Laboratory Work No. 6. Determination of γ quanta energy and the effective cross-section of interaction of γ quanta with matter using a scintillation spectrometer.

The aim of the work is to determine the energy of γ radiation of an unknown source. Measurements are carried out using a scintillation spectrometer.

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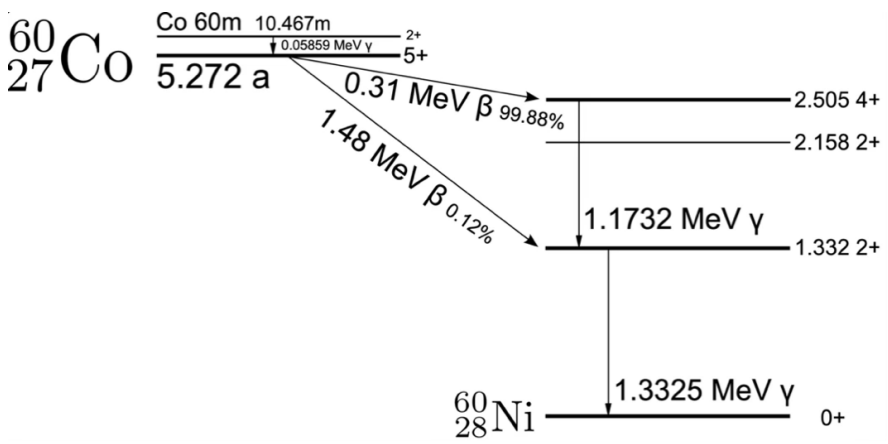

Figure 1. Decay of the radioactive isotope ^{60}Co

1. Introduction

Most atomic nuclei can exist in a number of states. The state with the lowest possible energy is called the ground state, while the states with higher energy are known as excited states. Transitions of excited nuclei to states of lower energy are commonly accompanied by emission of γ quanta. Such processes are referred to as γ transitions.

Atomic nuclei may appear in excited states either as a result of nuclear reactions or during α and β decays. Based on this principle, γ sources are constructed – these are α or β emitters decaying into different excited states. Quanta from such sources have strictly defined energies (monochromatic γ quanta) from several keV to several MeV.

As a rule, radioactive preparations that produce monoenergetic γ quanta are chosen as sources of gamma radiation. For example, in the β^- decay of radioactive isotope ^{60}Co into ^{60}Ni, γ quanta with energies of 1.33 and 1.18 MeV are observed. The decay scheme of ^{60}Co is shown in Fig. 1.

$$
\begin{aligned}
&{}^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni}^{*} + e^{-} + \tilde{\nu}_e, \\
&{}^{60}_{28}\mathrm{Ni}^{*} \rightarrow {}^{60}_{28}\mathrm{Ni}^{*} + \gamma_1 \ (1.16 \text{ MeV}), \\
&{}^{60}_{28}\mathrm{Ni}^{*} \rightarrow {}^{60}_{28}\mathrm{Ni} + \gamma_2 \ (1.33 \text{ MeV}).
\end{aligned}
$$

Another source of γ quanta is bremsstrahlung radiation of electrons. In

this case, γ quanta of various energies are emitted up to the limiting energy of the particle producing radiation as it accelerates (decelerates).

When γ radiation passes through matter, its beam intensity is attenuated due to interactions with atoms and nuclei of the medium. For γ quanta with energies up to about 10 MeV, the primary attenuation mechanisms are interactions with atomic electrons. The main processes of interaction of γ quanta with matter are:

Photoelectric effect – an electron is ejected from the atom, and the γ quantum is fully absorbed;

Compton effect – scattering of a γ quantum on a free electron (meaning its binding energy is negligible compared to the γ quantum energy). In the final state, an electron and a secondary photon of lower energy are observed;

Electron-positron pair production – occurs for photon energies above 1.022 MeV (twice the electron rest mass).

Photon–nucleus interactions at these energies can be neglected due to their very low probability.

2. Effective interaction cross sections

In physics of the microworld, the characteristics of the probabilities of interaction processes are the differential and total effective cross sections of reactions. Consider a stream of particles X hitting some target and interacting with particles Y of the target. The result of the reaction can be either the process of scattering, with particles X and Y attaining different kinematic characteristics, or the generation of new particles $(a, b, \ldots)$.

