Ministry of Health of Ukraine
Ukrainian Medical Stomatological Academy

It is approved
on meeting of department of
medical informatics, medical and biological physics
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Methodical instructions
for students' self-preparation work at preparation for a practical lesson
at home and at the classroom

Subject matter	**Medical and biological physics**
The unit	2. Bases of medical physics
Theme of lecture:	**X-ray radiation.**
Year	1
Faculty	Medical, Stomatological
Speciality	Medicine, Stomatology

Poltava - 2020

The topic significance:
X-ray nowadays is widely used with the purpose of diagnostic and therapy, fluorography, radio examination, a tomography, end so on. X- radiation is one of kinds of ionizing radiation. Ionizing radiation is radiation whose effect on a material causes ionization of the atoms of this material. Among there are: alpha-, beta- and gamma-radiation, X-radiation, neutron and proton flux. Only gamma-radiation and X-radiation are electromagnetic waves, others are particle fluxes.

Specific targets:
To familiarize with:
- History of discovering of X-ray
- Constitution of a X-ray tube
- Constitution of the roentgen machine

To know:
- The mechanism of originating of a braking radiation
- The mechanism of originating of characteristic radiation. A Moseley law .
- Views of interaction of X-ray with material:
  a) A coherent scattering
  b) A photoeffect
  c) A Compton effect
  d) Ionization

To be able to explain:
- The mechanism of activity of a X-rays on biological objects
- Use of X-ray in medicine :
- X-ray diagnosis
- Radio examination

- Radiographic analysis
- Tomography (sectional roentgenography)
- Roentgen therapy
- X-ray diffraction analysis in medical and biologic examinations

Basic knowledge, experience, skills necessary for studying the topic in connection with other subjects:

Previous (providing disciplines)	Obtainable skills
Physics	To write down formulas, to explain operation of devices and installations on electric circuits.
Biology Chemistry	To describe a constitution of a cell and organellas To know originating of ions, free radicals, peroxides, hydroperoxides. To write down chemical changes, to explain them

Materials for the before-class self-preparation work:

List of main term, parameters, characteristics, which student have to learn at preparation to class:

Term	Definition
X-ray	Electromagnetic radiation in wavelenght range 10 nm–10^{-2} nm
Braking radiation	– bremsstrahlung – X-radiation occurs when these accelerated electrons are braked in the material of the anode.
Characteristic radiation	It is created by atoms of elements with a high atomic number. Radiation occurs when the electrons in the shells of these atoms transit from one of the upper levels to one of the lower ones on the place of kicked out electron.
Coherent scattering	It is observed when the X-radiation quantum energy is less than that of atom ionization
Inner photoeffect	If energy of a photon hv is sufficient for fulfillment of work A_U on an electron detachment ($hv \geq A_U$), at interaction the X-ray radiation photon is absorbed, and the electron comes off atom, i.e. there is an ionization of material.
Compton effect	If photon energy hv considerably exceeds work on an electron detachment: $E >> AB$. The electron comes off atom (such electrons are termed *as Compton electrons)*, energy of a photon decreases, and the wavelength is accordingly enlarged.
Ionization	It is a process of transforming neutral atom into ion: breaking of molecules, or kicking electrons out the electron shells of atoms.

Theoretical questions to class:

1. Constitution of a X-ray tube.
2. Constitution of the roentgen machine.
3. The mechanism of originating of a braking radiation.
4. The mechanism of originating of characteristic radiation. A Moseley law
5. The mechanism of activity of X-ray on a cell.
6. How external and internal factors influence on effect of X-ray on a cell?
7. Explain features of use of X-ray in X-ray diagnosis.
8. Features of use of X-ray in roentgen therapy.
9. Explain features of a method a X-ray tomography.
10. Explain features of a method of the NMR-tomography (nuclear magnetic resonance tomography) (the phenomenon of nuclear magnetic resonance is used).
11. Explain features of a positron-emission tomography (PET) method.

