The gamma ray absorption coefficient

Introduction

The aim of the exercise is to study the phenomenon of absorbing gamma rays in matter and to determine the absorption coefficient for a selected absorbing material.

In 1911 Ernest Rutherford presented the view that a positive charge is concentrated in the middle of an atom in the form of a nucleus, which also contains nearly entire mass of the atom. The nuclei, as we now know well, are made of protons and neutrons. The number of protons in the nucleus (atomic number) is marked with the symbol Z; the number of neutrons is denoted by the symbol N. The total number of protons and neutrons in the nucleus is called the mass number A.

$$A = Z + N. \qquad (5.1)$$

Neutrons and protons, when considered collectively as members of a nucleus, are called nucleons. If we are interested in the properties of nuclei as independent objects (and not parts of atoms), we call them nuclides. We designate nuclides using the following symbol:

$$^{A}_{Z}X. \qquad (5.2)$$

Consider $^{197}_{79}Au$, for example. The superscript 197 is the mass number A. The chemical symbol Au tells us that this element is gold, whose atomic number is 79. From Eq. (5.1), the neutron number of this nuclide is the difference between the mass number and the atomic number, namely, 197 - 79 = 118.

Nuclides with the same atomic number Z but different neutron numbers N are called isotopes. The element gold has 31 isotopes, ranging from $^{173}_{79}Au$ to $^{204}_{79}Au$. Only one of them (^{197}Au) is stable. The remaining 30 are radioactive. Such radionuclides undergo decay (or disintegration) by emitting a particle and thereby transforming to a different nuclide.

Radioactive decays are divided into individual types depending on the type of particles emitted in the decay. The basic types of radioactive decays are briefly described below.

1. Alpha (α) decay. The process in which a $^{4}_{2}He$ nucleus (α particle) is emitted from a decaying nucleus, which is schematically written as follows:

   $$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He. \qquad (5.3)$$

   The final atom Y, arising in this decay, has two protons less than the initial atom X (shift rule).

2. Beta (β^-) decay. In this decay, an electron called β^- particle is emitted from the nucleus as well as the neutrino having a zero resting mass and zero electric charge. Schematic representation of this decay is as follows:

   $$^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + {}_{-1}^{0}\beta + {}_{0}^{0}\tilde{\nu}_e. \qquad (5.4)$$

   Due to the increase in the electrical charge of the nucleus Y, the final atom has one more proton than the X atom.

3. Beta (β^+) decay. In this decay, a positron (a positive electron) and an electron neutrino are sending from the nucleus. The schematic representation of this decay has the form:

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}\beta + {}^{0}_{0}\nu_e. \tag{5.5}$$

The final nucleus Y has one proton less than the X nucleus.

4. Gamma (γ) decay is the transition of the nucleus from the excited state to the lower energy state, which is based on the emission of a quantum electromagnetic radiation (photon), called the γ quantum to underline its nuclear origin, what can be written as:

$$ {}^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma, \tag{5.6}$$

where symbol (*) indicates the excited state of the X nucleus.

During γ decay, atomic and mass numbers remain unchanged. Only the structure of the nucleus changes from the configuration of nucleons corresponding to the higher energy to the configuration corresponding to the lower energy. The gamma quantum takes energy from the nucleus. Quantum γ emission may also be accompanied by α and β decays.

In the process of radioactive decay, the number of decayed nuclei decreases over time. Experiments show that at regular intervals, the number of radioactive nuclei of a given isotope of any element decreases the same number of times. Time T, in which the number of nuclides decreases by half is called the half-life. The law governing radioactive decay is statistic, i.e. we can never predict whether a single nucleus will decay. All nuclei of the same type always have exactly the same probability of decay, no matter how long they are alive. For example, half of the nuclei with a half-life of 1 year will decay in the first year, but the single nucleus that survived this year still has a 50% chance of survival also in the second year. If it survives two years, then the decay probability in the third year is still equal to 50%.

