layered images with a further difference in structures [30].

However, conventional radiography techniques have many advantages and continue to be widely used by clinicians and patients. The main advantages of standard radiography include:

- **Ease of carrying out the X-ray study.** A study on modern digital devices can be performed by an X-ray laboratory technician of any qualification: the system itself selects the dose and nature of exposure for a given area of study.
- **High resolution images.** Both digital and analog systems allow you to get clear pictures of different organs. In areas where

the anatomical structures are located "crowded" and have the same density here radiography with contrast helps to doctor.

- **Relative low coast of the X-ray study.** Practically all patients can afford standard radiography, therefore it is widely used both for general diagnostics and for monitoring the effectiveness of treatment, for example, in traumatology for bone fractures.
- **Obtaining an objective result of X-ray study in the form of an image.** Digital and analog radiographs can be stored in a convenient format (picture or photograph) and transferred to other doctors to clarify the diagnosis.

6. CT-scan method

The method of X-ray computed tomography (XCT or CT) is a modern method of X-ray diagnostics, which is based on the reconstruction of an image of a certain section of the patient's body by registering a large number of X-ray projections (images) of this section, made at different angles and then adding the resulting projections using special mathematical methods.

The first mathematical algorithms for CT were developed in 1917 by the Austrian mathematician J. Radon. The physical basis of the method is the exponential law of radiation attenuation, which is valid for purely absorbing media. In the X-ray range of radiation, the exponential law is satisfied with a high degree of accuracy, so the developed mathematical algorithms were first applied specifically for X-ray computed tomography.

In 1963, the American physicist A. Cormack again, but in a different way from Radon, solved the problem of tomographic reconstruction. In 1969, the English engineer-physicist G. Hounsfield from EMI Ltd. designed the EMI-scanner is the first computed X-ray tomograph, whose clinical trials were held in 1972. In 1979, Cormack and Hounsfield were awarded the Nobel Prize in Physiology or Medicine "for the development of computed tomography".

X-ray computed tomography makes it possible to obtain a layered image of organs and distinguish between structures that differ by only 0.1% in terms of absorption and at least 2 mm in terms of the size of image details. The examination time for obtaining a section can reach several seconds. Computer image processing makes it possible to distinguish more than a hundred degrees of change in the density of the tissues under study from zero (for water, cerebrospinal fluid) to a hundred or more (for bones), which makes it possible to distinguish differences between normal and pathological tissue sections

within 0.5–1%, that is a 20–30 times more than on conventional radiographs.

How is a CT scan done? Let us consider the method of X-ray tomography using the simplest analog tomograph as an example, which consists of a movable X-ray tube *XT* and film *Fl*. *XT* and *Fl* periodically move together relative to the object of study *Ob*. The scheme of CT is shown in Figure 22. As you can see, X-rays fan-shaped beam at any position of the X-ray tube (1, 2, 3, 4 and 5) pass through the same central point of the object relative to which the periodic movement of *XT* and *Fl* occurs. Its shadow image moves along with *Fl*, occupying successively positions 1, 2, 3, 4, and 5. The remaining inclusions in the body (bones, indurations, etc.) create a certain general "background" on *Fl*, since X-rays are not constantly obscured by inclusions. By changing the position of the center, it is possible to obtain a layered X-ray image of the body, that is, to obtain a three-dimensional (volumetric) image of the body.

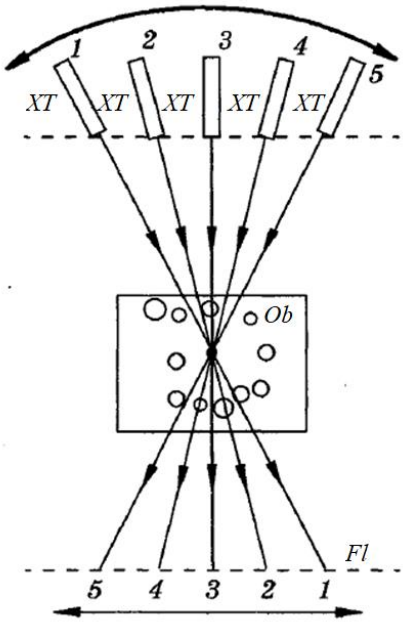

Fig. 22. Scheme of the simplest CT scanner. Numbers 1, 2 – 5 indicate the positions of the X-ray tube *XT* and film *Fl* relative to the axis of rotation around the object *Ob*. The point at which all lines intersect is called the center of the *Ob* layer [5]

6.1. Design and construction of an X-ray tomograph

How is a CT scan obtained? The XCT or CT scanner (Figure 23a), differs from conventional X-ray tomography in that it calculates images of organs in narrow given cross sections of the human body by computer processing of electrical signals from X-ray detectors (often use semiconductor detectors) instead of photographic film. One of the various methods of transmission and detection of radiation for CT research is shown in Figure 23b.

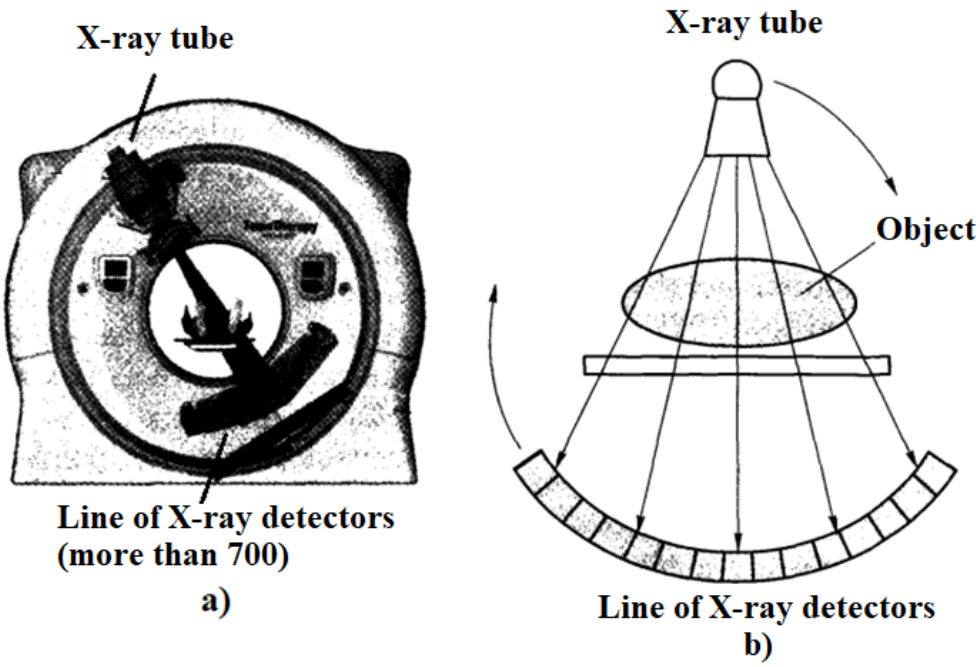

Fig. 23. a) Image of a modern XCT (CT) tomograph.
b) Scheme of the CT scanner. The X-ray tube again acts as an X-ray source. The radiation passes through the object and is partially absorbed by it, and the remaining radiation is recorded by a line of detectors. A line of detectors convert X-rays into electrical signals that are received by a computer [5]

A diverging beam of X-rays, passing through an object, hits a line of detectors, the number of which ranges from 300 to 700 or more (the resolution of the method depends on the number of detectors,

the more there are, the higher the image resolution). The X-ray emitter-detector system rotates around the object, creating X-ray "electronic images" of the object at different angles, through 1-2 degrees of rotation. During the study, the system usually makes a full turn and during this time makes 300 – 400 switching on of the emitter-detector system.

Numerous X-ray projections of the organ registered by the line of detectors in a given plane are transferred to a computer, which processes them according to a special program and calculates the X-ray density at each point of the studied section, after that it displays the resulting image in the gray scale of Hounsfield units (HU units) on the computer monitor screen. If necessary, this image can be contrasted (according to the mass absorption factor μ_m), enlarged and stored in the computer memory or on an external digital storage.

When examining a patient, a specific area of the patient's body is usually studied in detail, therefore, images of several parallel sections of this area are obtained on a CT scan. In modern CT scanners, to speed up the procedure for obtaining a sequence of such images, spiral scanning is used: the table with the patient moves evenly while the emitter-sensor system rotates (Figure 24).

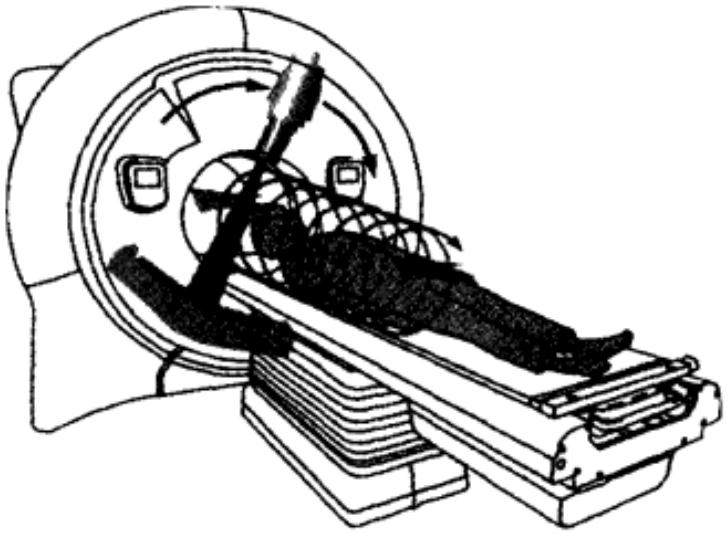

Fig.24. Scheme of spiral CT scan [5]

X-ray computed tomography makes it possible to obtain a layered image of organs and distinguish between structures that differ by only 0.1% in terms of absorption and at least 2 mm in terms of the size of image details. The examination time for obtaining a section can reach several seconds. Computer image processing makes it possible to distinguish more than a hundred degrees of change in the density of the tissues under study from zero (for water, cerebrospinal fluid) to a hundred or more (for bones), which makes it possible to distinguish differences between normal and pathological tissue sections within 0.5–1%, that is a 20–30 times more than on conventional radiographs.

6.2. CT generations

The design of an X-ray scanner has been developed for a long time. Five generation of tomography systems can be mentioned (Fig. 25).

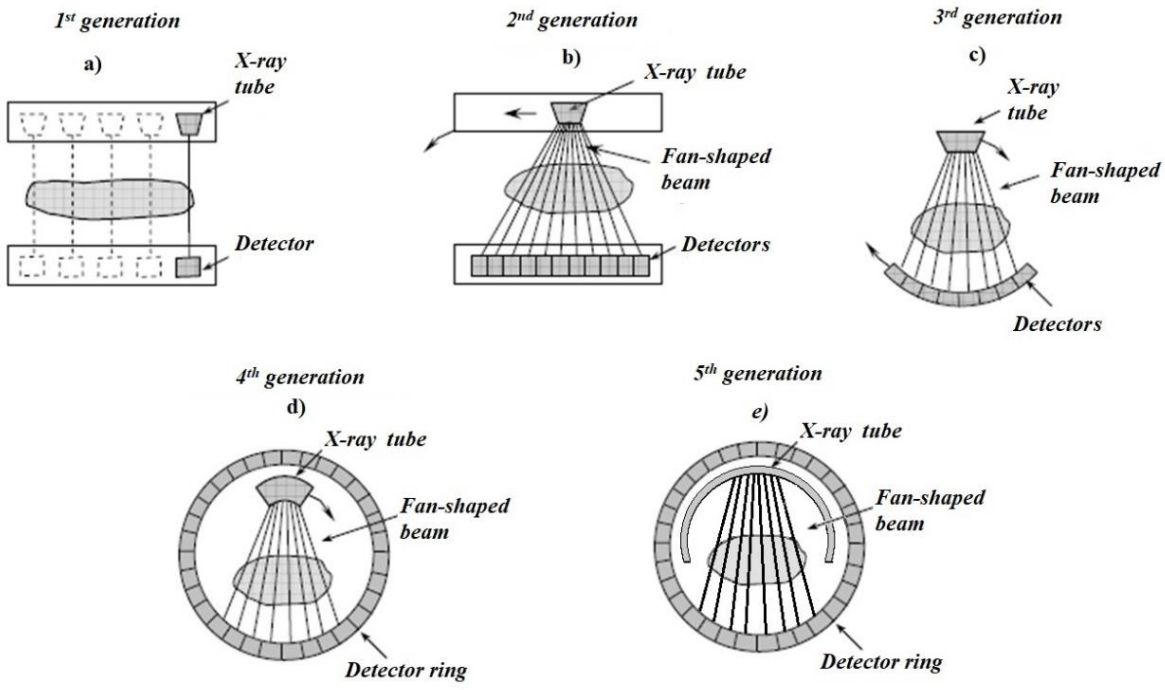

Fig. 25. Schematic representation of X-ray scanners [31]

Tomography instruments of the first generation, which appeared in 1973, had one narrow-beam X-ray tube (pencil beam) and one or two detectors, which moved synchronously along a ramp (Fig. 25a). The measurements were taken at 160 positions of the tube, then the ramp was rotated by 1^{o}, and the measurements were repeated. The data was gathered for 45 minutes then processed on a special workstation during 2.5 hours. The small detectors rarely detected any scattered radiation, and this was a large advantage of this scanner.

