Laboratory experiment

Measurement of absorption of ionizing radiation in materials

1.1 Tasks

1. For two selected materials, determine the linear absorption coefficient and the mass absorption coefficient for β-radiation. In one graph, plot the dependence of counting rate read by the Geiger-Müller (G-M) counter on the thickness of the absorber layer for both materials.

2. For two selected materials, determine the linear absorption coefficient, the mass absorption coefficient and the half-value thickness for γ-radiation. In one graph, plot the dependence of the counting rate read by the G-M counter on the thickness of the absorber layer for both materials.

3. Check out the absorption of α-radiation in different materials.

1.2 Theory

1.2.1 Atomic nucleus

Atomic nuclei of matter commonly found in nature consist of protons and neutrons. They are therefore positively charged and concentrate almost all of the mass of the atoms (electrons have the mass in comparison to protons and neutrons roughly 2000 times smaller). The number of protons in a nucleus is denoted by the atomic (proton) number Z (related to the charge of the nucleus), the number of neutrons by the neutron number N and the total number of nucleons (protons and neutrons) is given by the mass (nucleon) number A ($A = Z + N$, related to the mass of the nucleus). Based on the number of protons and neutrons in the nucleus we introduce terms nuclide, isotope and isobar.

Nuclide represents a set of identical atoms whose nuclei therefore have the same composition. This is represented by the notation ${}^{A}_{Z}\mathrm{X}^{N}$, where X represents chemical symbol, e.g., ${}^{238}_{92}\mathrm{U}^{146}$. Since the number of protons in a nucleus is determined by the chemical symbol, we often write the abbreviation ${}^{A}\mathrm{X}$, so for example, the notation ${}^{232}\mathrm{Th}$ gives $Z = 90$ (the position of thorium in the periodic table of elements) and $N = 232 - 90 = 142$.

Isotopes are nuclides that have the same atomic but different nucleon (and therefore mass) numbers. So, for example, we say that ${}^{12}_{6}\mathrm{C}^{6}$, ${}^{13}_{6}\mathrm{C}^{7}$ and ${}^{14}_{6}\mathrm{C}^{8}$ are different isotopes of carbon.

Isobars are nuclides that have the same nucleon but different atomic numbers, e.g., ${}^{40}_{18}\mathrm{Ar}^{22}$, ${}^{40}_{19}\mathrm{K}^{21}$, ${}^{40}_{20}\mathrm{Ca}^{20}$.

Protons and neutrons reside in the atomic nucleus in a very small space, so the protons are very strongly repelled from each other by electrostatic (Coulombic) force. The stability of the nucleus is provided by the **nuclear force**, which has very short range ($\sim 10^{-15}$ m) and is much stronger than electrostatic force. The essence of this force lies in the exchange of virtual particles – gluons[1], which are exchanged between quarks[2] of nearby nucleons.

1.2.2 Radioactivity

Of the more than 2 000 known nuclides, only 266 are stable. The others, no matter if they are found in nature or they are produced by nuclear reactions, more or less rapidly spontaneously decay into other nuclides, i.e., they are **radioactive**. It was found empirically that the nuclei are stable, i.e., do not undergo radioactive decay, only with a certain N/Z ratio. For stable light nuclei ($Z \leq 20$) this ratio is equal to one (the exceptions are nuclei ${}_{1}^{1}\mathrm{H}^{0}$ and ${}_{2}^{3}\mathrm{He}^{1}$), for heavier nuclei it increases further up to 1.52 for the heaviest stable nuclide ${}_{83}^{209}\mathrm{Bi}^{126}$. This means that to maintain the stability of the nucleus as the atomic number increases, the number of neutrons in the nucleus must increase faster than the number of protons. The larger number of neutrons somewhat reduces the mutual repulsion of protons. Some elements have only one stable isotope, while others have two or more stable isotopes. If the composition of a nucleus deviates from the optimal ratio between protons and neutrons, it becomes radioactive, i.e., it spontaneously decays, most often into another nucleus and a smaller particle, i.e.,

$$ {}_{Z}^{A}\mathrm{X} \rightarrow (A_1, Z_1)Y + (A_2, Z_2)\mathrm{particle}, $$

where $A = A_1 + A_2$. The resulting products always carry some kinetic energy, reflecting the fact that energy is released during radioactive decay. It follows then from the law of conservation of energy that the rest mass of the nucleus must be greater than the rest mass of the radioactive decay products. There are three types of radioactive decays:

1. decays in which Z changes at constant A (decay β^- and β^+, electron capture),
2. decays in which Z and A change simultaneously (α decay, nucleon emission, emission of heavier nuclei, spontaneous nuclear fission),
3. and decays by deexcitation of the nucleus, in which only the energy of the nucleus changes (emission of γ radiation, internal conversion).