The differential effective reaction cross section $\frac{d\sigma}{d\Omega}(\theta)$ in the target's rest frame is determined by the relation

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(\theta) = \frac{\frac{\mathrm{d}N}{\mathrm{d}\Omega}(\theta)}{I \cdot N_{\mathrm{targ}}}. \tag{1}$$

Here, $\frac{\mathrm{d}N}{\mathrm{d}\Omega}(\theta)$ is the number of particles emitted at an angle θ per unit time (per second), I is the magnitude of the incident particle flux, N_{targ} is the

number of particles Y in the target equal to $N_{\text{targ}} = Sln$, l and S are the target thickness target area in the beam, respectively, and n is the volume number density or concentration, i.e., the amount of target particles per unit volume.

Since the dimension of the number of particles scattered per unit time per unit solid angle is [s^{-1} sr^{-1}], the dimension of the particle flux is $I = \text{cm}^{-2}\text{s}^{-1}$, and the number of particles in the target is a dimensionless quantity, we obtain for the dimension of the differential cross section

$$\left[\frac{d\sigma}{d\Omega}\right] = \left[\frac{cm^2}{sr}\right]. \tag{2}$$

The total (or integral) effective reaction cross section has the dimension cm^2 and is the integral of (1) over the scattering angle θ.

Since the effective cross sections of microscopic processes in units of cm^2 represent very small quantities, an off-system unit, the barn (b), and its derivatives, the millibarn (mb) and microbarn (μb), are introduced.

$$1\ \text{b} = 10^{-24}\ \text{cm}^2 = 100\ \text{fm}^2,$$
$$1\ \text{mb} = 10^{-3}\ \text{b},$$
$$1\ \mu\text{b} = 10^{-6}\ \text{b}.$$

3. Interaction of gamma quanta with matter

Fig. 2 shows the total effective cross section for the interaction of photons with matter with energies from 10 eV to 100 GeV (1 GeV = 10^{12} eV) for two absorbing materials: carbon (Z = 6) and lead (Z = 82). The contributions of various physical processes to the total cross section are highlighted.

As already mentioned, in the energy range of γ quanta emitted by excited nuclei during transitions to the ground and lower excited states, i.e., at E_γ from 10 keV to approximately 10 MeV, three processes of photon-matter interaction are most significant: the photoelectric effect, Compton (incoherent) scattering, and the formation of electron-positron pairs. The total effective

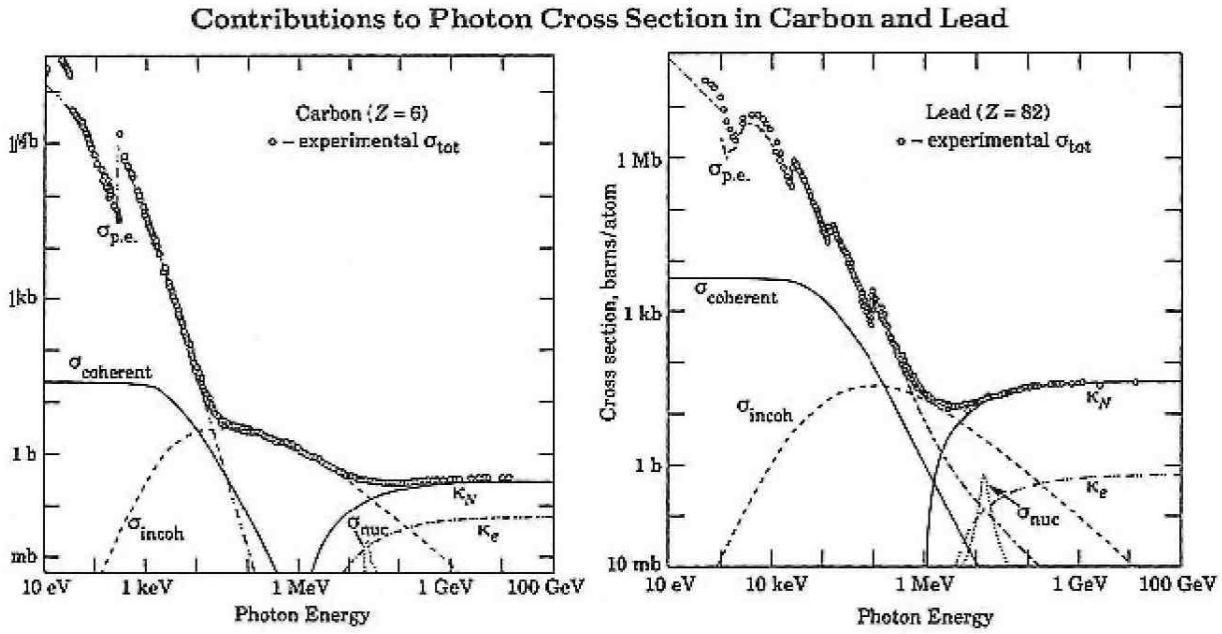

Figure 2. Cross section of photon interaction with carbon ($Z = 6$) and lead ($Z = 82$) at photon energies from 10 eV to 100 GeV.

cross section in this energy range is the sum of the effective cross sections of the individual processes involved in attenuating the primary flux:

$$\sigma = \sigma_{\rm ph} + \sigma_{\rm c} + \sigma_{\rm p}. \tag{3}$$

The effective cross section for each process, calculated per absorber atom, is a function of both the γ ray energy and the atomic number Z of the absorber substance.