The 2^{nd} generation instruments had several detectors working at the same time, and the X-ray tube produced a narrow fan beam ($\sim 30^{o}$) (Fig. 25b). They used parallel scanning, as well as the 1^{st} generation systems, but the range of the tube rotation angle increased to 30^{o}, and the amount of linear displacement required was dramatically reduced. Total duration of obtaining one image decreased to 2–3 minutes per slice of a head CT slice. Resolution, however, suffered to some extend due to the new beam geometry and the fact that the detectors were exposed to more scattered radiation.

In the 3^{rd} generation systems (middle 1970's, Fig. 25c) the tube emitted a wide fan-shaped beam which irradiated a large set (about 400–1000) of detectors placed on an arc. The wide beam could reach the entire patient (slice) at one time. The improved construction (with a ring rail providing the power supply for the tube) allowed continuous rotation of the tube and detectors over 360^{o}. This allowed avoiding the stage of moving the tube, and thus diminished the time required to get one image to 20 seconds and less. Due to the remarkable shortening of the procedure, scanners of this type were capable of studying moving parts of the body (lungs and abdomen) and made possible developing the helical data collection algorithm. They are sometimes called "rotate/rotate" scanners, unlike previous generations of "rotate/translate" systems. Nowadays, 3^{rd} generation CT scanners are still in existence.

Tomography systems of the 4th generation ("rotate/stationary" geometry Fig. 25d) had a closed fixed ring of detectors (~5000) and an X-ray tube, which produced a fan-shaped beam and was turned around the patient inside the ring (outside disposition is also possible). By removing the detectors from the rotating gantry and putting them in a stationary ring around the patient, detectors were able to maintain calibration, which allowed suppressing so-called *ring artifacts* in the CT images. The scanning time for each slice was as small as 0.7 second, and an improvement in the image quality was achieved.

In early 1980's the electron-beam scanners (the 5th generation scanners, Fig. 25e) were invented. A stationary cathode-ray (electron) gun placed behind the scanner ejects an electron beam, which passes through vacuum and is then focused and directed by electromagnets onto a tungsten target. The target has the shape of a circle arc (~210°) and is placed under the table for the patient. The targets are arranged in four rows, are very massive and have a flowing water cooling system. Opposite to the targets, an array of fast-response solid-body detectors is mounted, which is also stationary. Detectors form an arc of 216°. Scanners of this type are used in investigations of the heart, as they can produce an image in 33 – 50 milliseconds (up to 30 frames per second!), and the number of slices is not limited by heat capacity of the tube. This generation was invented specially to cardiologists; it was very expensive and not very versatile.

The 6th generation ("helical", or "spiral") scanners were introduced in practice in 1990's and combine the principles of the 3rd and 4th generations with the slip ring technology to create a system that could rotate continually around the patient without being limited by electrical wires. They require much shorter acquisition times (that is, as short as 30 seconds to scan the entire abdomen). The main drawback of helical CT scanners lies in the nature in which the data is collected. X-ray source and detector array rotate continuously as the patient table is moved progressively through the scanner, and thus

no full slices (planar sections) of data are available. This problem can be compensated for through the reconstruction process.

The 7th generation scanners employ a new geometry of the X-ray beam. It does not pass through a narrow collimator and thus has a cone shape. Accordingly, detectors are placed in a planar array instead of a linear array, and cover a large area. A very large number of slices is acquired in a very short period of time, and a much higher level of sophistication in the reconstruction process is needed.

6.3. Hounsfield scale

The Hounsfield unit (**HU**) **scale** is a scale of linear attenuation of radiation with respect to distilled water, the X-ray density of which was taken as 0 HU (at standard pressure and temperature).

For a material X with a linear attenuation coefficient (linear absorption coefficient) μ_X , the value HU is given by (27):

$$\frac{\mu_X - \mu_{water}}{\mu_{water} - \mu_{air}} \times 1000. \quad (27)$$

Where μ_{water} and μ_{air} are the linear attenuation coefficients for water and air under standard conditions.

After scanning the object and computer signal processing, the graphic image of the slice (graphic matrix) is reconstructed. In this case, each cell of the matrix corresponds to the computer-calculated absorption coefficient (AC) of tissues, which is also the attenuation coefficient, expressed in Hounsfield units HU. AC is similar in meaning to the degree of blackening of the X-ray, that is, it shows how much the tissue is able to attenuate X-rays. Bone absorbs X-rays more strongly than other tissues and has the highest AC (+800 +3000 HU). Air practically does not absorb and has the smallest AC (-1000 HU). The higher the tissue AC, then the stronger it absorbs radiation, the fewer photons of radiation reach the detector of the tomograph and the whiter it looks on CT: the bone is the whitest, the air is the blackest. Thus, the distinction between normal and pathological formations

on CT is made according to the gradations of the transition from black to white (gray gradations). AC is the main characteristic of a CT image in terms of density and in modern CT it ranges from -1000 to +3000 HU. Some tissues and their corresponding density parameters, expressed in Hounsfield units, are shown in Figure 26.

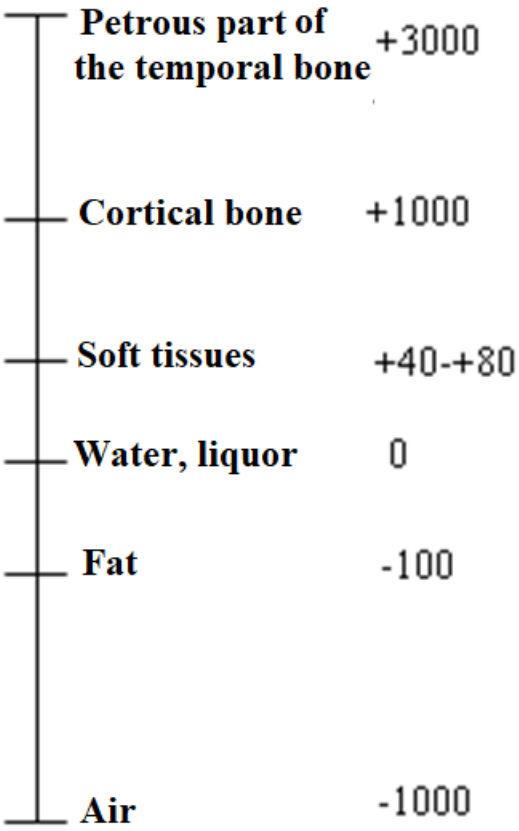

Fig. 26. The Hounsfield unit scale (HU) [32]

The standards were chosen for practical use in computed tomography of living organisms because their anatomical structures are largely composed of bound water.

The following Table 5 presents the structures and their HU values on next page [33].

Table 5

Average Hounsfield Unit (HU) values for different substances in CT

Substance			**Average HU values**
Air			−1000
Fat			−120 to −90
Soft tissue on contrast CT			+100 to +300
Bone		Cancellous bone	+300 to +400
		Cortical bone	+1800 to +1900
Subdural hematoma, Blood	For the first hours		from +75 to +100
	After three days		from +65 to +85
	After 10-14 days		from +35 to +40
Other fluids	Chyle		−30
	Water		0
	Bile		-5 to +15
	Abscess / Pus		0 or +20, to +40 or +45
Lungs			−700 to −600
Kidney			+20 to +45
Liver			60 ± 6
Muscle			+35 to +55
Lymph nodes			+10 to +20
White matter			from +20 to +30
Grey matter			from +37 to +45
Foreign body		Windowpane glass	500
		Aluminum, asphalt, car window glass, bottle glass, and other rocks	+2100 to +2300
		Limestone	2800
		Copper	14 000
		Silver	17 000
		Steel	20 000
		Gold, steel, and brass	+30 000 (upper limit of measure-ments)

EXPERIMENTS

611. Detecting X-rays using an ionization chamber

Aim of work

- Learning about the quantitative detection of X-rays.

Subjects matter of the experiment

- Detection of X-radiation by using an air-filled ionization chamber and measuring the ionization current I_C.
- Investigation of the relationship between the ionization current I_C and the capacitor voltage U_C and verifying the saturation characteristic.
- Investigation of the relationship between the saturation ionization current and the emission current I of the X-ray tube at a constant tube high voltage U.
- Investigation of the relationship between the saturation ionization current and the tube high voltage U at a constant emission current I.

Brief theory

X-radiation is detectable on account of its physical effects. For example, X-rays fog film stock and cause air and other gases to become electrically conductive, the photoeffect is observed at the surfaces of metals, and some fluorescent substances show luminescence. All these phenomena are caused by ionization of atoms or molecules of the transilluminated matter.

In the quantitative detection of X-rays, we can exploit this ionizing effect, e.g. by measuring the ionization current in a plate capacitor filled with air or another gas. Due the way it is designed and built, this type of arrangement is called an ionization chamber.

In the detection of X-rays, an X-ray beam passes through a diaphragm and strikes a plate capacitor in such a way that it does not

directly fall on the plates. This prevents falsification of the measurement results due to the photoeffect at the capacitor plates. The X-rays ionize a part of the gas volume in the capacitor. When we apply a voltage U_C to the capacitor, the charge carriers, electrons or ions, are collected at the capacitor plates. The current generated at the capacitor in this way corresponds to an ionization current I_C in the outer circuit that can be measured using a measuring amplifier.

At low voltages U_C, fewer and fewer charge carriers recombine in the gas volume as U_C increases, and more and more charge carriers are collected at the capacitor plates. Thus, the ionization current I_C increases with the voltage U_C. When U_C is increased beyond a certain point, I_C ultimately reaches a saturation value, as all charge carriers formed by the incident radiation per unit of time are captured (except for negligible recombination losses). This saturation value is an indicator for the intensity of the incident X-radiation.

On figure 27 you can see the simplified scheme of experiment.

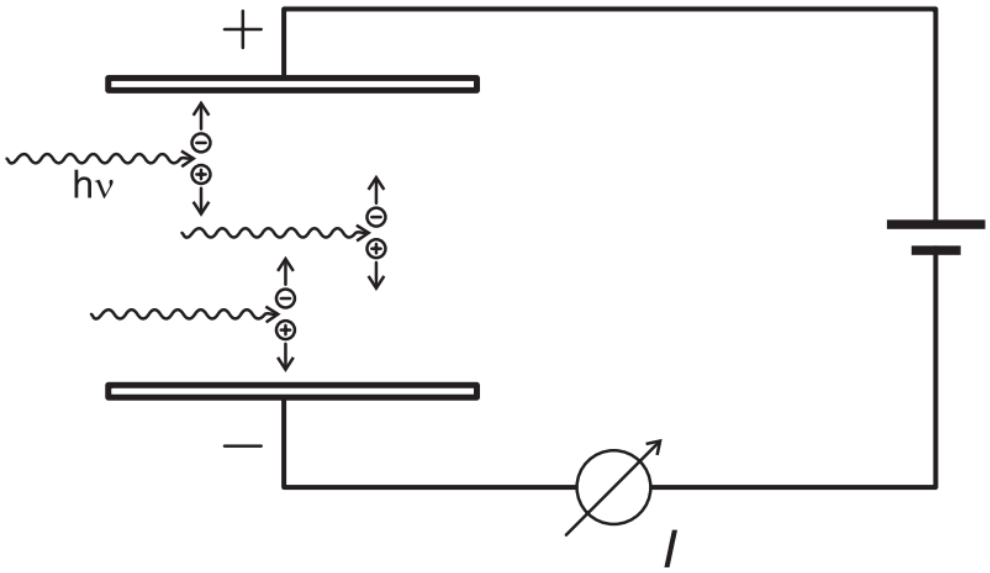

Fig. 27. Simplified scheme of experiment [34]

Equipment and setup (figure 28)

1. X-ray apparatus.
2. Plate capacitor x-ray.

3. Power supply 450 V DC.
4. Electrometer amplifier.
5. STE resistor 1 GΩ, 0.5 W.
6. Voltmeter, U # 200 V DC.
7. Voltmeter, U # 10 V DC.
8. Screened cable BNC/4 mm.
9. Connecting leads.