Practice work executed at class:

Analisys of X-ray pattern.

1. To familiarize with X-rayograms of different objects;
2. To analise X-rayograms of different objects*;*
3. To analyse and to explain peculiarities of technological solution at different X-ray applications.

The contents of the topic:

Ionization is a process of neutral atom transforming into ion. ***Ionizing radiation*** is radiation whose effect on a material causes ionization of the atoms of this material. They are subdivided into two types: electromagnetic radiation and streams of corpuscles. ***X-radiation*** and ***gamma-radiation*** are electromagnetic radiation, but ***alpha-, beta-radiation, neutron*** and ***proton fluxes*** are fluxes of subatomic particles (corpuscular radiation). Alpha-radiation is flux of helium atom nuclei, beta-radiation represent electron (and positron too) flux. Protons (hydrogen nuclei), deuterons (deuterium nuclei), ***heavy ions*** also can form streams. Nuclear particles not having a charge (neutron) also can indirectly produce ionization. Now in medicine π^{-}-mesons, rather perspective for radiative therapy because of their features of interaction with material, are used also.

X-RADIATION

X-radiation are electromagnetic waves with wavelengths less than the wavelength of ultraviolet radiation, but greater than that of gamma-radiation. Borders between ranges are appreciably conditional – the wavelength bands of these radiations partially overlap.

The longest wavelength X-radiation is overlapped by ultraviolet radiation, and the shortest wavelength is overlapped by long wave γ-radiation. Overlapping of the bands of X-radiation and gamma-radiation is accounted for by these radiations often being classified by the mechanism of their emergence.

Hence, shortwave radiation linked to braking of electrons in X-ray tubes, or to electron transitions in atoms, is known as X-radiation, whereas radiation occurring during intranuclear reactions is known as gamma-radiation. It is generally accepted that X-radiation has the wavelength within 0,001 nm to 10 nm.

Energy of quantums *(E)* of an X-rays and γ-radiation is determined under the formula:

$$E = h\nu = hc/\lambda;$$

Where h – Planck constant; ν – frequency of radiation; c– velocity of light; the λ – wavelength of radiation.

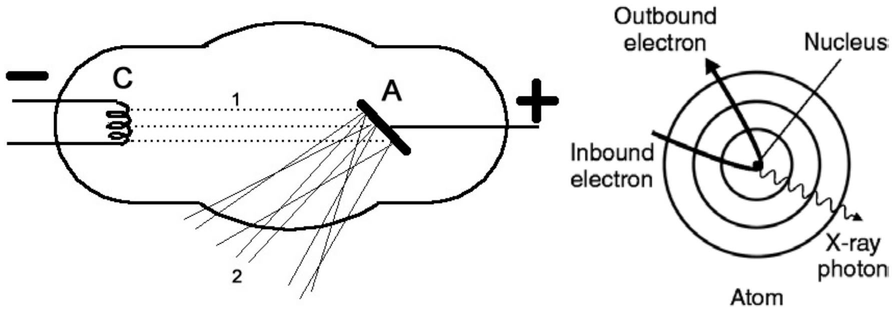
As to the mechanism of its emergence, X-radiation is classified as **bremsstrahlung,** which arises at sharp braking (slowdown) of electrons in vacuum X-ray tubes, and **characteristic radiation,** which arises at a radioactive decay of substances**.**

Bremsstrahiung X-radiation

According to Maxwell's theory, a charged decelerating particle radiates electromagnetic waves. In particular, a charged particle emits electromagnetic waves when colliding with atoms of any material (fig.1, A). It occurs in X-ray tube that is a two-electrode vacuum device. They are most common source of X-radiation

The heated cathode emits electrons. Under the affect of the difference of potentials U applied across the cathode and anode, the electrons accelerate and bombard the anode's surface.