3.1. Photoelectric effect

If the energy of a γ ray photon is greater than the binding energy of any electron in the atom's shell, the photoelectric effect occurs. This phenomenon consists of a photon being completely absorbed by the atom, and one of the electrons in the atomic shell being ejected from the atom. Using the law of conservation of energy, the kinetic energy of a photoelectron E_e can be determined: $E_e = E_\gamma - I_i - E_n$, where I_i is the ionization potential of the atomic shell from which the electron is ejected, E_n is the nuclear recoil energy,

and E_γ is the γ quantum energy. The nuclear recoil energy is usually small, so E_n can be neglected. The photoelectron energy is then determined by the relationship $E_e = E_\gamma - I_i$, where $i = \{K, L, M, \dots\}$ is the electron shell index. The "spikes" clearly visible in Fig. 2 in the effective cross section curve are a consequence of jumps in the photoelectric cross section with an increase in photon energy above the various ionization potentials of the atom's electron shells. The effective cross section of the photoelectric effect is the sum of the effective cross sections of the photoelectric effect on individual electron shells of the atom. An essential feature of the photoelectric effect is that it cannot occur on a free electron, since the laws of conservation of momentum and energy are incompatible in the case of the photoelectric effect on a free electron.

Since the absorption of a γ ray by a free particle is impossible, the photoelectric effect occurs with the highest probability (approximately 80%) on electrons in the atomic shell most strongly bound to the nucleus, i.e., the K-shell.

The photoelectric effect cross section strongly depends on the atomic number Z of the absorber: $\sigma_{ph} \sim Z^5$. The photoelectric effect is the main process responsible for the absorption of γ rays at low photon energies. At energies $E_\gamma < 0.5$ MeV, the effective photoelectric effect cross section decreases very sharply with increasing γ-ray energy: $\sigma_{ph} \sim 1/E^{7/2}$.

3.2. The Compton effect, or incoherent scattering of γ rays.

Scattering is called incoherent if the phase difference between the primary and scattered waves changes with time. Clearly, scattering accompanied by a change in γ ray energy is incoherent.

An electron can be considered free if the γ ray energy is many times greater than the electron's binding energy. As a result of the Compton effect, instead of a primary photon with energy E_γ, a scattered photon with energy $E'_\gamma < E_\gamma$ appears, and the electron that was scattered acquires kinetic energy

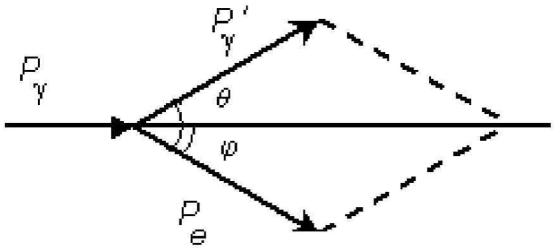

Figure 3. Scheme of γ quanta scattering on a free electron: P_γ and P'_γ are the momenta of the primary and scattered γ quanta, P_e is the electron momentum.

$E_e = E_\gamma - E'_\gamma$. Figure 3 shows a diagram of γ ray scattering by an electron.

Using the laws of conservation of momentum and energy, we can write:

$$\vec{P}_\gamma = \vec{P}'_\gamma + \vec{P}_e, \tag{4}$$

$$m_e c^2 + E_\gamma = E'_\gamma + E_e, \tag{5}$$

where P_γ and P'_γ are the momenta of the primary and scattered γ quanta, P_e is the electron momentum, $m_e c^2 = 0.511$ MeV is the rest energy of the electron.

It can be shown that the change in the wavelength of γ quanta during Compton scattering equals:

$$\lambda' - \lambda = \lambda_0(1 - \cos\theta) \tag{6}$$

where λ and λ' are the wavelengths of the primary and scattered γ quanta, $\lambda_0 = h/m_e c$ is a universal constant called the Compton wavelength of the electron, θ is the angle between the momentum directions of the incident and scattered γ quanta.