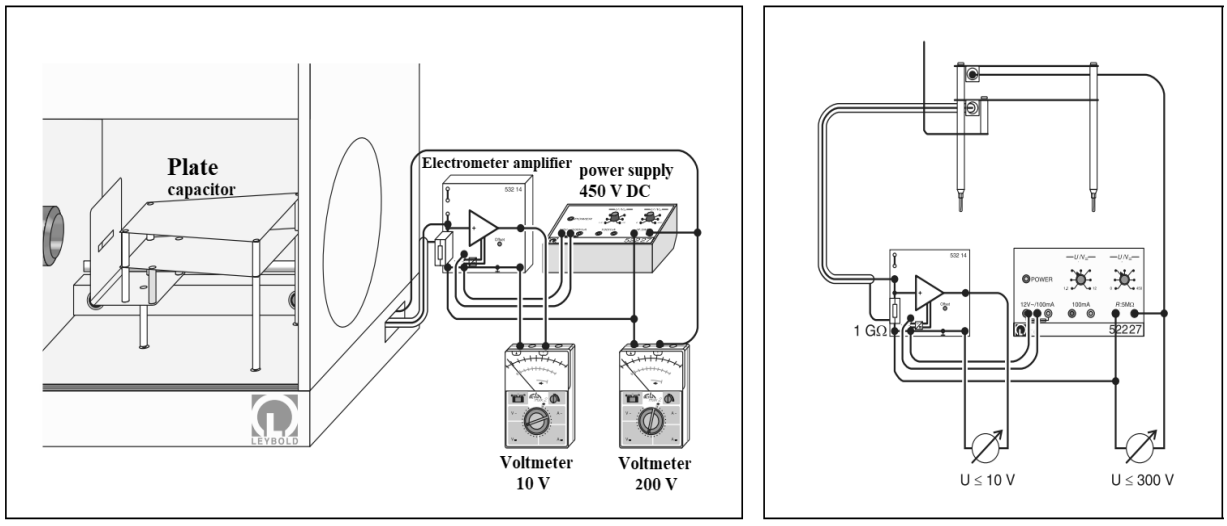

Figure a) Figure b)

Fig. 28. a) Experiment setup for measuring the ionization current in a plate capacitor. b) Connecting the plate capacitor and the electrometer amplifier for determining the ionization current [34]

Safety notes

The built-in protection and screening measures reduce the local dose rate outside of the X-ray apparatus to less than 1 μSv/h, a value which is on the order of magnitude of the natural background radiation.

- Before putting the X-ray apparatus into operation inspect it for damage and to make sure that the high voltage is shut off when the sliding doors are opened.
- Keep the X-ray apparatus secure from access by unauthorized persons.

- Do not allow the molybdenum anode of the X-ray tube to overheat.
- When switching on the X-ray apparatus, check to make sure that the ventilator in the tube chamber is turning.

Setup part

Set up the experiment as shown in Fig. 28a, Fig. 28b shows the electrical connections of the plate capacitor and the electrometer amplifier for determining the ionization current.

Mechanical setup:

- If necessary, demount the collimator of the X-ray apparatus and remove any experiment equipment from the chamber of the X-ray apparatus.
- Connect the adapter cable BNC/4 mm to the bottom capacitor plate (BNC socket) with the BNC plug and connect the connecting lead to the top capacitor plate (safety socket) of the plate capacitor X-ray.
- Lift the plate capacitor into the experiment chamber of the X-ray apparatus and insert the mounting plugs in the mounting sockets. Check to make sure that the capacitor plates are aligned parallel to the base plate of the X-ray apparatus, and correct if necessary.
- Feed the two cables into the free channel until they reappear on the right side of the X-ray apparatus

Electrical assembly:

- Connect the connecting lead to the positive pole of the 450 V DC power supply and connect the adapter cable BNC/4 mm to the electrometer amplifier fitted with the 1 GΩ resistor.
- Ground the electrometer amplifier to the negative terminal of the 450 V DC amplifier.

- Use one voltmeter each to measure the capacitor voltage U_C and the output voltage of the electrometer amplifier U_E.
- Plug in the X-ray apparatus to the mains power and switch it on.

If you think there is a problem with setup please ask engineer (teacher assistant) of lab or your professor.

Algorithm of measurements

Part I: Ionization current I_C as a function of the capacitor voltage U_C:

1. Set the emission current on X-ray apparatus control panel to I = 1.0 mA.
2. Set the tube high voltage U = 15 kV and switch on the high voltage using the key HV on/off.
3. To record a measurement series, increase the capacitor voltage U_C (200 V Voltmeter) in steps from 0 V to 140 V and determine the ionization current I_C for each step from the voltage U_E at the output of the electrometer amplifier:

$$I_C = \frac{U_E}{1\ \text{G}\Omega}$$

*Notes for calculating:

- U_E – it is your measurement from 10 V Voltmeter,
- 1 GΩ – it is the resistance of STE resistor and it is equal to

$$1\ 000\ 000\ 000\ \Omega = 10^9\ \Omega.$$

4. Write down your measurement results in the Table 6.

Table 6

Measurements for part I of experiment

Uc, V	For U = 15kV **Ic, nA**	For U = 20kV **Ic, nA**	**...**	For U = 35 kV **Ic, nA**
0				
10				
20				
…				
140				

5. Increase the tube high voltage U in steps from 5 kV to 35 kV, repeat the measurement series for each step and write down your measuring results in Table 6.

6. Plot set of graphs I_C versus U_C according results from Table 6

7. Proceed to part II of experiment.

Part II: Saturation ionization current I_C as a function of the emission current I:

1. Set the tube high voltage on X-ray apparatus control panel to U = 35 kV.

2. Set the capacitor voltage on 200 V Voltmeter to U_c = 140 V, so that the saturation value of the ionization current I_C is reached.

3. Increase the emission current on X-ray apparatus control panel I in steps from 0 mA to 1 mA and determine the corresponding ionization current I_C.

4. Write down your measuring results in the Table 7.

Table 7

Measurements for part II of experiment

I, mA	***I_c*, nA**
0	
0.01	
0.02	
…	
1.00	

5. Plot the graphs I_C versus I according to results from Table 7.

6. Proceed to part III of experiment.

Part III: Saturation ionization current I_C as a function of the emission current I:

1. Set the emission current on X-ray apparatus control panel I = 1.0 mA.

2. Set the capacitor voltage on 200 V Voltmeter to U_c = 140 V.

3. Increase the tube high voltage on X-ray apparatus control panel U in steps from 5 kV to 35 kV and determine the corresponding ionization current I_C.

4. Write down your measuring results in the Table 8.

Table 8

Measurements for part III of experiment

U, kV	I_c**, nA**
0	
5	
10	
…	
35	

5. Plot the graph I_C versus U according results from Table 8.
6. Complete a report from obtained results from Part I, II, III.

General questions for X-ray theory:

1. Define what are X-rays. Identify the range of wavelengths, energies and frequencies of X-rays. What is the difference between X-rays and visible light?
2. What is an X-ray tube (make a schematic drawing). How are X-rays obtained? (Write the electron energy conversion formula.)
3. Explain the phenomenon of thermionic emission.
4. How does the X-ray spectrum look like? What regions can you distinguish in it?
5. How are bremsstrahlung x-rays generated? What is the mechanism for generating characteristic X-rays?
6. Coherent elastic scattering. Scheme; conditions at which it may occur.
7. Compton scattering. Draw a scheme; write the equation showing conservation of energy in the system.
8. Photoelectric effect. Condition of observing, equation.
9. Characteristic X-rays: how it looks like in spectra, how it is produced?
10. Moseley’s law, which quantities does it correlate together.

Special questions for 611 lab: Detecting X-rays using an ionization chamber

1. What kind of X-ray radiation is called soft and hard? Which rays are used in diagnosis, why?
2. How are X-rays detected?
3. What are ions? Why is X-ray radiation called ionizing?
4. What is the effect of X-rays when passing through a living organism? What is radiation sickness?
5. Direct and indirect effects of ionizing radiation on the body. (Radiolysis of water, protein damage, lipid peroxidation).

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612. Determining the ion dose rate of the X-ray tube with molybdenum anode

Aim of work

- Learning about determining the ion dose rate of X-ray radiation.

Subjects matter of the experiment

- Introduction and explanation of the terms ion dose (exposure dose) and ion dose rate for quantifying the action of X-rays.
- Determination of the ion dose rate in an air-filled plate capacitor by measuring the ionization current.

Brief theory

In terms of radiation, the dose can be defined on the basis of both the ionizing action and the energy absorption of the X-rays when they pass through matter. The first case is the measure of the ion dose (also called the exposure dose) and the second the absorbed dose.

The ion dose (exposure dose) is defined (28):

$$J = \frac{dQ}{dm}, \tag{28}$$

J is the quotient of the charge dQ generated in air by charge carriers of one sign due to irradiation, and the mass dm of the irradiated volume element. Its derived SI unit is the coulomb per kilogram (C/kg): $1 \cdot C \,/\, kg = 1 \cdot A \cdot C \,/\, kg$.

The absorbed dose is defined as (29):

$$k = \frac{dW}{dm}, \tag{29}$$

k is the quotient of the energy dW absorbed by the irradiated material and the mass dm of the irradiated volume element. Its derived SI unit is the gray (Gy): $1Gy = 1 \cdot J \,/\, kg$.

The effective intensity of the X-rays is defined as the quotient of dose and time. The ion dose rate is defined as (30):

$$j = \frac{dJ}{dt}, \tag{30}$$

j is measured in $A\ /\ kg$ and the absorbed dose rate is defined as (31)

$$k = \frac{dK}{dt}, \tag{31}$$

k is measured in $Gy/s = (W\ /\ kg)$.

Determining the ion dose rate:

The ion dose rate can be measured in an air-filled plate capacitor by measuring the saturation value of the ionization current I_C. This is determined as (32):

$$I_C = \frac{dQ}{dt}. \tag{32}$$

By using (28) and (29), this gives us (33):

$$j = \frac{dI_c}{dm}. \tag{33}$$

As X-rays diverge as they propagate and are attenuated in air, the ion dose rate j is a location-dependent quantity, and would require a great deal of effort to measure. It is easier to measure the mean ion dose rate (38):

$$\langle j \rangle = \frac{I_c}{m}. \tag{38}$$

For which we need to determine the total ionization current I_C and the mass of the total irradiated volume V (39):

$$m = \rho V. \tag{39}$$

The density ρ of air is calculated as (40):

$$\rho = \rho_0 \cdot \frac{T_0}{T} \cdot \frac{p}{p_0}, \tag{40}$$

with ρ_0 = 1.293 $kg\ /\ m^3$, T_0 = 273 K and p_0 = 1013 Pa from the temperature T and barometric pressure p in the experiment chamber. The volume V can be calculated with the aid of Fig. 29.

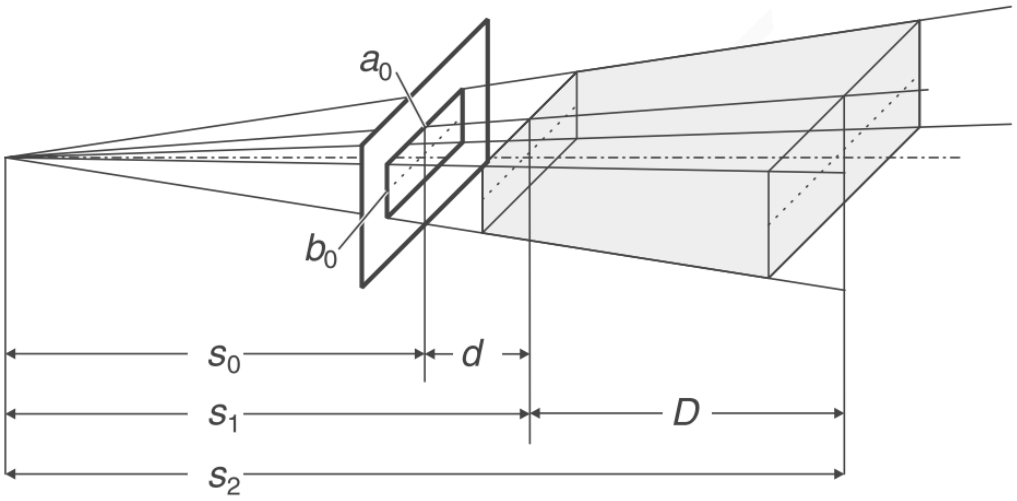


Fig. 29. Scheme of ray propagation in a flat capacitor [35]

Measuring example and evaluation

T = 303 K and $P = 101.7\ kPa$ (take appropriate values for the day when you carry out the work). We can calculate air density ρ from equation (40). Air volume V can be found from equation (45). Mass of air m can be calculated from equation (39).

Calculating the irradiated volume V:

In Fig.30, the focal spot of the X-ray tube is presumed to closely approximate a point. The rectangular diaphragm in front of the plate capacitor shapes the radiation cone of the X-ray tube into a beam which penetrates the volume V of air to be calculated. The distance between the focal spot and the rectangular diaphragm is s_0 = 15.5 cm. The dimensions of the diaphragm are a_0 = 4.5 cm and b_0 = 0.6 cm. The X-rays propagate in a straight line, and thus illuminate at any given distance s from the focal spot a rectangle behind the diaphragm with the dimensions (41):

$$a(s) = \frac{s}{s_0} \cdot a_0 \text{ and } b(s) = \frac{s}{s_0} \cdot b_0. \qquad (41)$$

The irradiated volume of air in the plate capacitor is thus equivalent to the integral (42):

$$V = \int_{S_1}^{S_2} a(s) \cdot b(s) \cdot dS. \quad (42)$$

With the integral limits (43):

$$s_1 = s_0 + d \; and \; s_2 = s_0 + d + D, \quad (43)$$

where $d = 2.5$ cm is distance from diaphragm to plate capacitor. $D = 16$ cm is length of plate capacitor.

This gives us (44):

$$V = \frac{1}{3} \cdot \frac{a_0 b_0}{s_0^2} (s_2^3 - s_1^3). \quad (44)$$

And thus (45):

$$\boldsymbol{V = a_0 b_0 D \left(\frac{s_2^2 + s_2 s_1 + s_1^2}{s_0^2}\right) = 125 \ \mathbf{cm^3}}. \quad (45)$$

Equipment and setup (figure 29)

1. X-ray apparatus.
2. Plate capacitor X-ray.
3. Power supply 450 V DC.
4. Electrometer amplifier.
5. STE resistor 1 GΩ, 0.5 W.
6. Voltmeter, U ≤ 200 V DC, input resistance ≥10 MΩ.
7. Voltmeter, U ≤ 10 V DC.
8. Screened cable BNC/4 mm.
9. Connecting leads.