Bremsstrahlung (braking) X-radiation occurs when these accelerated electrons are broken in the material of the anode. The anode has a sloping surface to direct the emerging X-radiation at an angle to the tube axis (fig.1, B). The anode surface is made of materials with a high atomic number Z.



A B

Fig.1. A) X-ray tube. 1– electron flux, 2 – X-rays, C – cathode, A – anode.
B) Bremsstrahlung X-radiation origination.

When the electron is broken in the anode material, only part of its energy is expended on exciting X-radiation. The remaining part of this energy is expended on anode heating. Since the ratio of these parts is random, the energy of the emitted quantum of X-radiation ***hν*** can vary within wide limits. Therefore, when the anode is bombarded with a huge amount of electrons, a continuous X-radiation spectrum is formed.

The energy of the emitted quantum of X-radiation ***hν*** is less than or equal to the energy of the electron (***eU***) bombarding the anode. $E = h\nu = hc/\lambda < eU.$

Therefore, at the given voltage (***U***) applied to the X-ray tube anode, the wavelength in the X-radiation spectrum will be:

$$hc/\lambda < eU \quad => \quad \lambda > hc/eU \quad => \quad \lambda_{min} = hc/eU$$

If we denote the X-radiation wavelength in nm (1 nm = 10^{-9} m), and the tube voltage in kilovolts (1 kV = 10^3 V), then, after substituting the numeric constants into the formula, an expression convenient for practical use is obtained: $\lambda_{min} = 1{,}24/U.$

An increase in the tube voltage (U) makes the power of the bremsstrahlung X-radiation increase (in proportion to U^2), and the maximum of the spectrum radiation energy is shifted towards shorter wavelengths: $\lambda_{max} \approx 3/2\, \lambda_{min}$.

The radiation penetrating capacity, when interacting with a material, depends on the radiation quantum energy. Shortwave radiation has higher quantum energy and penetrates a material deeper. Hence, it is known as hard radiation. Long wave radiation is less penetrating and it is known as soft radiation. Therefore, by increasing the anode voltage, one can change the spectral composition of radiation and increase its hardness.

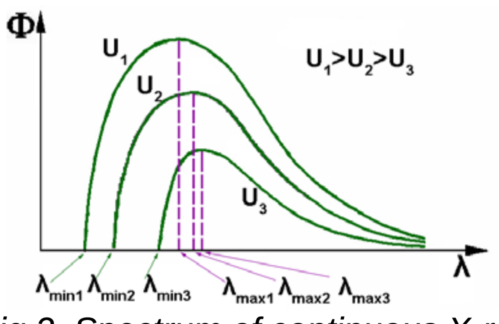


Fig.2. Spectrum of continuous X-ray at different voltage.

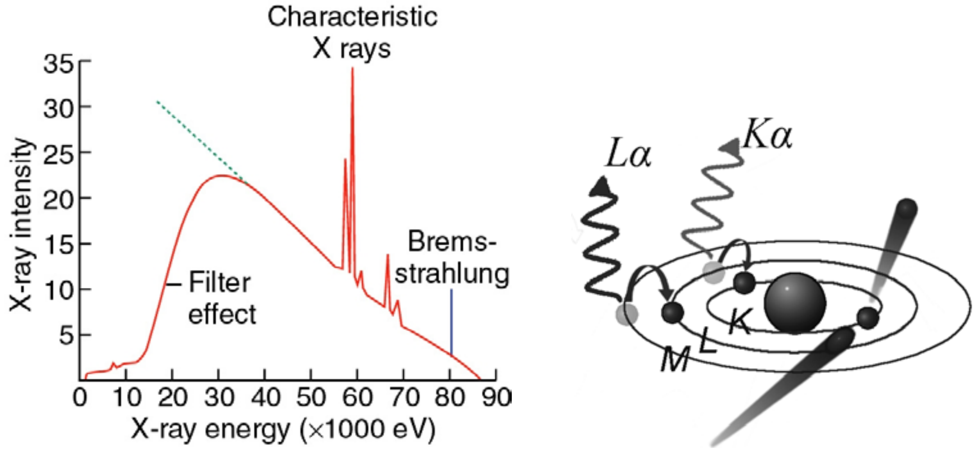
If the filament temperature is increased, electron emission from the cathode and the current in the tube circuit increase. At this, the radiation power increases in proportion to the anode current, but the spectrum energy distribution remains invariable.