The change in wavelength during Compton scattering is independent of λ and is determined only by the scattering angle of the γ quantum θ. The kinetic energy of an electron is determined by the relation:

$$E_e = \frac{E_\gamma}{1 + \frac{m_e c^2}{2E_\gamma \sin^2\frac{\theta}{2}}} \tag{7}$$

The effective cross section for scattering a gamma quantum by an electron is independent of the characteristics of the absorber material. The effective cross section for this same process, calculated per atom, is a linear function of the atomic number (or number of electrons in the atom) Z.

The Compton scattering cross section decreases with increasing gamma quantum energy: $\sigma_c \sim I/E$.

In Compton scattering of gamma quanta produced by transitions of atomic nuclei from excited states to the ground and lower excited states, the gamma quanta's energies are typically much greater than both the binding energy of the electrons in the atom and the kinetic energies of these electrons. Therefore, in formulas (4)–(7), the primary electron is assumed to be at rest. Incoherent scattering of a gamma quantum in this case results in the transfer of part of the quantum's energy to the electron and the emergence of a gamma quantum with lower energy (and longer wavelength). However, this same process of incoherent scattering is used in modern physics to produce monoenergetic beams of high-energy γ rays. For this purpose, a beam of photons from a laser is scattered at large angles by a beam of accelerated high-energy electrons extracted from an accelerator. Such a source of high-energy and high-density γ rays is called a laser-electron-gamma source (LEGS). In the currently operating LEGS source, laser radiation with a wavelength of 351.1 μm (0.6 eV) is scattered by electrons accelerated to energies of 3 GeV, converting it into a beam of γ rays with energies of 400 MeV.

3.3. Formation of an electron-positron pair.

In this process, the γ quantum interacting with matter is consumed, with its energy used to create a particle-antiparticle pair, namely, an electron and a positron. It can be shown from the laws of conservation of momentum and energy that pair formation cannot occur in a vacuum. Pair formation occurs only in the Coulomb field of a particle that receives some of the momentum and energy. Such a particle could be an atomic nucleus or an electron. Pair formation in the field of another quantum is also possible in principle. How-

ever, the probability of such a process is so low that it has practically never been observed.

Pair formation in the field of a nucleus can occur if the quantum energy satisfies the relation: $E_\gamma \geq 2m_e c^2 + E_n$, where the first term corresponds to the rest energy of the pair (electron and positron), and the second is the recoil energy of the nucleus. Since the recoil energy of the nucleus is relatively small, the energy determined by the first term is the pair production threshold ($2mc^2 = 1.022$ MeV). A single gamma quantum of any energy cannot transform into a pair, since the laws of conservation of energy and momentum are not simultaneously satisfied. Pair production primarily occurs in the Coulomb field of atomic nuclei, and the effective cross section of this process (k_N in Fig. 2) is proportional to the square of the nuclear charge Z^2.

The pair production threshold in the field of an electron is $4m_e c^2$. This is due to the fact that the recoil energy is received by the electron, which has a small mass, and it cannot be neglected. Pair production in the field of an electron has a relatively low probability (see k_e in Fig. 2).

Fig. 4 and Fig. 5 show the dependences of the linear absorption coefficient $\tau = \sigma n$ in aluminium and lead on the photon energy. Using graphs for various substances similar to those shown in Figs. 2, 4, and 5, we can approximately determine the boundaries of the γ quanta energy ranges and Z values in which a particular mechanism of γ ray interaction with matter is most significant.

As seen from these graphs, Compton effect plays a major role in attenuating the γ ray intensity in aluminium at 60 keV $< E_\gamma <$ 15 MeV and in lead at 0.7 MeV $< E_\gamma <$ 5 MeV. Photoelectric absorption in aluminium is most significant at $E_\gamma <$ 50 keV and in lead at $E_\gamma <$ 0.5 MeV. Pair production dominates over these two processes at higher γ quanta energies: in aluminium at $E_\gamma >$ 15 MeV and in lead at $E_\gamma >$ 6 MeV.

We note once again that none of the above-mentioned mechanisms of γ ray interaction with matter affects the internal structure of atomic nuclei. At high γ ray energies ($E_\gamma >$ 10 MeV), the probability of photon interaction with atomic nuclei increases. One of the possible outcomes of such interactions is the excitation of individual nuclear states. Additionally, if the γ