Setup part

Set up the experiment as shown in Fig. 30a, Fig. 30b shows the electrical connections of the plate capacitor and the electrometer amplifier for determining the ionization current.

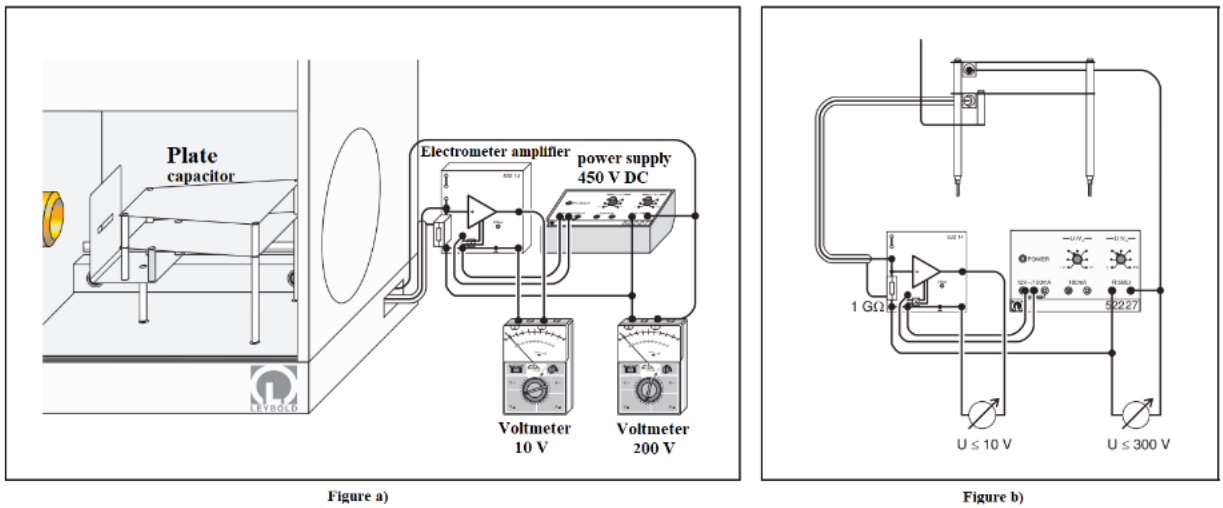


Fig. 30. a) Experiment setup for measuring the ionization current in a plate capacitor. b) Connecting the plate capacitor and the electrometer amplifier for determining the ionization current [34]

Safety notes

The built-in protection and screening measures reduce the local dose rate outside of the X-ray apparatus to less than 1 μSv/h, a value which is on the order of magnitude of the natural background radiation.

- Before putting the X-ray apparatus into operation inspect it for damage and to make sure that the high voltage is shut off when the sliding doors are opened.
- Keep the X-ray apparatus secure from access by unauthorized persons.
- Do not allow the molybdenum anode of the x-ray tube to overheat.
- When switching on the X-ray apparatus, check to make sure that the ventilator in the tube chamber is turning.

Mechanical setup:

- If necessary, demount the collimator of the X-ray apparatus and remove any experiment equipment from the chamber of the X-ray apparatus.
- Connect the adapter cable BNC/4 mm to the bottom capacitor plate (BNC socket) with the BNC plug and connect the connecting lead to the top capacitor plate (safety socket) of the plate capacitor X-ray.
- Lift the plate capacitor into the experiment chamber of the X-ray apparatus and insert the mounting plugs in the mounting sockets. Check to make sure that the capacitor plates are aligned parallel to the base plate of the X-ray apparatus, and correct if necessary.
- Feed the two cables into the free channel until they reappear on the right side of the X-ray apparatus

Electrical assembly:

- Connect the connecting lead to the positive pole of the 450 V DC power supply and connect the adapter cable BNC/4 mm to the electrometer amplifier fitted with the 1 GΩ resistor.
- Ground the electrometer amplifier to the negative terminal of the 450 V DC amplifier.
- Use one voltmeter each to measure the capacitor voltage U_C and the output voltage of the electrometer amplifier U_E.
- Plug in the X-ray apparatus to the mains power and switch it on.

If you think there is problem with setup, please ask engineer (teacher assistant) of lab or your professor.

Algorithm of measurements:

Part I: Saturation ionization current I_c as a function of the emission current I:

1. Set the tube high voltage on X-ray apparatus control panel to $U = 35$ kV.

2. Set the capacitor voltage $U_c \geq 140$ V on 200 V Voltmeter, so that the saturation value of the ionization current I_C is reached.

3. To record a measurement series, increase the emission current on X-ray apparatus control panel I in steps from 0 to 1 mA and determine the ionization current I_C for each step from the voltage U_E at the output of the electrometer amplifier:

$$I_C = \frac{U_E}{1G\Omega}$$

*Notes for calculating:

- U_E – it is your measurement from 10 V Voltmeter,
- 1 GΩ – it is resistance of STE resistor and it is equal to

$$1\text{G}\Omega = 1\ 000\ 000\ 000\ \Omega = 10^9\ \Omega.$$

4. Write down your measuring results and the calculated mean ion dose rate in the Table 9:

Table 9

Measurements for part I of experiment

I, mA	I_C, nA	$\langle j \rangle, \mu A\ /\ kg$
0.0		
0.01		
0.02		
…		
1.00		

5. Plot the graph $\langle j \rangle$, *μA/kg* versus I, *mA*: $\langle j \rangle = f(I)$ according results from Table 9.

6. Proceed to part II of experiment.

Part II: Saturation ionization current I_C as a function of the tube high voltage U:

1. Set the emission current on X-ray apparatus control $I = 1.0\ mA$.

2. Set the capacitor voltage $U_c \geq 140$ V on 200 V Voltmeter.

3. Increase the tube high voltage U in steps from 5 kV to 35 kV and determine the corresponding ionization current I_C.

4. Write down your measuring results and the calculated mean ion dose rate in the Table 10:

Table 10

Measurements for part II of experiment

U, kV	I_C, nA	$\langle j \rangle, \mu A\ /\ kg$
5		
10		
…		
35		

5. Plot the graph $\langle j \rangle$, *μA/kg* versus I, *mA*: $\langle j \rangle = f(I)$ according results from Table 10.

6. Make a conclusion about the obtained results and issue them in the form of a written report.

General questions for X-ray theory:

1. Define what are X-rays. Identify the range of wavelengths, energies and frequencies of X-rays. What is the difference between X-rays and visible light?
2. What is an X-ray tube (make a schematic drawing). How are X-rays obtained? (Write the electron energy conversion formula.)
3. Explain the phenomenon of thermionic emission.
4. How does the X-ray spectrum look like? What regions can you distinguish in it?

5. How are bremsstrahlung X-rays generated? What is the mechanism for generating characteristic X-rays?
6. Coherent elastic scattering. Scheme; conditions at which it may occur.
7. Compton scattering. Draw a scheme; write the equation showing conservation of energy in the system.
8. Photoelectric effect. Condition of observing, equation.
9. Characteristic X-rays: how it looks like in spectra, how it is produced?
10. Moseley's law, which quantities does it correlate together.

Special questions for 612 lab: Determining the dose

1. Define α, β, γ-radiation and X-rays.
2. Dosimetry is …
3. Absorbed dose. Unit of measurement. Designation. Formula.
4. Equivalent dose. Designation. Unit of measurement. Formula. What does the quality factor mean? What is the quality coefficient of α, β, γ and X-ray radiation?
5. Effective dose. Unit of measurement. Designation. Formula. What does the tissue-weighting coefficient represent? Give an example of weighting coefficients of various organs.
6. Exposure dose. Unit of measurement. Designation. Formula.
7. Dose limit is… Dose limit for personnel and the public.
8. What creates a natural background radiation? What is it equal to?
9. Protection against ionizing radiation. List the main methods of protection.

613. Contrast medium

Aim of work

- Investigation of how a contrast medium affects the absorption of X-rays

Brief theory

During X-ray investigations of living creatures, on first sight only the bones are clearly visible because, on account of their composition, they absorb a considerable amount of the Xrays. The imaging and distinction of individual organs is a lot more difficult because they usually have an X-ray absorption very similar to that of the surrounding tissue. A gall bladder or kidney is not visible on the X-ray image, likewise the coronary arteries

The way out of this is to fill the organs to be recorded in the X-ray image with a strongly absorbing material. Such a material is called a contrast medium because in the X-ray image it ensures clear contrast between the investigated organ and the other tissues.

Elements with a high atomic number Z are particularly suitable for this, provided in a form when they are not toxic. Many elements are excluded on account of the toxicity of their compounds, and essentially there are only two groups of substances which are in practical use.

There is non-soluble barium sulphate which can be drunk in the form of a suspension and is used for imaging the digestive tract while it moves through it.

Other organs such as the kidneys or the gall bladder can only be filled with a contrast medium from the outside with great difficulty. For this reason an attempt was made to find a contrast medium which can be injected into the bloodstream and which is then excreted by either the kidneys or the liver. Most usually iodine compounds are used for such purposes as they are biologically relatively harmless compared

to compounds made up of heavier elements. Typically, contrast media based on tri-substituted aromatic iodine compounds are used. Depending on the remaining side chains, one distinguishes between ionic and non-ionic contrast media which have different pharmacokinetics. Some are preferably excreted by the kidneys, others via the liver.

When imaging blood vessels, e.g. the coronary arteries, the contrast medium is injected directly into the blood vessels, if required via a catheter close to the organ, and it should then be quickly excreted again.

This experiment investigates the effect of a contrast medium on the absorption of X-rays. Because for the model of blood vessels described here the contrast medium only flows through plastic tubes and between plastic plates, a simple and cheap iodine compound such as potassium iodide can be used instead of the tri-substituted aromatic iodine compounds used with people.

The model of a blood vessel consists of a tube with a diameter of 2 mm, covered by a plastic plate. Liquids such as water or a contrast medium can be injected from outside the X-ray apparatus while the X-ray tube is switched on. Initially the model is filled with pure water. After the apparatus is switched on, the fluorescent screen will have no image, just a uniform green glow, tubes inside the model remain invisible. Next, the water is replaced with a solution of potassium bromide. Then the parts of the equipment with the potassium bromide solution in them appear as dark areas on the screen (see Fig. 31).

Fig.31. Picture of a model blood vessel with a contrast medium on a fluorescent screen, taken with a digital camera [36]

Equipment and setup (figure 32)

1. X-ray apparatus.
2. X-ray tube, Mo.
3. Blood vessel model for contrast medium.
4. Potassium bromide KBr, 100 g.
5. Beaker (glass with liquid), 150 ml.
6. Glass rod, 200 mm, 6 mm diam.
7. Wide-necked flask, brown glass, 250 ml.

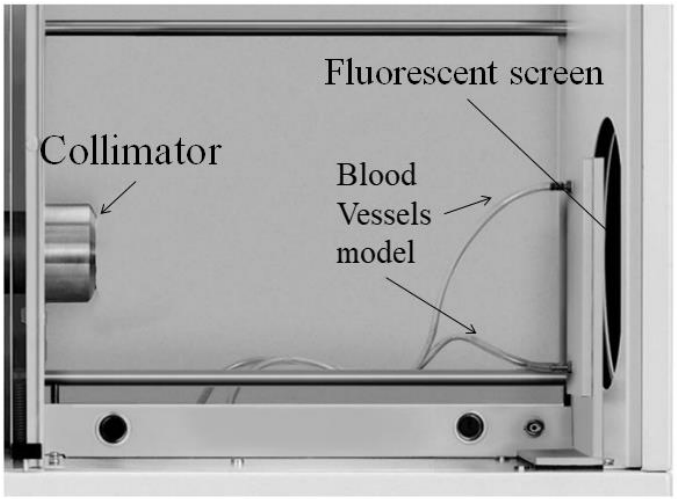


Fig. 32. Experiment setup for measuring influence of a contrast medium on the absorption of X-rays [36]

Safety notes

The built-in protection and screening measures reduce the local dose rate outside of the X-ray apparatus to less than 1 μSv/h, a value which is on the order of magnitude of the natural background radiation.

- Before putting the X-ray apparatus into operation inspect it for damage and to make sure that the high voltage is shut off when the sliding doors are opened.
- Keep the X-ray apparatus secure from access by unauthorized persons.
- Do not allow the molybdenum anode of the X-ray tube to overheat.
- When switching on the X-ray apparatus, check to make sure that the ventilator in the tube chamber is turning.

Setup part

The experiment set-up is shown in Fig. 32.

- If the goniometer is present, remove it from the experiment chamber of the X-ray apparatus and take out the collimator.

- The blood vessel model should be set up in the experiment directly in front of the fluorescent screen, with the tubes equipped with stoppers running through the X-ray apparatus' channel to the outside of the unit.
- Close the leaded glass sliding door.

Note: During the experiment it must be ensured when inserting and removing tubes through the channel of the X-ray device that the tubes are closed by means of the appropriate stopper. If any liquid escapes, the power supply is to be cut off IMMEDIATELY and the device is to be taken out of use. Only then may the device be cleaned. If a considerable quantity of iodine solution has escaped into the device, it is best to send it to the manufacturer for cleaning.