If by N_0 we denote the number of radioactive nuclei of the radioactive source at the initial moment $t_0 = 0$, then their reduced number of N after the time t is expressed by the formula (law of radioactive decay):

$$N(t) = N_0 e^{-\lambda t}, \tag{5.7}$$

where λ is a characteristic property of each radionuclide, called the decay constant. Its unit in the SI system is the inverse of the second (s^{-1}). The λ decay constant and the half-life T are related as follows:

$$T = \frac{ln2}{\lambda} \cong \frac{0.693}{\lambda}. \tag{5.8}$$

Radioactive nuclide can also be characterized by the so-called average lifetime τ. The average lifetime is the inverse of the decay constant (λ) and this is the time after which the initial number of N_0 nuclides decreases e times (e - the basis of natural logarithm).

The properties of nuclear radiation are revealed in its interaction with matter. The nature of this interaction is different for charged particles, such as α or β, and another for

γ quanta. An experiment to investigate the interaction of particles with matter can be carried out for all kinds of particles in a manner schematically shown in Figure 5.1.

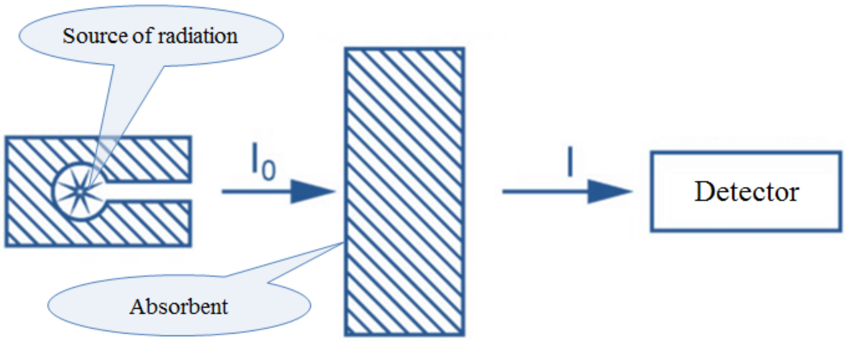

Fig. 5.1 Scheme of a set for measuring the absorption of nuclear radiation.

The nuclear radiation source is covered with a thick-walled cover provided with a small hole through which the radiation in the form of a focused beam appears outside. Such a shield, or other device for obtaining a narrow stream of particles, is called a collimator. The flow of I_0 particles coming out of the collimator falls on the layer of the tested material (absorbent) of a specified thickness x. In the absorbent, as a result of interaction with matter, particles of particular energy are dispersed and flying out with different energies and angles with respect to the original direction of incidence. Under certain conditions the creation of new particles is also possible. As a consequence, the detector will register other (usually reduced) intensity (I) of particles.

Gamma radiation is an electromagnetic radiation with a wavelength between $10^{-10} \div 10^{-15}$ m. It has a high ability to penetrate through matter and can interact with electrons, nuclei, magnetic field of electrons, as well as the electric field of nuclei. These interactions can lead to complete absorption or to the scattering of gamma radiation. In practice, three phenomena play an important role, namely:

1. Photoelectric effect describes a situation in which the gamma photon interacts with the atom's electron and transfers its energy to it, causing the electron to be ejected from the atom. The kinetic energy of the resulting photoelectron is equal to the energy of the incident gamma photon minus the energy that originally bound the electron to the atom (binding energy).
2. Compton scattering is an interaction in which an incident gamma photon loses enough energy to an atomic electron to cause its ejection, with the remainder of the original photon's energy emitted as a new, lower energy gamma photon whose emission direction is different from that of the incident gamma photon, hence the term "scattering".
3. Pair production becomes possible with gamma energies exceeding 1.02 MeV. By interaction with the electric field of a nucleus, the energy of the incident photon is converted into the mass of an electron-positron pair. Any gamma energy in excess of the equivalent rest mass of the two particles (1.02 MeV) appears as the kinetic energy of the pair and in the recoil of the emitting nucleus.