In the following we briefly discuss some radioactive decay mechanisms.

β^- decay

It occurs in nuclei with an excess of neutrons compared to the optimal N/Z ratio. In such a case, the excess neutron in the radioactive nucleus is converted into a proton, with the emission of a β^- particle (electron e^-) and an electron antineutrino $\bar{\nu}_e$. The emission of the antineutrino is required by the law of conservation of lepton number. In this way, the number of protons in the nucleus increases while the number of neutrons decreases towards a lower value of the N/Z ratio necessary for the existence of a stable nucleus. In general, the β^- decay can be written as

$$ {}_{Z}^{A}\mathrm{X}^{N} \rightarrow {}_{Z+1}^{A}\mathrm{Y}^{N-1} + \mathrm{e}^- + \bar{\nu}_e. $$

[1] Gluons are intermediate (exchange) particles of strong interaction, there are 8 of them and they carry the so-called colour charge.

[2] Particles composed of quarks are called hadrons, which include nucleons. There are 6 quarks (and 6 antiquarks).

Since the kinetic energy of the newly formed nucleus can be mostly neglected, the energy released in the radioactive decay can be arbitrarily divided between the kinetic energy of the electron and the antineutrino. The energy spectrum of the emitted electrons is therefore continuous from very small values up to a certain maximum value. Within β^- decay, the nucleus Y can be produced in an excited state, and during the transition to the ground state (deexcitation) a photon of γ radiation is emitted.

β^+ decay

It is characteristic for nuclei with an excess of protons with an inappropriately low N/Z ratio. It involves the conversion of one proton to a neutron, with the emission of a β^+ particle (positron e^+, the antiparticle to electron) and an electron neutrino ν_e. This decay increases the N/Z ratio:

$$ {}^{A}_{Z}\mathrm{X}^{N} \rightarrow {}^{A}_{Z-1}\mathrm{Y}^{N+1} + \mathrm{e}^+ + \nu_e. $$

The emitted positron, after many collisions, soon annihilates with an electron of the environment to create two photons of γ radiation ($\mathrm{e}^+ + \mathrm{e}^- \rightarrow 2\gamma$).

Electron capture

This is another mode of β decay in which the nucleus gets rid of an excess proton, which is converted to a neutron by capturing an orbital electron from the K or L shell of the atomic electron cloud

$$ {}^{1}_{1}\mathrm{p} + \mathrm{e}^- \rightarrow {}^{1}_{0}\mathrm{n} + \nu_e. $$

During the electron capture, only the neutrino is emitted from the nucleus, but it interacts only very weakly with matter, so it cannot be detected by conventional means. Into the vacancy in the K or L shell soon an electron from a higher energy level jumps over, thus emitting a photon of X-rays from the atomic electron cloud.

α decay

Within this decay, the nucleus emits a cluster of two protons and two neutrons – the helium nucleus ${}^{4}_{2}\mathrm{He}^2$, also called the α particle

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

In this way, the nucleus charge is reduced by two units in one step. The emission of helium nuclei is aided by the fact that the helium nucleus is very strongly bound, compared to the emission of other light nuclei. At the formation of a cluster of two protons and neutrons, binding energy is released, taking the α particle to a higher energy level and allowing it to tunnel through the potential barrier of the nucleus. For this reason, the energy spectrum of the α decay is discrete. As in other cases, the α decay can produce the nucleus Y in an excited state, so that during the transition to the ground state, it emits a photon of γ radiation.

Examples of radioactive decays of some nuclides can be found in Tab. 1.1.

1.2.3 Kinetics of radioactive decay

The radioactive decay rate is different for each radioactive nuclide and the quantities that describe it are characteristic for each radioactive nuclide.