Algorithm of measurements

Part I: Influence of water H_2O on the absorption of X-rays

1. Remove the yellow caps from the two blood vessel model tubes.
2. Fill one of the syringes with water **H_2O from beaker** and connect it to the blood vessel model tube.
3. Then the second free tube without a cap should be directed into a **beaker** of water **H_2O** and held above it.
4. Press the first syringe and inject the entire water **H_2O** solution into the blood vessel model.

Notes about filling the blood vessel model:

- To fill the system with water, you may need to draw water into the syringe several times.
- The blood vessel model will be completely filled when bubble-free water flows from the second tube.

5. Close the tubes of the blood system model using the yellow caps. The closed tubes can be placed on the table.
6. **Make sure the leaded glass sliding door is closed**. Now you can proceed to setting up the X-ray apparatus.

7. Set the high voltage on X-ray apparatus control panel to **U = 35 kV** and set up an emission current **I = 1.0 mA**. Turn on the power using the **HV ON/OFF button**. The fluorescent screen should light up green.

8. Shade the area around the fluorescent screen as much as possible and take a photo of the screen with your phone. After that turn off the power using the **HV ON/OFF button**.

9. Make your thoughts about obtained picture in a notebook and also you may discuss it with your teammates and professor or teacher assistant.

10. Remove all liquid from tubes back to **H_2O beaker** by the syringe and close all tubes by caps.

11. Proceed to part II of experiment.

Part II: Influence of potassium bromide KBr on the absorption of X-rays

1. Remove the yellow caps from the two blood vessel model tubes.
2. Fill one of the syringes with **potassium bromide KBr from beaker** and connect it to the blood vessel model tube.
3. Then the second free tube without a cap should be directed into a **beaker** of **KBr** and held above it.
4. Press the first syringe and inject the entire **KBr** solution into the blood vessel model.

Notes about filling the blood vessel model:

- To fill the system with solution, you may need to draw **KBr** solution into the syringe several times.
- The blood vessel model will be completely filled when bubble-free **KBr** solution flows from the second tube.

5. Close the tubes of the blood system model using the yellow caps. The closed tubes can be placed on the table.

6. **Make sure the leaded glass sliding door is closed**. Now you can proceed to setting up the X-ray apparatus.

7. Set the high voltage on X-ray apparatus control panel to **U = 35 kV** and set up an emission current **I = 1.0 mA**. Turn on the power using the **HV ON/OFF button**. The fluorescent screen should light up green.

8. Shade the area around the fluorescent screen as much as possible and take a photo of the screen with your phone. After that turn off the power using the **HV ON/OFF button**.

9. Make your thoughts about obtained picture in a notebook and also you may discuss it with your teammates and professor or teacher assistant.

10. Remove all liquid from tubes back to **KBr beaker** by the syringe and close all tubes by caps.

11. Create a report from the obtained results. Try to use pictures in your report.

General questions for X-ray theory:

1. Define what are X-rays. Identify the range of wavelengths, energies and frequencies of X-rays. What is the difference between X-rays and visible light?
2. What is an X-ray tube (make a schematic drawing). How are X-rays obtained? (Write the electron energy conversion formula.)
3. Explain the phenomenon of thermionic emission.
4. How does the X-ray spectrum look like? What regions can you distinguish in it?
5. How are bremsstrahlung X-rays generated? What is the mechanism for generating characteristic X-rays?
6. Coherent elastic scattering. Scheme; conditions at which it may occur.
7. Compton scattering. Draw a scheme; write the equation showing conservation of energy in the system.

8. Photoelectric effect. Condition of observing, equation.
9. Characteristic X-rays: how it looks like in spectra, how it is produced?
10. Moseley's law, which quantities does it correlate together.

Special questions for 613 lab: Contrast medium

1. Absorption of X-rays in a medium. Describe the reasons of absorption and write down the formula.
2. Linear and mass absorption coefficients.
3. X-ray diagnostics. On which physical law is it based? Compare mass absorption coefficients of bones (Ca_3PO_4) and water.
4. In which cases contrast agents should be used for X-ray diagnostics? Give example of contrast agents.
5. Describe the methods of radioscopy, radiography, fluorography, electroradiography, angiography, X-ray computed tomography.
6. Direct and indirect effects of ionizing radiation on the body. (Radiolysis of water, protein damage, lipid peroxidation).

621. X-ray computed tomography

Aim of work

- Studying basic principles of an X-ray computed tomography scanner.

Subject of matter:

- Understanding the material absorption of the X-rays.
- Understanding the 3D-image reconstruction used for the computed tomography.
- Device adjustment and graphical tools for biological tissue identification.

Brief theory

The Hounsfield unit (**HU**) **scale** is a scale of linear attenuation of radiation with respect to distilled water, the X-ray density of which was taken as 0 HU (at standard pressure and temperature).

For a material X with a linear attenuation coefficient (linear absorption coefficient) μ_X , the value HU is given by equation (46):

$$\frac{\mu_X - \mu_{water}}{\mu_{water} - \mu_{air}} \times 1000. \qquad (46)$$

Where μ_{water} and μ_{air} are the linear attenuation coefficients for water and air under standard conditions.

After scanning the object and computer signal processing, the graphic image of the slice (graphic matrix) is reconstructed. In this case, each cell of the matrix corresponds to the computer-calculated absorption coefficient (AC) of tissues, which is also the attenuation coefficient, expressed in Hounsfield units HU. AC is similar in meaning to the degree of blackening of the X-ray, that is, it shows how much the tissue is able to attenuate X-rays. Bone absorbs X-rays more strongly than other tissues and has the highest AC (+800 +3000 HU). Air practically does not absorb and has the smallest AC (-1000 HU).

The higher the tissue AC, then the stronger it absorbs radiation, the fewer photons of radiation reach the detector of the tomograph and the whiter it looks on CT: the bone is the whitest, the air is the blackest. Thus, the distinction between normal and pathological formations on CT is made according to the gradations of the transition from black to white (gray gradations). AC is the main characteristic of a CT image in terms of density and in modern CT it ranges from -1000 to +3000 HU.

The essence of the method of back-projection (Radon transform)

An X-ray tube together with a collimating system creates a narrow fan-shaped beam having a divergence angle of 30^{o}–50^{o}. The degree of attenuation of the X-ray beam passing thought an object is recorded by detectors which transform the radiation into electrical signals. These analogue signals are then amplified by electronic units and converted to the digital form. Some materials are very effective in transforming X-ray radiation; most often two types of detectors are used: luminescent and gas detectors.

In the former type, a luminescent crystal is connected to a photomultiplier tube to transform light flashes into electronic signals. The amount of light generated is proportional to the energy of radiation which has been absorbed. Detectors of this kind were used in 1^{st} and 2^{nd} generation scanners. Their disadvantages are impossibility of close disposition of the detectors and persistence (afterglow effect).

A gas detector is an ionization chamber filled with xenon or krypton. Ionized gas allows electrons to come to tungsten plates, thus electronic signals, that proportional to the incoming radiation intensity, are generated. The plates are separated by gaps of 1.5 mm. Gas detectors were developed for the 3^{rd} generation scanners and provide high resolution and sensitivity. Their efficiency is close to 100% since they can be located very close to each other.

Solving the mathematical problem of reconstruction of tomography image belongs to a class of ill-posed problems (1st order operator equation). Exact and unambiguous solving of problems of this kind is, in general case, impossible.

Detector obtains data reflecting the interaction of X-ray radiation with the matter of which the studied object is made. Energy of photons decreases while they pass through the object due to photoelectric effect (absorption) and Compton effect (scattering). Attenuation coefficient μ, which is the feature of a certain material, can be found by the law of attenuation of intensity (Eq. 47):

$$I = I_0 e^{-\mu d}. \tag{47}$$

Where d is the object's thickness in m, I_0 is the beam intensity emitted by the source in Watts per area (W/m^2), and I is the intensity measured by the detector in W/m^2.

The narrow beam is scattered by all voxels (volume elements or volumetric pixels) as shown in Fig. 33.

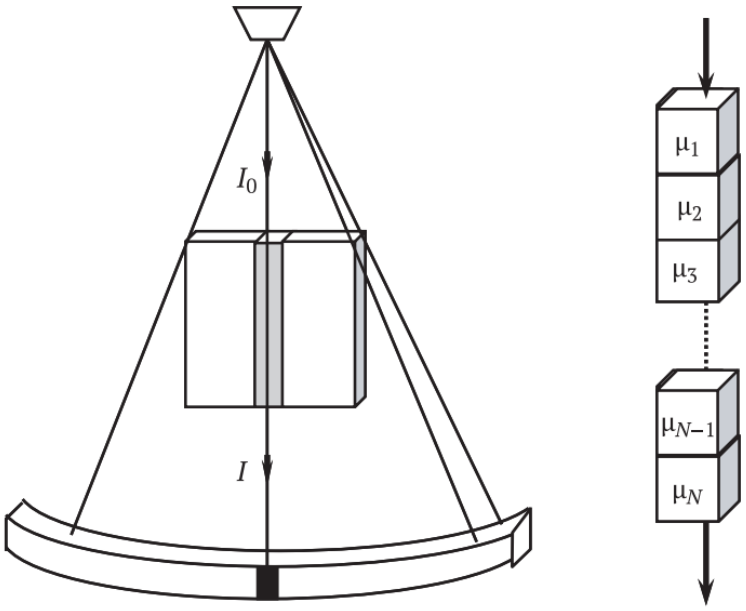


Fig. 33. Passing of an X-ray beam through a series of voxels [31]

The total attenuation coefficient for a beam passed through a certain series of voxels is $\mu_\Sigma = \mu_1 + \mu_2 + \ldots + \mu_{N-1} + \mu_N$, and it is this value which can be defined from the measurement, because $I = I_0 \exp(-\mu_\Sigma d)$.

It is possible to determine the absorption (attenuation) coefficients for each voxel by the method of back-projection (or Radon transform), which is based on obtaining information on absorption of X-ray radiation in many directions (Figure 34b). Consider, as an example, the case of four voxels (Figure 34a).

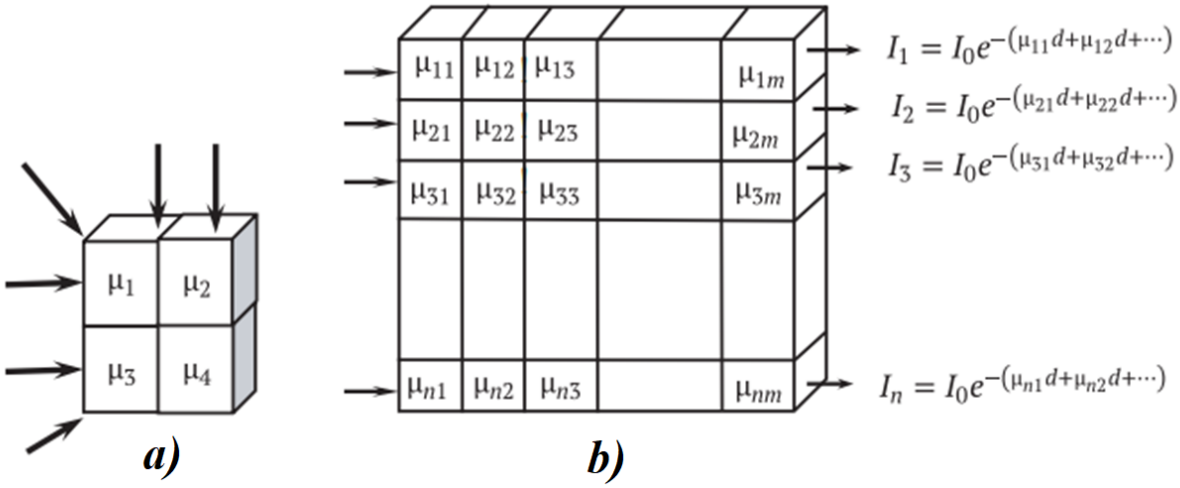


Fig. 34. Passing of an X-ray beam through a series of voxels in a slice. a) Object consists of 4 voxels, b) Object consists of many voxels [31]

This slice (of 4 voxels) is irradiated in several orientations, and as a result we get a number of different total coefficients (μ_{12}, μ_{23}, μ_{13}, μ_{14}, μ_{34}) giving a system of 6 equations where are 4 unknown elements (μ_1, μ_2, μ_3, μ_4):

$\mu_1 + \mu_2 = \mu_{12}$ *(horizontal),*

$\mu_3 + \mu_2 = \mu_{32}$ *(diagonal),*

$\mu_1 + \mu_3 = \mu_{13}$ *(vertical),*

$\mu_1 + \mu_4 = \mu_{14}$ *(the second diagonal),*

$\mu_2 + \mu_4 = \mu_{24}$ *(the second vertical),*

$\mu_3 + \mu_4 = \mu_{34}$ *(the second horizontal),*

To solve this system, as we know from math, we have to choose 4 equations that consist of 4 unknown elements ($\mu_1, \mu_2, \mu_3, \mu_4$). For instance, let's choose 4 equations for *horizontal, diagonal, vertical, the second diagonal* orientations:

$\mu_1 + \mu_2 = \mu_{12}$ *(horizontal),*

$\mu_3 + \mu_2 = \mu_{32}$ *(diagonal),*

$\mu_1 + \mu_3 = \mu_{13}$ *(vertical),*

$\mu_1 + \mu_4 = \mu_{14}$ *(the second diagonal),*

By solving this system, we obtain attenuation coefficients for the considered voxels ($\mu_1, \mu_2, \mu_3, \mu_4$). Each voxel is represented as a pixel on the image, whose brightness corresponds to the attenuation level provided by corresponding volume unit.