As a result of the above mentioned processes of interaction, the intensity of the γ radiation, as it passes through the absorbing medium, decreases. The intensity of γ radiation depending on the thickness (x) of the absorbent layer decreases according to the law:

$$I = I_0 e^{-\mu x}, \tag{5.9}$$

where: I_0 is the intensity of the beam incident on the absorbent, I - the intensity after passage of the absorbent layer with the thickness x, μ - the total linear absorption coefficient. It should be added that the above equation is valid in conditions of good geometry, i.e. when the γ beam is parallel and narrow.

The total linear absorption coefficient μ is the linear sum of the absorption coefficients: for the photoelectric effect, the Compton effect and the process of pair production. The contribution of other influences is so small that it can be omitted. The value of μ depends on the absorbent material and on the γ radiation energy. Fig. 5.2 shows the dependence of absorption coefficients on γ quanta energy for each of the discussed processes in lead (the dotted lines) and the dependence of the total absorption coefficient for lead, copper and aluminum (continuous lines).

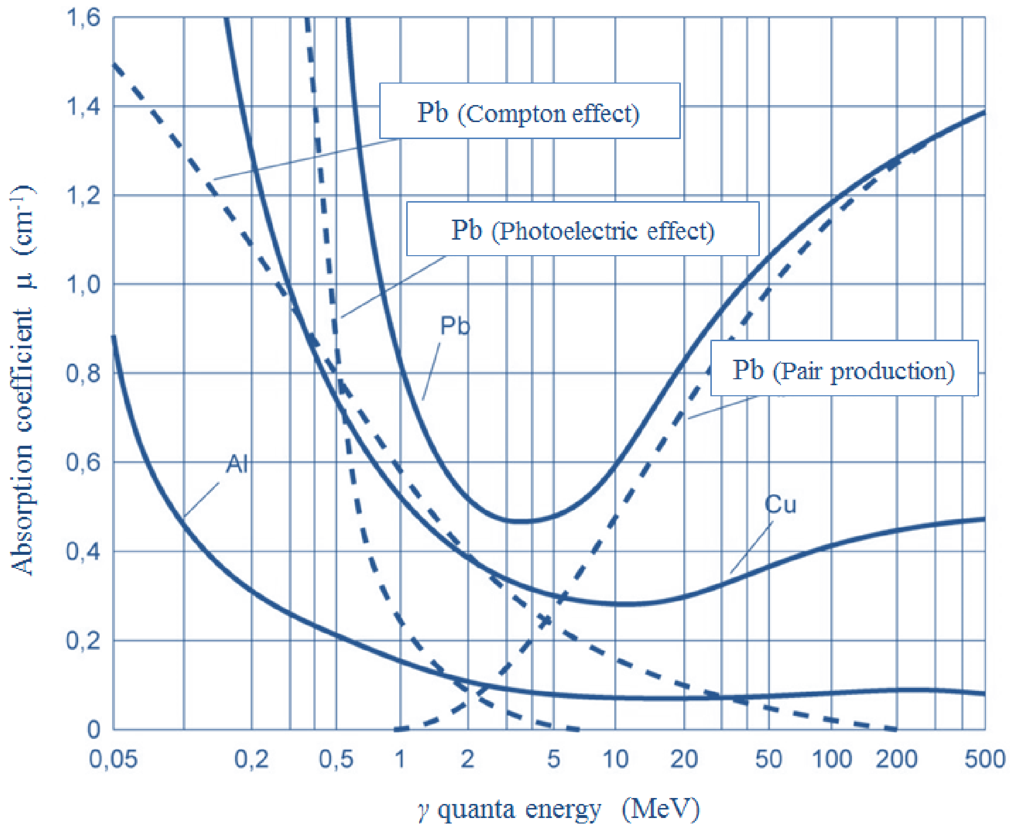

Fig. 5.2 The absorption coefficient μ of γ radiation as a function of radiation energy for copper, aluminum and lead.

When describing the absorption of radiation, we often use other characteristic quantities, such as a mass absorption coefficient, that is equal:

$$\mu_m = \frac{\mu}{\rho}, \tag{5.10}$$

where ρ is the absorbent density, and the thickness of the half-reduction expressed by the formula:

$$x_{1/2} = \frac{ln(2)}{\mu}, \quad (5.11)$$

where $x_{1/2}$ means such a thickness of the absorbent for which $I = \frac{1}{2} I_0$.