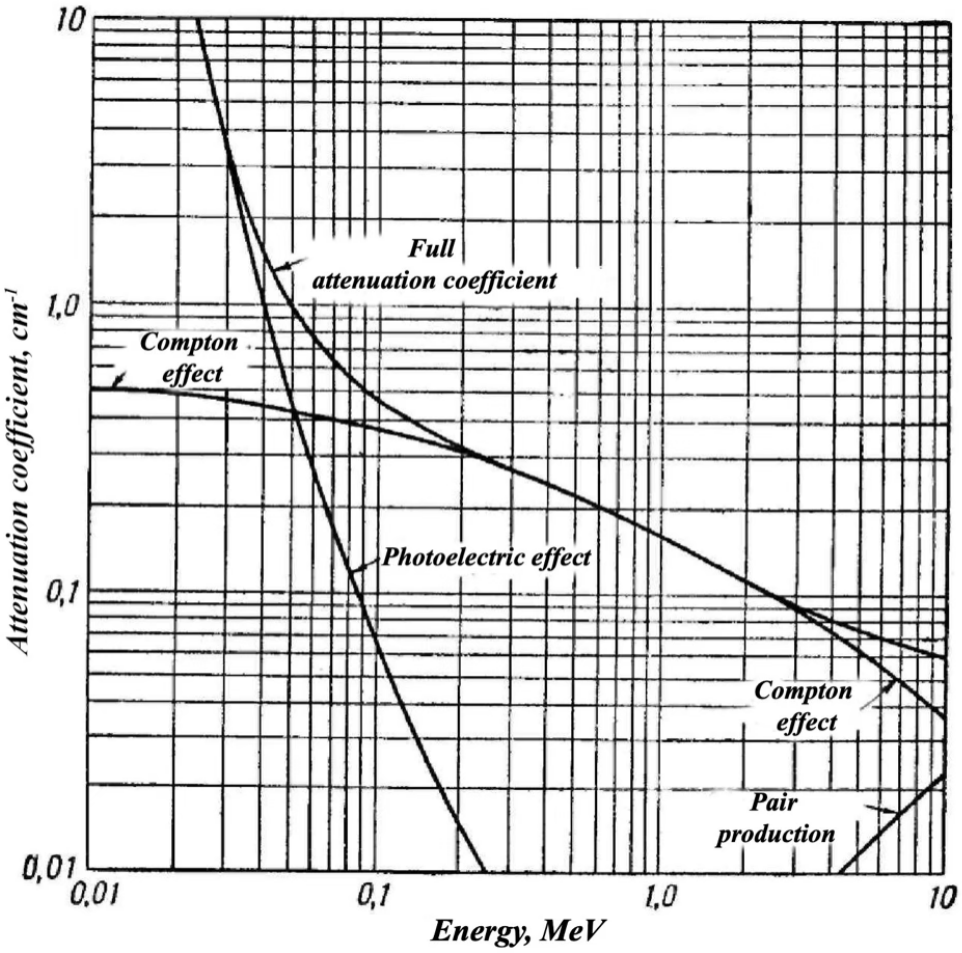

Figure 4. Dependence of the linear absorption coefficient in aluminium on the photon energy.