Only near 1% of electron flux energy spends on X-ray producing; main part spends on anode heating.

High-energy X-ray photons are obtained with help of betatron – device-accelerator of nuclear particles.

Characteristic X-radiation

Characteristic X-radiation is created by atoms of elements with a high atomic number (***Z***). Radiation occurs when the electrons in the shells of these atoms transit from one of the upper levels to one of the lower ones. During such transitions, the difference of level energies is large and the wavelength of the emerging photon belongs to the X-radiation band.



A B

Fig.3. X-ray generation. A – spectrum generated by X-ray tube containing bremsstrahlung and characteristic radiation; B – scheme of characteristic radiation

Since the structure of the lower levels of all heavy atoms is similar, the spectra of characteristic X-radiation of different heavy atoms are also similar. These spectra are linear ones and are described by the ***Moseley law:***

$$\sqrt{\boldsymbol{v}} = \boldsymbol{A}(\boldsymbol{Z} - \boldsymbol{B}),$$

where v is the frequency corresponding to the line of the characteristic X-radiation occurring during transition of an atom with atomic number Z from the ***n****-th* stationary state to the ***k****-th* state; A and B are constants whose values are determined by the values of numbers n and k.

Moseley law allows to determine a nucleus charge on a position of X-ray spectrum lines.

The X-ray tube can be used not only for obtaining bremsstrahlung radiation, but for generating characteristic radiation as well. This occurs when the X-ray tube voltage is increased to make the energy of electrons bombarding the anode sufficient to excite an atom. In this case, the X-radiation spectrum will contain bremsstrahlung and characteristic radiation (fig.3).

A specific feature of characteristic X-ray spectra is that they do not depend on the chemical compound containing the atom. This is because the energy of the inner levels of an atom remains invariable during formation of chemical compounds. Therefore, for example, the X-ray spectrum of an oxygen atom is the same for O_2, CaO and H_2O, whereas the optical spectra of these compounds differ largely. Due to this feature of the X-ray spectrum of an atom, the radiation came to be known as characteristic.

Interaction of X-radiation with a material

Three main types of interaction:

- coherent scattering (Rayleigh scattering);
- photoeffect;
- incoherent scattering (Compton effect or compton scattering).

The X-ray radiation impinging on a body, in part is reflected (insignificantly) from its surface, but in basic passes in depth of body, where, interacting with electrons of atoms of material, it is absorbed, scattered and in part permeates through without interaction with it.

Mechanisms of X-ray radiation absorbing depend on a relation between energy of photon $E=hv$ and ionization energy A_u.

Coherent scattering

Coherent scattering is observed when the X-radiation quantum energy is less than that of atom ionization (i.e. the energy required for detaching an electron from an atom). Hence, coherent scattering is characteristic for long-wave X-radiation. At coherent scattering, the direction of propagation of X-radiation changes without radiation energy absorption by the material.

At coherent scattering only a direction of electromagnetic radiation propagation (a direction of a photon motion) varies. It is used for ***X-ray diffraction analysis*** – revealing of interior structure of material with a regular arrangement of atoms and molecules.

The X-ray radiation, permeating a crystal, owing to the phenomena of diffraction on a crystal and subsequent interferences, shapes on a photographic plate the symmetric pattern of spots (the diffraction pattern) which is termed *a Laue pattern* named German scientist Maks von Laue. He for the first time has predicted an opportunity of X-ray application for definition of body structure.