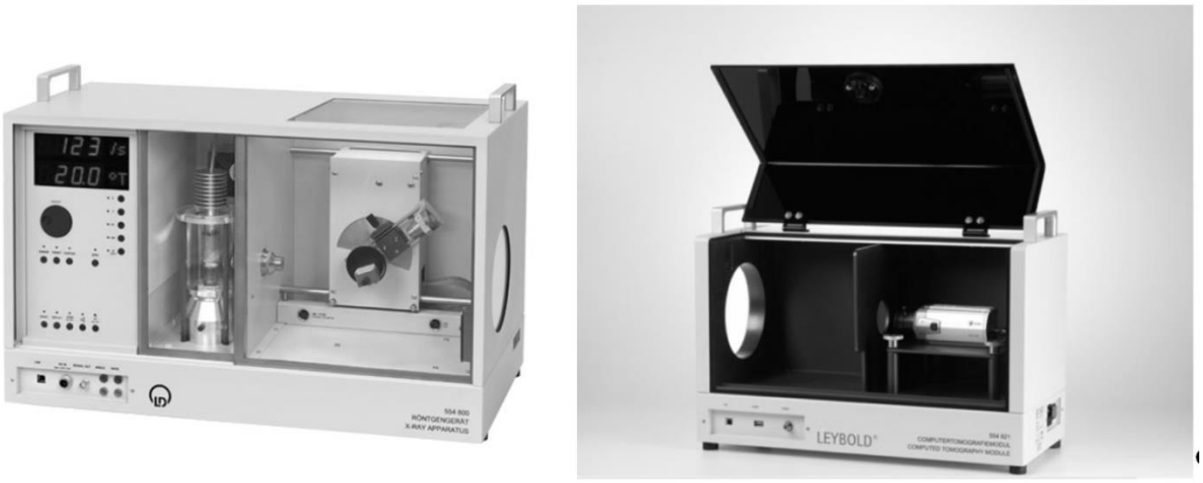
In practice computed tomography images are built of a quite larger number of pixels, and values of μ for corresponding quantity of voxels should be calculated. In modern instruments the digital matrix of the obtained image has usually the size of 512x512 of 256x256 pixels.

Computer processing of the image allows distinguishing more than one hundred attenuation levels, that is, densities of the investigated tissues: from 0 for water or liquor to > 100 for bones. This allows differentiating normal and pathological tissue regions with the accuracy of 0.5 – 1%, which is 20 – 30 times better that using standard radiography.

Equipment and setup (Figure 35a, b)

1. X-ray apparatus.
2. X-ray tube, Au (with golden anode).
3. Chamber for placing the objects.
4. Computed tomography module (include cover, camera and opening for the luminous screen with sealing ring).
5. Laptop with installed CT scan program.

6. Model objects (plastic egg, Lego cubes, stuffed frog or another biological object).



a) *b)*

Fig. 35. a) X-ray apparatus with chamber for placing the objects. b) Computed tomography module (include cover, camera and opening for the luminous screen with sealing ring) [37]

Safety notes

The built-in protection and screening measures reduce the local dose rate outside of the X-ray apparatus to less than 1 μSv/h, a value which is on the order of magnitude of the natural background radiation.

- Before putting the X-ray apparatus into operation inspect it for damage and to make sure that the high voltage is shut off when the sliding doors are opened.
- Keep the X-ray apparatus secure from access by unauthorized persons.
- Do not allow the anode of the x-ray tube to overheat.
- When switching on the X-ray apparatus, check to make sure that the ventilator in the tube chamber is turning.

Setup part

1. Place the camera on a rail end opposite to the X-ray tube and secure it with the screw.

2. Put the object 1 (plastic egg) in the centre of the holder.

3. Close the glass doors of the apparatus and turn it on by the power button on the side panel.

4. Make sure that the apparatus and the camera are connected to the computer via a USB cable. Launch the "Computed tomography" program (Fig. 36).

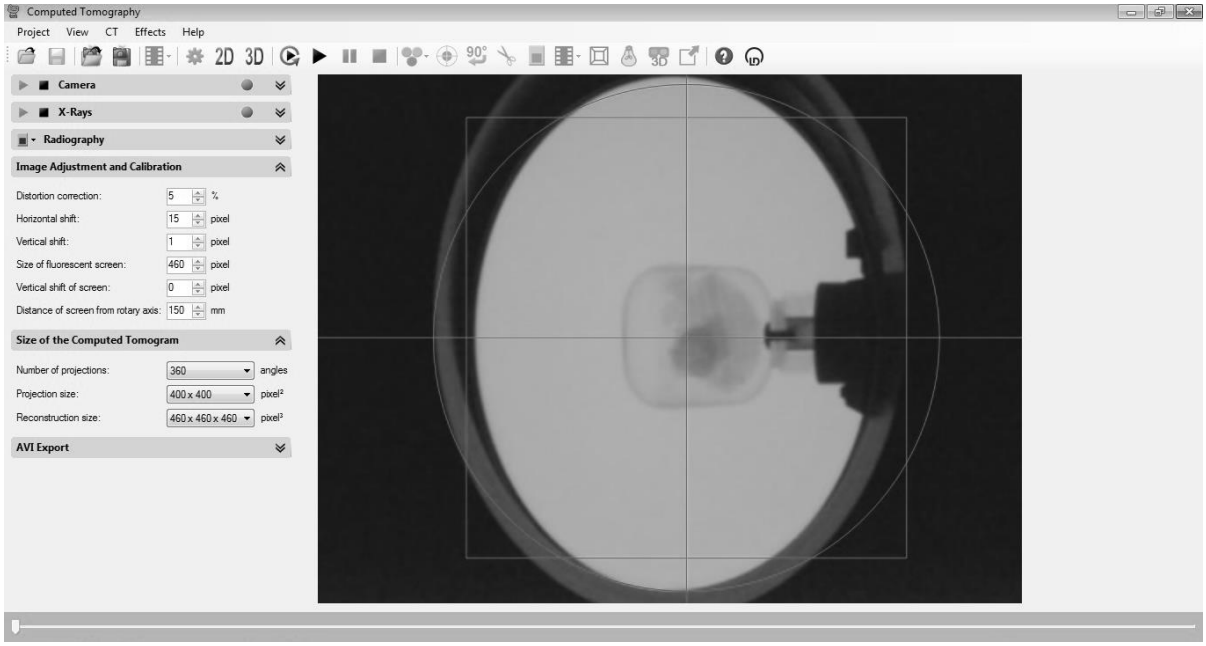


Fig. 36. Interface of the "Computed tomography" program

5. A red circle should flash on and off in the "**Camera**" line, indicating that the camera is connected.

6. Press the button ► in the "**X-rays**" line. The doors of the apparatus will be blocked, and the tube will start glowing. In the window on the right-hand side the image of the studied object will appear instead of the black square.

7. Move the centre of the red cross to the centre of the object using parameters "**Horizontal shift**" and "**Vertical shift**." Set the distance

from the rotation axis of the studied object to the camera in the line "**Distance of screen from rotary axis**".

8. Choose the size of the recorded area ("**Projection size**" parameter) in the "**Size of the Computed Tomogram**" line so that the studied object's image is within the red square. After that choose an appropriate "**Reconstruction size**" parameter (this value cannot be bigger than the projection size).

9. "**Number of projections**" parameter sets the number of rotation angles. The larger is this value, the better is the resolution of the image; however, the experiment duration also increases. Choose the value 180.

Algorithm of measurements

Part I: Obtaining image of egg by CT scan method.

1. Choose the CT menu in the upper bar of the program window and press "**Start CT scan**" (Fig 38).

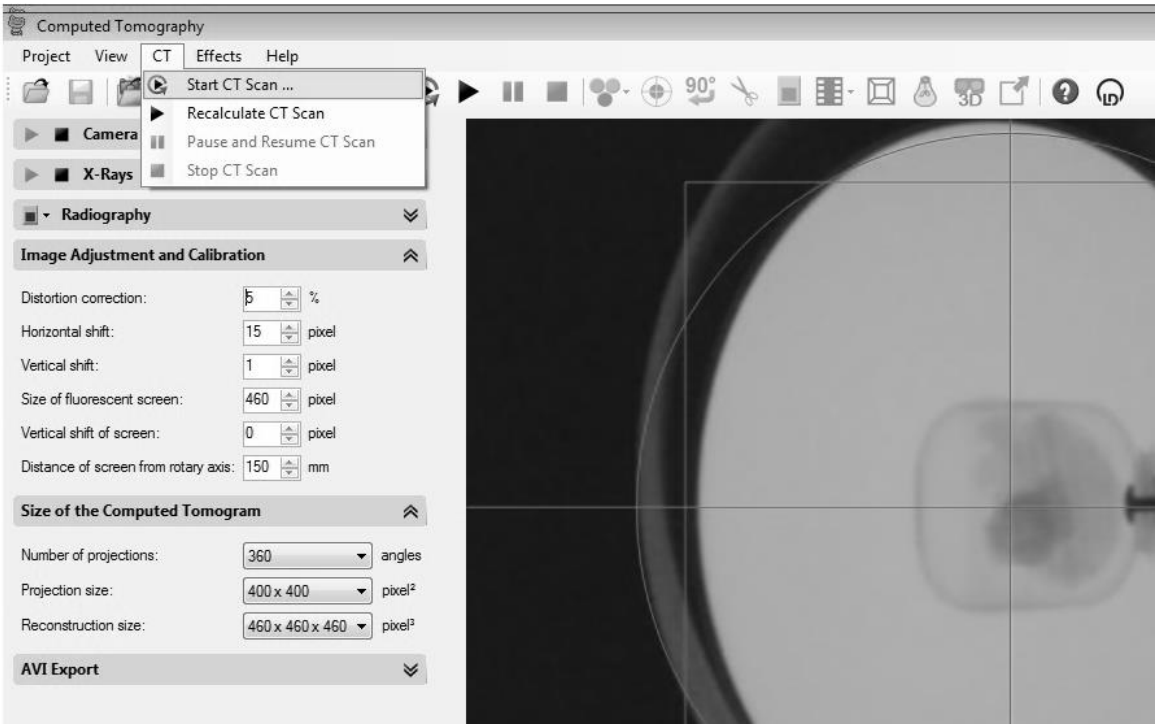


Fig. 37. Start CT scan

2. In the appearing dialog, choose the folder to save your results and name of the experiment.

3. You can check experiment results using buttons **2D** and **3D** on the instrument bar (Figure 38).

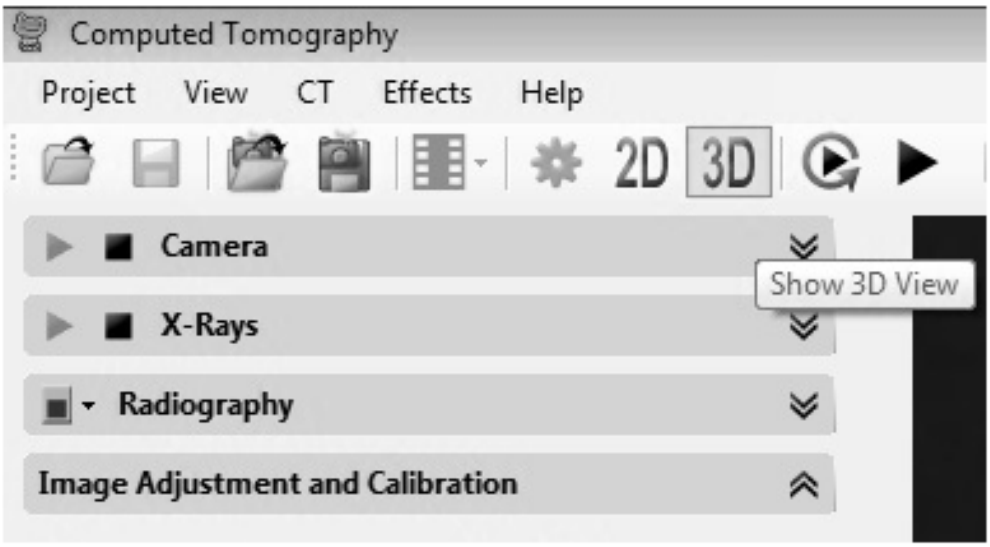


Fig. 38. The instrument bar. Here is example how to change view from 2D to 3D

4. Switch to the **3D mode**. Move the cursor to the object's image. You can turn the image by pressing and holding the left button of the mouse. To zoom in and out, press and hold the right button and move the mouse forward or backward. Slices of the image can be changed by the roller of the mouse.