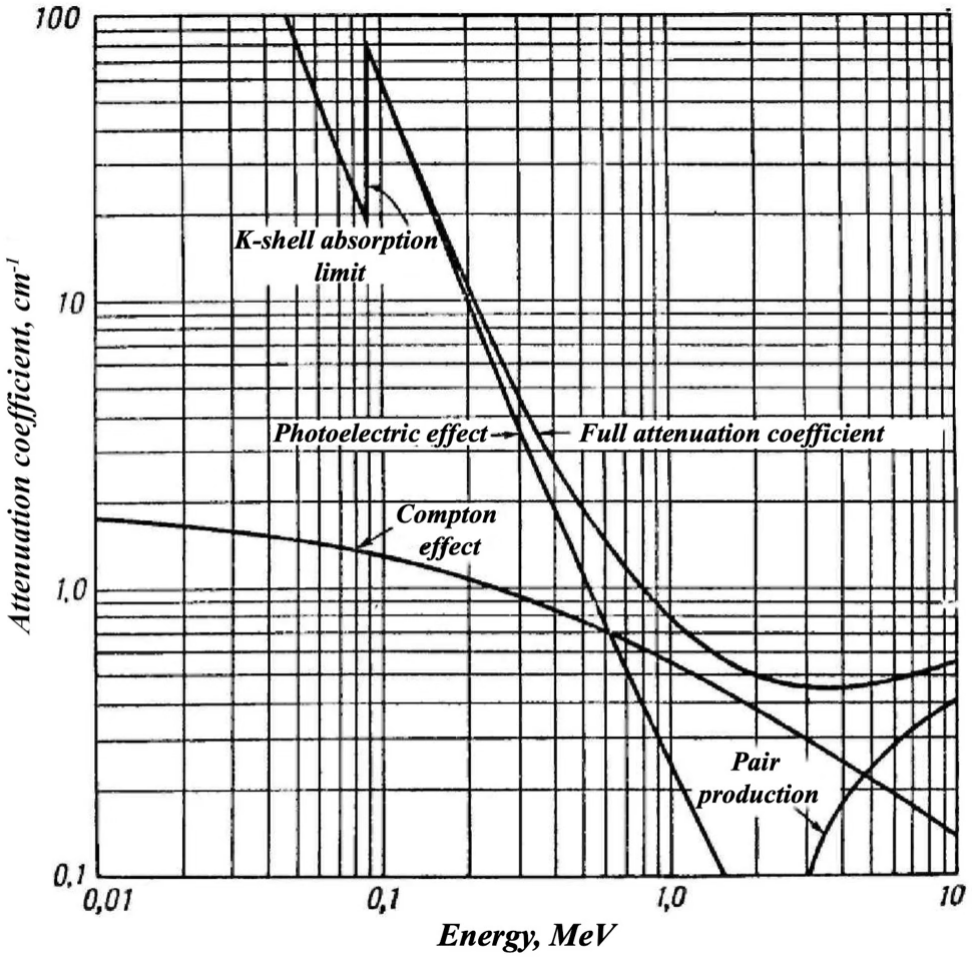

Figure 5. Dependence of the linear absorption coefficient in lead on the photon energy.

quantum energy is greater than the binding energy of a nucleon in a nucleus, the absorption of a high-energy γ ray will be accompanied by the emission of the nucleon from the nucleus. At γ ray energies of approximately 20-25 MeV for light nuclei ($A < 40$) and 13-15 MeV for heavy nuclei, a maximum is observed in the effective nuclear photoabsorption cross section, which is called the giant dipole resonance (σ_{nuc} in Fig. 2).

4. Determining the Effective Cross Section for Gamma Quantum Interaction by the Absorption Method

4.1. Law of Attenuation of the Gamma Quantum Flux Intensity in a Substance

The law of attenuation of a parallel beam of gamma quanta in a layer x of a substance with n atoms per unit volume is easily derived from the definition of the effective cross section σ in differential form. The number of gamma quanta interacting with the substance is equal to the number of quanta $\mathrm{d}I$ emitted from the primary beam I upon interaction with an absorber containing $N\mathrm{d}x$ atoms:

$$-\mathrm{d}I = I\sigma n\mathrm{d}x \tag{8}$$

When integrating differential equation (8), it is assumed that all γ quanta of the primary beam pass through the same absorber thickness (the flow is parallel) and that the effective cross section does not change as they pass through the substance. Then, from (8), we obtain an exponential law for the attenuation of the primary γ quanta intensity:

$$I(x) = I(0)\exp(-\sigma n x) \tag{9}$$

Here σ is the total effective cross-section of the interaction of gamma

quanta with the absorber substance, equal to the sum of the effective cross-sections of all physical processes responsible for the interaction of a photon with matter at a given energy, $n = \frac{N_a \rho}{A}$, where $N_a = 6.022 \cdot 10^2 3$ mol is Avogadro's number, A is the mass number, ρ is the density of the absorber substance, x is the thickness of the absorber in units of length (cm).

If the radiation consists of γ quanta of different energies, which have, accordingly, different effective cross-sections of interaction with the absorber, the total intensity of the radiation after passing through a thickness x of the substance is:

$$I(x) = \sum_i I_i(0) \exp(-\sigma_i n x) \tag{10}$$

Various materials that attenuate the γ ray flux are used to protect against γ radiation.

The protective properties of a material are characterized by its linear absorption coefficient $\tau = \sigma n$. The ability of materials to attenuate γ radiation is often also characterized by the mass absorption coefficient $\mu : \mu = \tau/\rho$, where ρ is the density of the absorber material. It is important to note that both the linear and mass absorption coefficients depend not only on the mechanism of interaction between the γ quantum and the atom of the material, but also on the macroscopic properties of the absorber material, primarily its density ρ.

In contrast to these properties, the effective cross section calculated per atom is independent of the state of aggregation of the absorber material and is a function only of the radiation energy, the atomic number Z, and the type of interaction process.