Decoding of Laue patterns in case of unknown crystalline structure represents a difficult problem. If the crystal structure is known, Laue method enables to determine lengths of waves, that is to carry out ***X-ray spectroscopy***.

Inner photoeffect

If energy of a photon *hv* is sufficient for fulfillment of work A_U on an electron detachment ($hv \geq A_U$), at interaction the X-ray radiation photon is absorbed, and the electron comes off atom, i.e. there is an ionization of material. The come off electron gets a kinetic energy; if the kinetic energy of an electron is appreciable, it ionizes the next atoms by a collision [encounter, hit, impact] *(secondary ionization)*.

If energy of a photon is insufficient for an electron detachment there is an excitation of atom or a molecule. At some materials it gives in the subsequent radiation in the field of a visual gamut *(roentgenoluminescence)*. In tissues of an organism owing to excitation of atoms and molecules photochemical reactions propagate.

During photoeffect, X-radiation quanta interact with the inner-shell electrons of an atom, the electron being detached from the atom (atom ionization). However, since the inner-shell electrons have a stronger binding to the nucleus than outer-shell electrons do, the X-radiation quantum expends all its energy on detaching the electron from the atom, i.e. radiation absorption occurs.

Incoherent scattering

If photon energy hv considerably exceeds work on an electron detachment: E >> AB there is a Compton's effect or an incoherent dispersion.

The electron comes off atom (such electrons are termed as Compton electrons), energy of a photon decreases, and the wavelength is accordingly enlarged; direction of a photon motion varies too.

Radiation with a major wavelength generated at it is termed secondary, it is diffused on every possible directions. If Compton's electrons have a sufficient kinetic energy, they ionize the next atoms by a collision.

At incoherent scattering, X-radiation quanta interact with the outer-shell electrons of an atom, i.e. electrons having a weaker binding with the nucleus than the inner-shell electrons do. At this, the electron is detached from the atom (the atom is ionized) and acquires kinetic energy.

Part of the X-radiation quantum energy is expended on detaching the electron and imparting there to kinetic energy. In so doing, a radiation quantum is formed, which has a lesser energy (with a longer wavelength), and moves in a direction differing from that of the initial quantum, i.e. radiation dissipation occurs. It is just because the scattered quantum energy differs from that of the initial quantum that such type of scattering is known as incoherent. Electrons detached from atoms during the Compton's effect are known as Compton's electrons.

Absorption of the X-ray radiation by material

When X-radiation passes through a material, its radiation flux Φ attenuates. If the X-radiation is monochromatic, the radiation flux attenuated by the homogeneous material is described by the ***Bouguer law:***

$$\Phi = \Phi_0 \cdot e^{-\mu d},$$

where Φ is the radiation flux incident on the material; Φ_0 is the radiation flux that has passed through a material layer with the thickness *d* and retained its direction of propagation; and *μ* is a *linear attenuation factor* for X-radiation. Linear attenuation factor depend on material density *ρ*, atomic number Z and wavelength of incident X-ray.

The mass extinction coefficient is peer to the relation of the linear extinction coefficient to density of an absorbent and does not depend on density of absorbing material: $\mu_m=\mu/\rho$.

Attenuation of X-radiation flux by a material occurs due to interaction of radiation with the electron shells of the atoms. All three mechanisms of such interaction enable: *coherent scattering, incoherent scattering,* and *photoeffect.*

In general, during interaction of X-radiation with a material, all three effects contribute to the total value of the attenuation factor. Hence, we can write

$$\mu=\mu_c + \mu_i + \mu_{ph},$$

where μ_c, μ_i and μ_{ph} are the components of the total μ due to coherent, incoherent and photoeffect scattering respectively.

Overall attenuation of X-radiation flux by a material is due to the processes of radiation scattering, and processes causing radiation energy absorption by the material. Therefore, the expression for ***μ*** is often written as $\mu = \tau + \sigma$, where ***τ*** and ***σ*** are the components of ***μ*** related to radiation absorption and radiation scattering respectively.