Various detectors such as photographic plates, Wilson chambers, crystal counters, bubble chambers, scintillation counters and Geiger - Müller counters are used to register nuclear radiation. Because in this exercise the measurements will be performed on the last of these, we will briefly discuss its structure and principle of operation.

The Geiger-Müller counter (G-M counter) belongs to the group of ionizing detectors. The principle of operation of these detectors is based on the recording of the ionic current generated in the detector's space. Fig. 5.3 shows the the G-M meter and the typical way of connecting it to the electronic system.

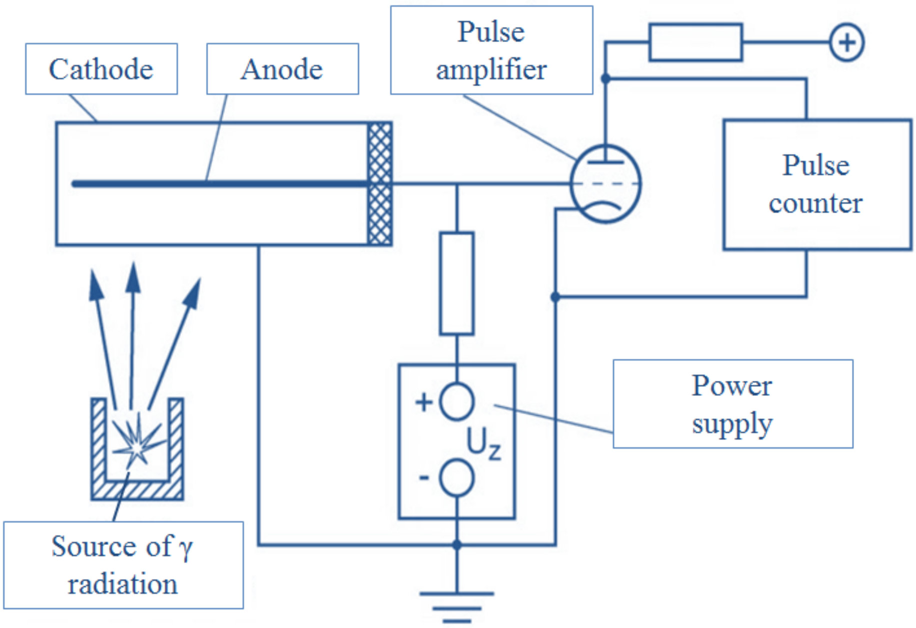

Fig. 5.3 Scheme of the construction and electronics of the Geiger - Müller meter.

The G-M counter is usually in the shape of a cylinder. It consists of a tube filled with gas and two electrodes embedded inside the tube. The inner electrode (anode) is a thin wire with a diameter of about 0.1 mm, usually made of tungsten. The second electrode (cathode) is usually a counter coating. In metal counters, the coating serves directly as a cathode, in glass-filled meters a cathode is formed by covering the glass with a conductive layer. The G-M meter is filled with a mixture of noble gas and the gas consisting of organic compound pairs.

The particles passing through the G-M counter trigger electrical discharges in the gas that fills the detector. The current flowing in the circuit with the anode, cathode and resistor R generate short voltage pulses at the R resistance. These pulses are amplified in a tube amplifier, and then recorded by pulse counter.

The laboratory set

One of the elements of the exercise set is a lead cover shielding the radiation source, schematically shown in Figure 5.4.