5. Experimental setup

The experimental setup for the laboratory work consists of a γ ray source enclosed in a lead block, a scintillation detector with a NaI(Tl) crystal and a photomultiplier, a high-voltage rectifier with a voltage stabilizer and a count-

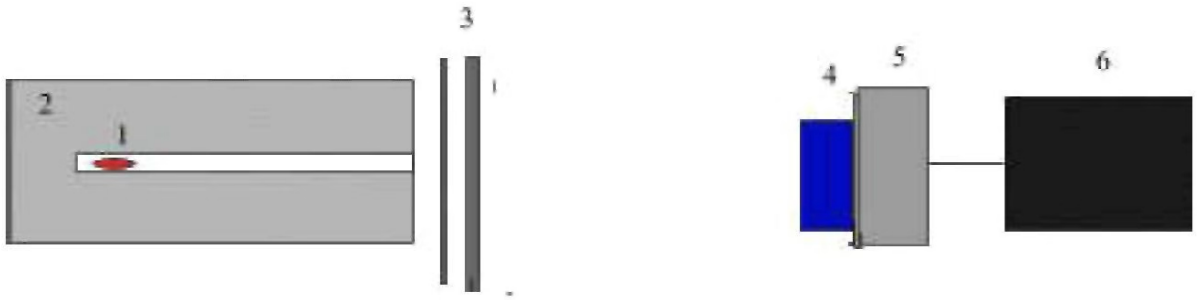

Figure 6. Block diagram of the γ spectrometer. 1 – γ ray source; 2 – lead collimator; 3 – absorbers; 4 – NaI(Tl) crystal; 5 – PMT; 6 – power supply and counting unit.

ing device.

The lead block (see Fig. 6), in which the γ ray source is placed, has a long, narrow opening – a collimator – that cuts out from the total solid angle, a very small angle in which γ quanta are emitted. This results in the emerging particle beam becoming approximately parallel. The lead block also serves as a radiation shield. The metal absorber plates are placed at the greatest possible distance from the γ ray detector (the so-called "good geometry conditions"). In this setup, they are positioned above the lead block in the path of the γ ray beam (in Fig. 6, the setup is rotated 90 degrees). The need to position the absorber plates as far from the detector as possible is due to the fact that one of the processes that attenuates the γ ray beam is the Compton effect, which produces secondary γ rays, the incidence of which on the detector should be avoided if possible, since their registration together with the primary beam quanta leads to a systematic error in determining the effective cross section. With sufficiently thick absorbers, there is a risk of the production and entry of third-generation γ rays, arising from Compton scattering of secondary quanta, into the detector. Therefore, it is recommended to measure the γ radiation intensity within a range of approximately three times its attenuation.

5.1. The Scintillation Spectrometer

Scintillation spectrometers are widely used for the detection of γ quanta. A scintillation spectrometer consists of a **scintillator** and a **photomultiplier tube (PMT)** (Fig. 7).

To detect γ radiation in scintillation spectrometers, the interaction of γ rays with the scintillator material is used. As charged secondary particles pass through the scintillator material, their energy is expended on excitation and ionization of the material. Transitions from excited states to lower energy levels are accompanied by the emission of photons, resulting in a flash of light in the scintillator. Thus, the scintillator transforms the energy of the incident γ ray into a large number of low-energy secondary γ rays – fluorescence photons.

Fig. 7 shows a diagram of the scintillation detector device. Secondary photons generated in the scintillator by the incident γ ray beam pass through a light guide to the photocathode. The photocathode is deposited on the inner end surface of the glass bulb of the photomultiplier, which maintains a high vacuum necessary for the free movement of electrons.

Under the influence of photons, a photoelectric effect occurs at the photocathode, releasing electrons that enter the photocathode-dynode (electrode) electron-optical system. As a result of secondary electron emission at the dynodes, electrons knock secondary electrons out of them, creating an electron avalanche that grows from dynode to dynode. The shape of the dynodes is selected for efficient acceleration and focusing of secondary electrons. The secondary electron emission coefficient of the dynodes ranges from 2 to 5, depending on the dynode surface material and the electron energy set by the voltage divider. A potential difference of 100-150 V is maintained between the dynodes. The overall gain of photomultiplier tubes, which typically have 10 to 14 dynodes, reaches values of approximately $10^6 - 10^9$. The amplitude of the voltage pulse created across the load of the last dynode (anode) of the photomultiplier tube is typically several tenths of a volt and, under certain conditions, is proportional to the energy lost by the particle in the scintillator.