For radiodiagnosis photons with energy about 60–120 keV are used. At this energy the mass extinction coefficient in basic is determined by a *photoeffect*, which characteristics described by ***τ***. Then the magnitude of ***τ*** is proportional to the material density (***ρ***), the third power of ***Z*** (element serial number) and the third power of the radiation wavelength:

$$\tau = k\lambda^3 Z^3,$$

where ***k*** – coefficient of proportionality. It explains major inpouring ability of hard radiation.

The application of X-radiation in medicine

Radiodiagnostics has 3 kinds:

1) Roentgenoscopy. The image is surveyed on X-ray phosphoric screen.

2) Radiographic analysis (roentgenography). The image is fixed on a film.

3) X-ray tomography. From Greek “tomo” – slash, stratum. It is the receiving of numeral image; it allows visually, with the help of a computer to estimate a stratum lying on particular depth.

X-ray diagnostics is based on the strong dependence of the X-radiation absorption capacity of a material on the atomic number z.

When X-rays pass through a human body, different tissues absorb the radiation in a different manner. Thus, bone tissue, containing calcium and phosphorous atoms (Z equal to 20 and 15 respectively), absorbs X-radiation dozens of times stronger than soft tissues do because they are composed primarily of oxygen and hydrogen (Z equal to 8 and 1 respectively).

Therefore, when a human body is radiated with X-rays, the radiation flux, in passing through soft tissues, is absorbed weakly, whereas the bones absorb a much greater part of the incident radiation.

To register the X-rays that have passed through a human body, either photo film or special screens that luminescence under the affect of X-rays are used. Such luminescence of some materials under the affect of X-rays is known as X-ray luminescence.

Examining human's internal organs with X-rays by using luminescent screens is known as radioscopy, and using photo film is known as X-ray filming.

Several techniques of X-ray diagnostics use contrast substances. If the explored organ and environmental tissues approximately equally attenuate an X-ray radiation then special contrast agents are applied. When examining the gastrointestinal tract, the gastric cavity and the intestines are filled with barium sulphate.

During X-ray examination of the blood vessels (angiography), substances containing iodine are introduced into the patient's bloodstream. For diagnosis of dens diseases the X-ray film is stayed in a mouth and a source of X-ray – outside. In an intraoral picture the image of 2-3 dens is usually gained. If the X-ray film as well as a source of radiation, settles down outside of an oral cavity, it is possible to receive pantomogram.

X-rays have an adverse effect on live tissue. Therefore, to mitigate this effect, techniques employing weak radiation fluxes have been developed. For example, electron-optical converters are used.

Digital roentgenoscopy / roentgenography

Advantage in application of computer technique consists that the X-ray film distinguishes change of density on 2 % (2 % contrast sensitivity), the good image of small changes of density in object therefore is impossible to receive, i.e. small differences of contrast.

At a computer X-ray apparatus contrast sensitivity achieves 0,2 %, in details less than 2 mm. It allows to see very small tumor-similar formations, aneurysms of vessels and others.

X-ray computer tomography

The technique of X-ray computer tomography (CT, CAT – Computer-Aided Tomography) has the largest information content, but technically, it is the most involved one.

The concept of the CT method consists in the following. A thin X-ray is radiated through a thin flat area of the human body (layer), and the value of the flux that has passed is registered. By emitting the ray through different areas in the layer in different directions, it is possible, at a sufficiently large number of measurements, to calculate the radiation absorption value for each small area (ceil) of the layer being examined.

The radiation absorption magnitude in each cell depends on its properties (density, and serial number of elements comprising the cell substance). If the calculation results are displayed on a screen as a 2D image, where the layer areas differing for the radiation absorbed are different as to image brightness or color on the screen, a visual presentation of the internal structure of the selected layer of the body is obtained.