5. Coloring of the image may be set in the "**Effects**" – "**Colour spectrum**" menu.

6. Observe what happens when you modify the "**Intensity**" and "**Transparency**" parameters (Fig. 39).

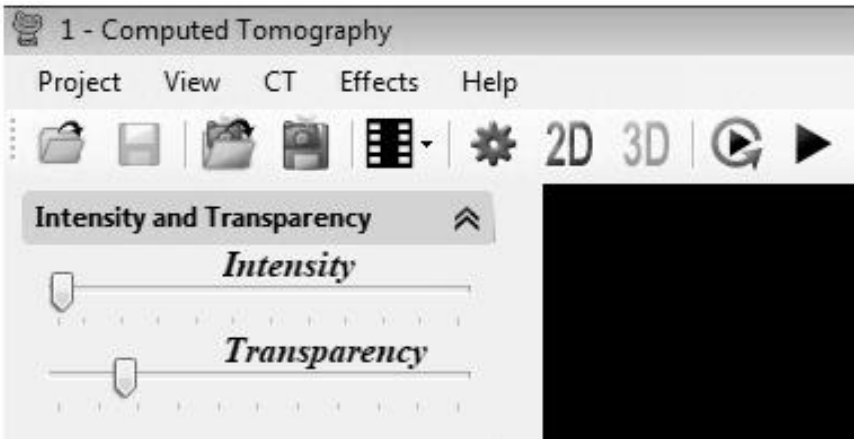


Fig. 39. Intensity and Transparency parameters

7. Write down what is inside the egg. Example of 3D image is presented in figure 40.

8. Choose the menu item "**Reset Angle and Zoom**" from the "**Effects**" menu; choose the perpendicular orientation of the egg by the button "**Rotate by 90°**". Move the cursor to the edge of the egg and press once the left button of the mouse. Using the ruler which will appear on the screen, measure the egg's diameter. Write down the value you obtain.

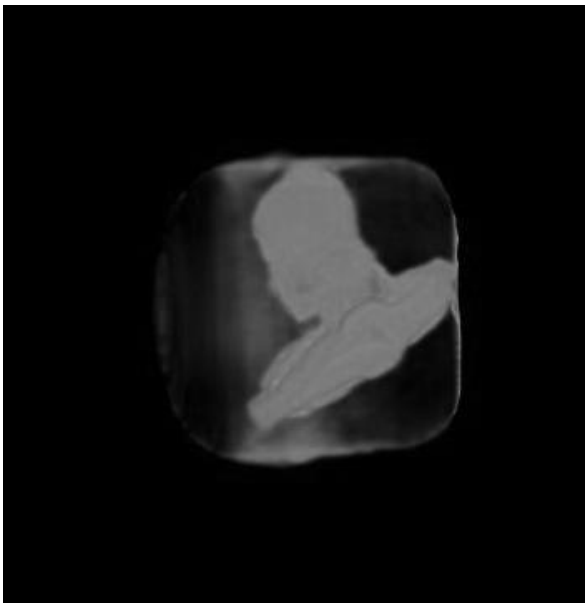


Fig. 40. Example of obtained 3D picture from CT program

Part II: Obtaining image of Lego block by CT scan method.

1. Put the object 2 (grey Lego block) in the centre of the holder.
2. Repeat steps 5–9 and start the experiment.
3. In the “Effects” – “Colour spectrum” menu choose the “5 colours” regime.
4. Find the foreign body inside the object, describe its position (in the centre, on the side, etc.), measure its sizes (length, width, height).

Part III: Obtaining image of the object 3 by CT scan method.

1. Put the object 3 (coloured Lego block) in the centre of the holder.
2. Repeat steps 5–9 and start the experiment.
3. In the “Effects” – “Colour spectrum” menu choose the “5 colours” regime.
4. Find the foreign body inside the object, describe its position (in the centre, on the side, etc.), measure its sizes (length, width, height).

Part IV: Obtaining image of the object 4 by CT scan method.

1. Put the object 4 (biological object). Make sure that the sample on the platform does not touch the camera during rotation! Before you begin the measurements, show the setup to the teacher or engineer.
2. Set the “Number of projections” to 360, and tick the checkbox “Full resolution.” Launch the experiment.
3. Investigate the object changing the “Intensity” and “Transparency” parameters. Obtain the reconstruction of the skin, skeleton, and viscera of the biological object.
4. Create the report from the obtained results. You should use pictures from CT program (photos or screenshots) in your report.

General questions for X-ray theory:

1. Define what are X-rays. Identify the range of wavelengths, energies and frequencies of X-rays. What is the difference between X-rays and visible light?
2. What is an X-ray tube (make a schematic drawing). How are X-rays obtained? (Write the electron energy conversion formula.)
3. Explain the phenomenon of thermionic emission.
4. How does the X-ray spectrum look like? What regions can you distinguish in it?
5. How are bremsstrahlung X-rays generated? What is the mechanism for generating characteristic X-rays?
6. Coherent elastic scattering. Scheme; conditions at which it may occur.
7. Compton scattering. Draw a scheme; write the equation showing conservation of energy in the system.
8. Photoelectric effect. Condition of observing, equation.
9. Characteristic X-rays: how it looks like in spectra, how it is produced?
10. Moseley's law, which quantities does it correlate together.

Special questions for 621 lab: X-ray computed tomography

1. Disadvantages of conventional radiography techniques.
2. Define the XCT method. How is a CT scan done?
3. Hounsfield scale. What is it used for? What are the indicators of various organs.
4. Design and structure of an X-ray tomograph.
5. Absorption of X-rays formula: attenuation coefficient. Write a formula. Give an explanation of the quantities included in it.
6. The essence of the method of reverse projection (Radon transform). Consider an object consisting of 2×2 voxels. Write down the system of equations.
7. How many degrees of density can computer image processing distinguish?
8. Generations of CT scanners. Their design. How has the scanning time changed from the 1st to the 5th generation of tomographs?

663. Attenuation of X-ray beam as a function of the absorber thickness or composition

Aim of work

- Investigating the attenuation of X-rays.

Subjects matter of the experiment

- Investigating the attenuation of X-rays as a function of the absorber thickness.
- Approving of the Beer-Lambert-Bouguer law.
- Investigating the wavelength dependency of the attenuation coefficient.

Brief theory

X-rays can be absorbed to some degree by any material. The fraction of the beam energy lost in the material depends on the thickness of the absorbing layer, the composition of the material, and the wavelength of the X-ray radiation. The energy loss happens due to several processes: transformations of the photons' energy into other energy types (absorption in the proper sense) and changing their propagation direction (scattering).

The absorption law can be derived under assumption that the fraction of the energy lost after passing a relatively thin material layer is proportional to the thickness of this layer. The proportionality factor is a so-called attenuation coefficient μ, which depends on the atomic number Z of the material and on the radiation wavelength λ.

Imagine that a monochromatic beam with the intensity I_0 passes through a plate with the thickness x (Figure 41).

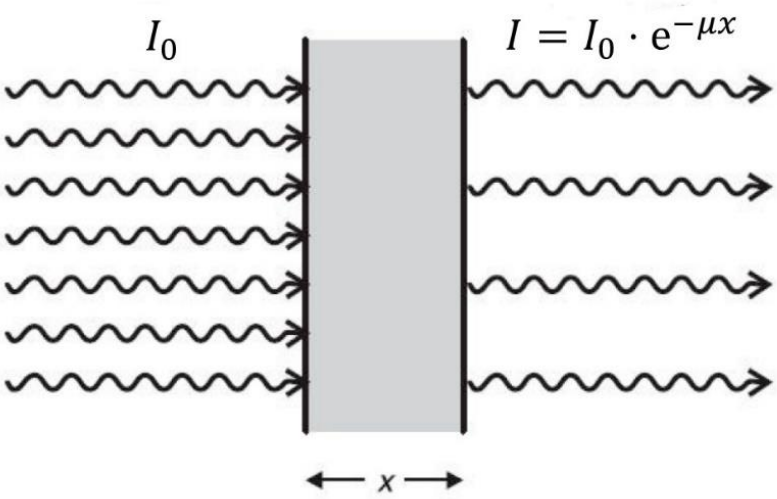


Fig. 41. diagram of changes in the intensity of an X-ray beam when passing through absorbing material [38]

Let's consider a thin layer of thickness dx inside the plate, in which the absorption can be assumed proportional to the layer thickness.

Then the relative attenuation of the beams in the considered layer can be written as (48):

$$\frac{dI}{I} = -\mu\, dx \tag{48}$$

Where I is the X-ray beam intensity at the boundary of the considered layer. The minus sign in the right-hand side of the formula points to the fact that the beam becomes weaker as it passes through the layer dx. By integration of Equation (48) we get (49):

$$-\int_{I_0}^{I} \frac{dI}{I} = \mu \int_{0}^{x} dx$$

$$\ln I = -\mu x + C \tag{49}$$

The constant C is found from the boundary conditions: at $x = 0$ intensity $I = I_0$ (the beam is just entering the material), and hence

$ln\, I_0 = C$. Then Eq. (2) can be rewritten as $\ln I - \ln I_0 = -\mu x$. Finally (50),

$$I(x) = I_0 \cdot \exp(-\mu x) \qquad (50)$$

The value μ is called linear attenuation coefficient. An absorption edge, i.e. an abrupt transition from an area of low absorption to one of high absorption, may be observed when the energy $h\nu = \frac{hC}{\lambda}$ of the X-ray quantum just exceeds the energy required to move an electron out of one of the inner electron shells of the absorber atoms.

Equipment and setup (Figure 42)

1. X-ray apparatus LD Didactic.
2. Goniometer.
3. End-window counter for α,β,γ and X-rays.
4. Set of aluminum absorber foils located on a holder.
5. Set of different metal absorber foils located on a holder.

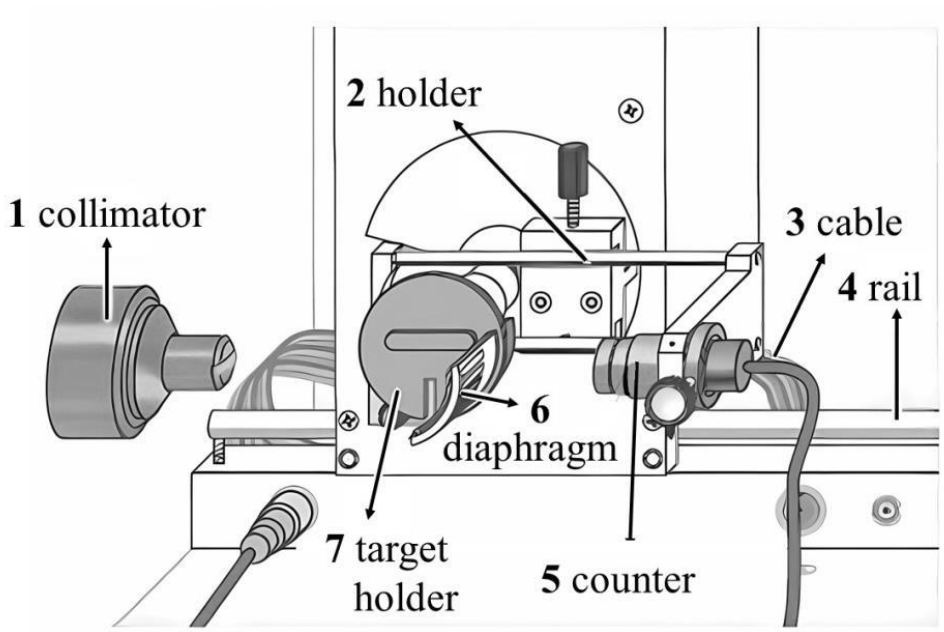


Fig.42. Experimental setup for investigating the attenuation of X-rays depending on the absorbent material substance and the thickness substance and the thickness of the absorbent substance [38]

The following paragraph is just a description of the device, don't make any changes in the apparatus.

Experimental setup consists of a collimator ***1***, goniometer on the rail ***4*** connected by the cable 3 to the electronic unit. The protective cap on the counter ***5*** should be taken off before the measurements. The horizontal target holder ***7*** is replaced by the set of absorbing plates ***6***, as show in Figure 43. The target and the counter are positioned first to the zero angle. This position should correspond to the empty gap in the diaphragm ***6***. The empty diaphragm should be in the middle between the collimator and the counter (5 cm away from the counter); this can be regulated by the holder ***2***.

Safety notes

1. The X-ray apparatus fulfills all regulations governing an X-ray apparatus and fully protected device for instructional use and is type approved for school use in Germany (NW 807/97 R*ö*).

2. The built-in protection and screening measures reduce the local dose rate outside of the X-ray apparatus to less than 1μSv/h, a value which is on the order of magnitude of the natural background radiation.

3. Before putting the X-ray apparatus into operation inspect it for damage and make sure that the high voltage is shut off when the sliding doors are opened (see Instruction Sheet for X-ray apparatus).

4. Keep the X-ray apparatus secure from access by unauthorized persons.

5. Do not allow the anode of the X-ray tube to overheat. When switching on the X-ray apparatus, check to make sure that the ventilator in the tube chamber is turning.

6. The goniometer is positioned only using a built-in step motor! Do not block the handle of the target and do not apply force to move it.

Algorithm of measurements

Part I: Attenuation as the function of the thickness.