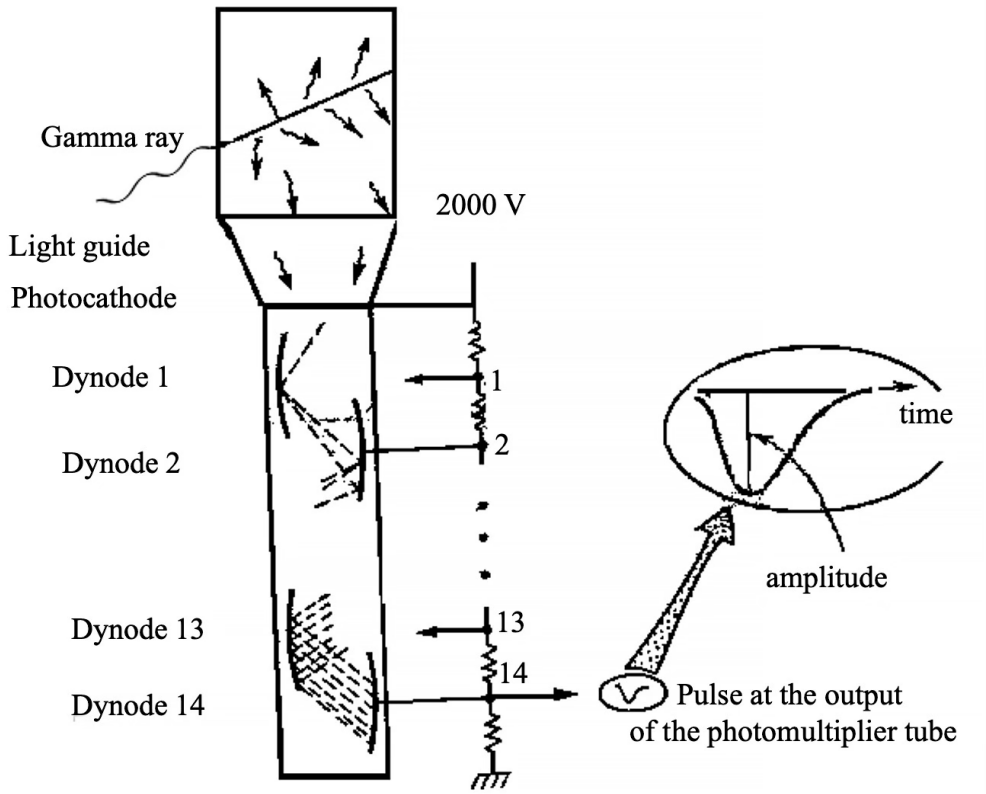

Figure 7. Schematic diagram of the scintillation detector. A particle entering the scintillator generates fluorescence photons, which travel through a light guide to the photocathode of the photomultiplier.

The most widely used scintillator for γ spectroscopy is the thallium-doped sodium iodide crystal NaI(Tl). Its advantages include:

- High light yield that is **linear** with deposited electron energy over the range from 1 keV to 5 MeV;
- Relatively high density ($\rho = 3.67$ g/cm^3) and high atomic number of iodine ($Z = 53$), ensuring efficient absorption of γ rays.

Because of these properties, NaI(Tl) provides good efficiency and proportionality, making it ideal for γ ray spectroscopy.

6. Experimental procedure

1) Measure the radioactive background (number of counts per unit time) with the γ source covered by a lead plug.

2) Measure the attenuation of the gamma beam intensity when passing through absorbers of varying thicknesses. To do this, measure the number of counts per unit time from the gamma source without an absorber and with two sets of absorber plates with a statistical accuracy of at least 3%. It is important to remember that the distribution of random discrete variables, i.e., in this case, the number of detected gamma rays, obeys the Poisson distribution, for which the variance σ^2 of the random variable N is $\sigma^2 = N$. Conduct at least three series of measurements for each set of absorbers.

3) Calculate the effective cross-section for different absorbers. To do this, plot $\ln I(x)$ graphs, taking into account statistical measurement errors and measurement errors in determining the absorber thicknesses. Using the graphs, determine the value of $\tau = \sigma n$ and, by calculating the number of atoms per unit volume of the absorber, determine the effective cross-section for the two substances (Pb, Al). Estimate the scatter in the slope of the $\ln I(x)$ graphs relative to the x-axis. Present the measured

effective cross-sections in barns and cm^2, indicating the measurement error.

4) Identify the source of γ radiation using reference data (available in the laboratory), using the slope of the logarithmic dependence $\ln I(x)$, and compare the obtained cross-sections with the theoretically expected values.

5) Measure the γ ray spectrum of the source and mark the peaks on it that correspond to the energy of the γ ray source.

To submit the work, provide:

1) tables of experimental measurements: background radiation, number of counts per unit time without an absorber and with two sets of absorbing plates, indicating the statistical error for each measurement;

2) graphs of the dependence of $\ln I(x)$ taking into account the statistical errors of the measurements and the errors in determining the absorber thickness;

3) calculations of the effective cross-section for Pb and Al absorbers in barns and cm^2, indicating the measurement error;

4) the identified isotope in the γ source and its decay scheme;

5) the γ source spectrum with the γ radiation energy peaks marked on the graph.