Applying this technique to several layers, one can obtain a layer wise image of the structure of different organs. This method yields the highest information content when identifying malignant tumors. The resolving power of advanced CT-scanners allows detecting tumors as small as several millimeters in size.

To implement different techniques involving X-radiation, X-ray units generating radiation of required intensity and *hardness* are required. In case of X-radiation, soft radiation is that with longer wavelengths, and hard radiation is that having shorter wavelengths.

The basic part of an X-ray unit is the X-ray tube. The voltage applied across the anticathode and the cathode is 60 to 120 kV. By changing this voltage, the required radiation hardness can be obtained. At higher U values, harder radiation is obtained, and at lower values, the radiation is softer. Changing the voltage makes the radiation flux to change as well. At the same time, an X-ray unit should allow for changing the magnitude of the flux (I) without affecting the radiation-hardness, i.e. without changing the value of U. Therefore, to change the radiation flux, the current intensity in the tube has to be changed, this being achieved by changing the cathode temperature.

The anticathode is made of materials having the highest possible value of z. This, however, is not the sole requirement to the anticathode material. When the anticathode is bombarded with electrons, only 1 to 2 % of the electrons' energy is converted to X-radiation energy. The remaining part of the electrons' energy is spent on heating the anticathode. Hence, the part of the anticathode bombarded by electrons, known as the anticathode mirror, is heated to high temperatures. Therefore, it should be made of refractory materials. Tungsten and molybdenum meet these two requirements to the mirror material. It is common practice to manufacture anticathode mirrors of these materials.

At intense heating of the anticathode, measures should be taken to cool it. For this, in some tubes, rotating anticathodes are used, whereas other tubes have anticathodes provided with inner channels for cooling fluid flow.

The affect of X-rays on tissues for treatment purposes is known as ***X-ray therapy***, which is a special case of radiation therapy.

Self-control material:

B. Test tasks

1. What law describe attenuation of a X-radiation in material?
   A) Moseley law
   B) Bouguer law
   C) Planck law
   D) Einstein law
2. What is a spectrum of a brake X-radiation?
A) Continuous B) Line C) Fractional D) Striated; E) Dotted.
3. What is a spectrum of a characteristic X-radiation?
   A) Continuous B) Line C) Fractional D) Striated; E) Dotted.

4. What is a cause of originating of X-rays?
A) Cathode beams; B) Ultraviolet beams; C) Movable neutrons; D) Movable electrons.

5. How will change the X-ray spectrum at magnification of a current of heat of the cathode?

A) Minimal wave length will decrease;

B) Minimal wave length will increase;

C) Will not change;

D) General intensity will increase.

6. With what method is it possible to cause occurrence of characteristic lines in a X-ray spectrum?

A) To increase a current of heat of the cathode;

B) To reduce a current of heat of the cathode;

C) To increase a voltage between the anode and the cathode;

D) To reduce a voltage between the anode and the cathode.

7. How will change frequency of characteristic lines of a X-ray spectrum at magnification of a serial number of chemical element of which the anode is made?

A) Will not change;

B) Will increase;

C) Will decrease;

D) Frequency does not depend on a serial number.

8. At what relation of energy of quantum of a X-rays and an ionization energy will be observed the inner photoemissive effect?

A) h v = 0; B) h v <A_u; C) h v≥ A_u; D) h v>> A_u.

9. What is characteristic X-radiation?

A) The radiation originated at an electron (flying through an atom electron shell) slowdown by electrons of an atom shell;

B) The radiation originated at an electron (flying through an atom electron shell) slowdown by a nucleus of atom;

C) The radiation originated at an electron slowdown owing to a collision with a nucleus of atom;

D) The radiation originated at radiation of energy by electrons, substituting an electron, kick out the inner orbital by an accelerated electron.

Literature recommended

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Methodical elaboration have prepared by senior lecturer, PhD biol.Sc. Korovina L.D.