- Without the zirconium filter

1. Set the high voltage level at the X-ray tube equal to U = 21 kV.
2. Set the emission current of $I = 0.05\ mA$.
3. Set the angle step $\Delta\beta = 0$.
4. Set the exposition time $\Delta t = 100\ s$.
5. Press the **TARGET** button.
6. Using the **ADJUST** handwheel, choose one of the angles 0,10,20,30,40,50, and 60 degrees. Measurements are started by **SCAN** button; to see the results of every scan on the display of the apparatus, press the **REPLAY** button.
7. Fill in the results in the Table 11.

- With the zirconium filter

1. Put the zirconium filter into the collimator.
2. Set the high voltage level at the X-ray tube equal to U = 21 kV.
3. Set the emission current of $I = 0.15\ mA$.
4. Set the angle step $\Delta\beta = 0$.
5. Set the exposition time $\Delta t = 200\ s$.
6. Press the **TARGET** button.
7. Using the **ADJUST** handwheel, choose one of the angles 0,10,20,30,40,50, and 60 degrees. Measurements are started by **SCAN** button; to see the results of every scan on the display of the apparatus, press the **REPLAY** button.
8. Fill in the results in the Table 11:

Table 11

Dependence of X-ray attenuation on the thickness of the substance

Thickness x, mm	Rate **R** (1/s) without the filter	R/R_0	Rate **R** (1/s) with the filter	R/R_0
0				
0.5				
1.0				
1.5				
2.0				
2.5				
3.0				

**Notes for calculating*:

- $\boldsymbol{R_0}$ is the original counting rate in front of the attenuator. According to this Table, the $\boldsymbol{R_0}$ can be found at $x = 0$.
- $\boldsymbol{R}$ is the counting rate behind it, we can quantify the transmission of the radiation to characterize the permeability of an attenuator using:

$$T = \frac{R}{R_0} \tag{51}$$

Where T is a transmittance of an attenuator.

When we insert the measurement data from Table 11 in equation (51) we obtain the transmittance of an attenuator T.

9. Plot the set of graphs ln (R/R_0) versus x for: $ln\left(\frac{R}{R_0}\right) = f(x)$ **a)** without **Zr** filter and **b)** with **Zr** filter. Figure 43a shows the attenuation of X-ray radiation depending on the thickness d of the aluminum absorber, which is well described by a straight line passing through the origin, where circles: measurement with zirconium filter, squares: measurement without zirconium filter.

10. Plot the set graphs of transmittance T as a function of the thickness x for: $R/R_0 = f(x)$ of the aluminum absorbers **a)** without **Zr** filter and **b)** with **Zr** filter. Fig. 43b shows how this depends on the thickness d of the absorber, where circles: measurement with zirconium filter, squares: measurement without zirconium filter. Check how the plotted set of points corresponds to the expected exponential function from equation (50).

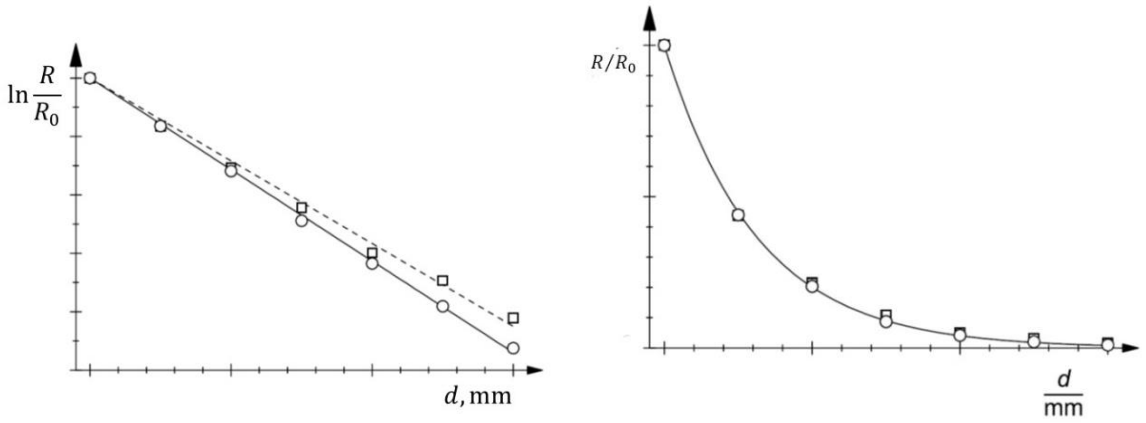


Fig. 43. a) Floating-point representation of transmission R/R_0 as a function of the thickness *d* of the aluminum absorbers.
b) Transmittance R/R_0 as a function of the thickness *d* of the aluminum absorbers [38]

Part II: Attenuation as the function of the material

- Without the zirconium filter.

1. Remove the zirconium filter from the collimator.
2. Set the high voltage level at the X-ray tube equal to $U = 21$ kV.
3. Set the emission current of $I = 0.02\ mA$.
4. Set the angle step $\Delta\beta = 0$.
5. Set the exposition time $\Delta t = 30\ s$.
6. Press the **TARGET** button.
7. Using the **ADJUST** handwheel, choose one by angles 0, $10, 20^0$ degrees. Measurements are started by **SCAN** button; to see the results of every scan on the display of the apparatus, press the **REPLAY** button.
8. Fill in the results in the Table 12.

9. Set the emission current $I = 1.00\ mA$.

10. Set the exposition time $\Delta t = 300\ s$.

11. Using the **ADJUST** handwheel, choose one by angles 0, $30, 40, 50, 60^0$ degrees. Measurements are started by **SCAN** button; to see the results of every scan on the display of the apparatus, press the **REPLAY** button.

12. Fill in the results in the Table 12.

- With the zirconium filter.

1. Plate the zirconium filter on the collimator.
2. Set the high voltage U = 30 kV.
3. Set the emission current $I = 0.02\ mA$.
4. Set the angle step $\Delta\beta = 0$.
5. Set the exposition time $\Delta t = 30\ s$.
6. Press the **TARGET** button.
7. Using the **ADJUST** handwheel, choose one by angles 0, $10, 20^0$ degrees. Measurements are started by **SCAN** button; to see the results of every scan on the display of the apparatus, press the **REPLAY** button.
8. Fill in the results in the Table 12.
9. Set the emission current $\mathrm{I} = 1.00\ mA$.
10. Set the exposition time $\Delta t = 300\ s$.
11. Using the **ADJUST** handwheel, choose one by angles 0, $30, 40, 50, 60^0$ degrees. Measurements are started by **SCAN** button; to see the results of every scan on the display of the apparatus, press the **REPLAY** button.
12. Fill in the results in the Table 12:

Table 12

Dependence of the attenuation of X-ray radiation on the material of the substance

Material	$\boldsymbol{Z}$	I, mA	$\Delta t, s$	**R** (s^{-1}) with filter	**R** (s^{-1}) without filter	R/R_0	Attenuation coefficient μ (cm^{-1})
Empty gap		0.02	30				
C	6	0.02	30				
Al	13	0.02	30				
Fe	26	1.00	300				
Cu	29	1.00	300				
Zr	40	1.00	300				
Ag	47	1.00	300				

- Measuring the background radiation level

1. Set the voltage $U = 0\ kV$.
2. Set the emission current $I = 0\ mA$.
3. Set the exposition time $\Delta t = 300\ s$.
4. Write down the results in the Table 12:
5. Plot the set of graphs for $\mu\ (cm^{-1})$ versus $\boldsymbol{Z}$: $\mu = f(Z)$ according to the results from *Table 2* and dependence of radiation attenuation on the charge number of the absorber atom $R(1\ /\ s) = f(Z)$.
6. Present your results in the form of a report with the main conclusions for this work.

**Notes for calculating attenuation coefficient $\mu\ (cm^{-1})$*:

- Figure 44 shows the relationship between the linear attenuation coefficient μ and the atomic number *Z*, where circles: measurement with zirconium filter, squares: measurement without zirconium

filter. Below Z = 40 (Zr), the attenuation coefficient increases steeply as the atomic number rises. When Z reaches 40, we observe an abrupt decrease, which is more apparent for the filtered radiation. This reduction is due to the fact the certain excitations are no longer possible in Zr (binding energy of the K shell is too great). The unfiltered radiation contains a high-energy component which can still generate this excitation, so that the decrease in μ is less.

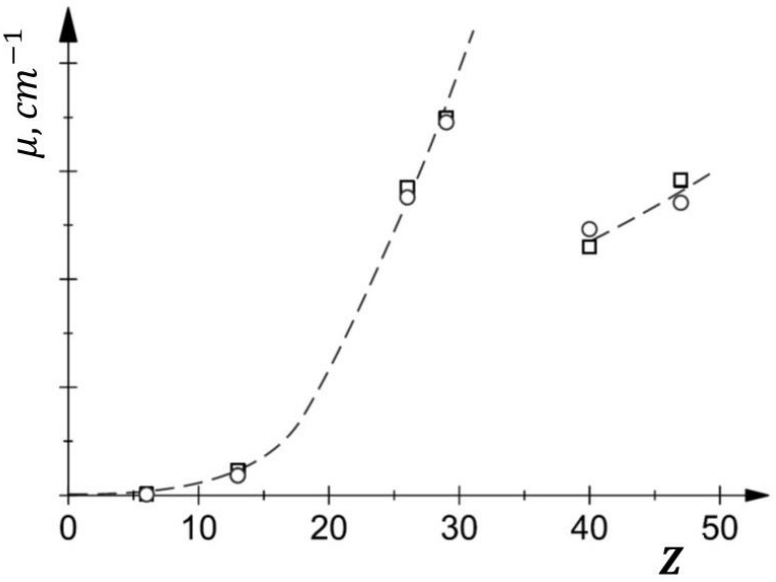


Fig. 44. Linear attenuation coefficient μ as a function of the atomic number Z of the absorber [38]

Thus, using the following relation, we can find μ:

$$R = R_0 \cdot exp(-\mu \cdot x) \Rightarrow \frac{R}{R_0} = exp(-\mu \cdot x) \Rightarrow ln\frac{R}{R_0} =$$

$$= ln(exp(-\mu x)) \Rightarrow \ln\frac{R}{R_0} = -\mu x \Rightarrow \ln\frac{R}{R_0} = \mu x \Rightarrow \mu = \frac{1}{x}\ln\frac{R_0}{R}.$$

In this experiment the value x = 1 mm.

General questions for X-ray theory:

1. Define what are X-rays. Identify the range of wavelengths, energies and frequencies of X-rays. What is the difference between X-rays and visible light?

2. What is an X-ray tube (make a schematic drawing). How are X-rays obtained? (Write the electron energy conversion formula).
3. Explain the phenomenon of thermionic emission.
4. How does the X-ray spectrum look like? What regions can you distinguish in it?
5. How are bremsstrahlung X-rays generated? What is the mechanism for generating characteristic X-rays?
6. Coherent elastic scattering. Scheme; conditions at which it may occur.
7. Compton scattering. Draw a scheme; write the equation showing conservation of energy in the system.
8. Photoelectric effect. Condition of observing, equation.
9. Characteristic X-rays: how it looks like in spectra, how it is produced?
10. Moseley's law, which quantities does it correlate together.

Special questions for 663 lab: Attenuation of X-ray beam as a function of the absorber thickness or composition

1. What contributions of absorption processes are taken into account by the linear and mass absorption coefficients? Give definition of the mass absorption coefficient and write the formula. What happens to the mass absorption coefficient as the atomic number Z increases?
2. What is transmittance of an attenuator T? What formula is used for this expression?
3. What does counter register in the experimental setup?
4. What function does the zirconium filter perform in this experiment?
5. What happens to the count rate value R when the thickness of the plate increases and the atomic number Z of the element increases?

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Appendix

Table A1

Radiation quantity table with description

Radiation Quantity (conventional term)	**Description of Quantity**	**SI Units**	**Conventional Units**	**Equivalent Expression Relationship between Quantities**
Exposure (X)	Amount of ionization per mass of air due to X and gamma rays $X = dQ/dm$	Coulombs/kg (C/kg)	Roentgen (R)	$1R = 2.58 * 10^{-4}$ C/kg 1C/kg=3876 R
Absorbed dose (D)	Amount of energy imparted by radiation per mass $D = dE/dm$	Gray (Gy)	Radiation absorbed dose (rad)	1 Gy = 1 J/Kg=100rad
Kerma (K)	Kinetic energy released per unit mass	Gray (Gy)	Radiation absorbed dose (rad)	K(mGy)=3.39 $*$ $10^{-4} * X$(C/kg)
Dose equivalent (H)	A measure of radiation-specific biological damage in humans	Sievert (Sv)	rem	H(Sv)=$W_R * D\ (Gy)$
Effective dose equivalent (H_E)	A measure of radiation- and organ system-specific damage in humans	Sievert (Sv)	rem	H_E(Sv) $= \Sigma W_T * H_T$(Sv)
Activity (A)	Amount of radioactivity expressed as the nuclear transformation rate	Bequerel(Bq)	Cuire (Ci)	1Ci=3.7*10^{10} Bq 1 Bq=1*s^{-1} (dps)

*Rem – a unit of effective absorbed dose of ionizing radiation in human tissue, equivalent to one roentgen of X-rays.

Dps- disintegration per second;

H_T- equivalent dose to organ or tissue;

W_R- radiation weighting factor;

W_T – tissue weighting factor;

1 erg = 10^{-10} Joule.