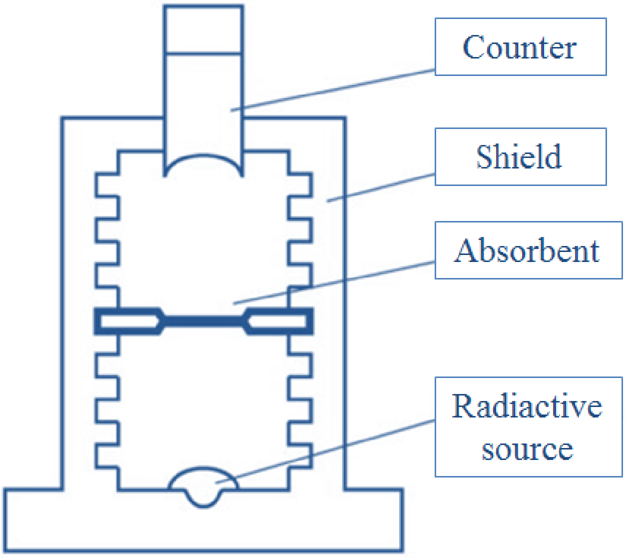

Fig. 5.4 Scheme of the lead cover shielding the radiation source.

A G-M counter is placed on the lead shield. A hole with an area equal to the cross-section of the meter is cut out in the cover. In the side walls grooves are cut into which absorbents can be inserted. At the bottom of the shield construction there is a radioactive gamma source. The G-M meter uses standard electronic equipment that provides the meter with high voltage power supply and enables the measurement of pulse counts.

Proceeding

1. Ask the teacher to connect the system to the power supply and set the appropriate high voltage. Attention! It is not allowed to follow the above-mentioned activities without the teacher inspection. It is also forbidden to change the voltage on the counter during the further exercise.
2. Establish with the teacher a way of background determination. By the counter background level we mean the number of $N(t)$ pulses registered at a given time, e.g. 100 s in the absence of a radioactive source. Counts in this state are generated by the apparatus itself, and also occur due to cosmic radiation and natural radiation of the Earth.
3. On the counter, press the measurement time switch key to 100 seconds.
4. Pulses counting can be started by pressing the "start - stop" key. After completing the counting, (when the "gate" light goes out) save the number of counts (N) and delete the result with the "reset" key.

5. Perform 3 measurements of N_0 counts without absorbent.
6. Measure the number of N_x pulses by placing the absorbent plates with the total thickness x between the source and the G-M meter. Take three times N_x measurements for each absorbent thickness.
7. Record the results of measurements in the table.

Table of measurements and calculation results

Absorbent Number	Thickness x (mm)	Number of counts N_1	Number of counts N_2	Number of counts N_3	Average number of counts $\overline{N}$	Intensity I-I_B (1/s)	ln (I)
0							
1							
2							
3							
4							
5							
6							
7							
8							
9							

Record the background intensity (I_B) and the uncertainty of the absorbent thickness u(x_i).

Processing of the results

1. Calculate the average number of counts $\left(\overline{N} = \frac{N_1+N_2+N_3}{3}\right)$.
2. Calculate the intensity (I) according with the formula $\left(I = \frac{\overline{N}}{t}\right)$, and then calculate the difference I - I_B. Save the results in the table.
3. Make a graph of the dependence of the intensity on the absorbent thickness I(x). Put the bars of uncertainty on the graph, adopting a simplified version of the uncertainty of intensity $\left(u(I) = \sqrt{I}\right)$. Estimate the thickness uncertainty u(x).
4. Calculate the value of natural logarithm from intensity (ln(I)).
5. Make a graph of the dependence of ln(I) on the absorbent thickness x.
6. Use the linear regression method to draw a straight line that reflects the dependence of ln(I) on x. The equation of this line has the form: $\left(ln(x) = -\mu x + ln(I_0)\right)$ which is a modified equation 5.9. The slope (-μ) is negative because the line is ascending to the left. The linear absorption coefficient (μ) is numerically equal to the absolute value of the slope of the graph being considered. From the linear regression method, determine its value. Save it with the SI unit. Specify also its uncertainty u(μ).
7. Use the formula 5.11 to calculate the thickness of the half reduction $x_{1/2}$. From the law of propagation of uncertainties, specify u($x_{1/2}$).

Supplementary literature

1. Andrzej Kubiaczyk, Evaluation of Uncertainty in Measurements, Warsaw University of Technology, http://www.if.pw.edu.pl …