Nuclide	Half-life of decay	Decay type	Energy of particles (MeV)	Energy of photons (MeV)
$^{22}_{11}\mathrm{Na}^{11}$	2.58 yr	89 % β^+, 11 % EC	0.54 1.83	1.28
$^{60}_{27}\mathrm{Co}^{33}$	5.27 yr	β^-	0.31	1.17 1.33
$^{90}_{38}\mathrm{Sr}^{52}$	28.1 yr	β^-	0.54	-
$^{90}_{39}\mathrm{Y}^{51}$	64.2 h	β^-	2.25	-
$^{241}_{95}\mathrm{Am}^{146}$	458 yr	α	5.24-5.54	0.027-0.37

Table 1.1: Radioactive decays of some nuclides. For β decays, maximum energy of the particles is given, For α decays, range of discrete energies of the particles is given.

Decay constant

Radioactive decay causes the number of radioactive atoms to gradually decrease over time. The fundamental law of radioactive decay states that in a sufficiently short time interval $\mathrm{d}t$, a constant fraction $\mathrm{d}N$ of the N number of radioactive nuclei present always decays

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}t} = \lambda. \tag{1.1}$$

This constant is referred to as the decay constant. For example, a value of $\lambda = 10^{-3}\ \mathrm{s}^{-1}$ tells us that one thousandth of a sufficiently large set of nuclei of a radioactive nuclide decays every second.

The probabilistic nature of radioactive decay is the reason that the fundamental law and other relations describing the rate of decay apply well only to large sets of radioactive atoms. For this reason it is never possible to determine when any given atom in a given ensemble will decay.

Activity

The rate of decay of a radioactive nuclide is defined as the time change (loss) in the number of radioactive atoms per unit time. The corresponding quantity is called activity

$$A = \frac{\mathrm{d}N}{\mathrm{d}t}. \tag{1.2}$$

Combination of Eqs. (1.1) and (1.2) results in

$$A = \lambda N. \tag{1.3}$$

The dimension of the activity is s^{-1}, the unit is becquerel (Bq), or "decays per second."

Activity time rate

Differential equation Eq. (1.1) can be rewritten into the form $-\mathrm{d}N/\mathrm{d}t = \lambda N$, where the minus sign stands for the fact that the number of radioactive atoms decreases. Separation of variables subsequently results in

$$-\frac{\mathrm{d}N}{N} = \lambda \mathrm{d}t \quad \longrightarrow \quad -\int_{N_0}^{N}\frac{\mathrm{d}x}{x} = \lambda\int_0^t \mathrm{d}y \qquad \longrightarrow \qquad N = N_0\mathrm{e}^{-\lambda t},$$

where N_0 is the initial number of atoms of radioactive nuclide. Substituting this result into Eq. (1.3) results in the time rate of the activity in the form

$$A = A_0\mathrm{e}^{-\lambda t}. \tag{1.4}$$

Decay half-life

The half-life is defined as the interval during which the original activity of a radioactive nuclide drops by one half. From the relation (1.4) we successively obtain

$$\frac{A_0}{2} = A_0 \mathrm{e}^{-\lambda T} \quad \longrightarrow \quad \ln \frac{1}{2} = -\lambda T \qquad \longrightarrow \qquad T = \frac{\ln 2}{\lambda}.$$

The half-lives of some radioactive nuclides are given in Tab. 1.1.

1.2.4 Ionizing radiation

The radiation emitted by radioactive nuclides is a stream of particles and photons. Their energy lies in the order of keV to MeV, which is several orders of magnitude higher than the ionization energy of atoms and molecules. For this reason, as they pass through the matter, they cause intense ionization[3] – hence the name ionizing radiation. Apart from the ionization, excitation[4]of atoms and molecules also takes place here. The electrons released during ionization have such energies that they themselves cause secondary ionization and excitation.

Each single ionization or excitation reduces the energy of the ionizing particle by the corresponding value of the ionization or excitation energy. Since this energy represents only a small fraction of the energy of the particle, a large number of ions, free electrons and excited states are produced along the path of the ionizing particle. In this way, the particle deposits its energy to the matter until it gradually loses its ability to ionize and excite and is absorbed by the environment. If the layer of matter is thick enough, all the particles deposit all their energy to the matter and the radiation is completely absorbed. The thickness of the layer that completely absorbs the radiation is referred to as the range.

Let's denote the energy deposited by the primary and secondary particles of ionizing radiation to the absorbing material as ϵ. The quantity expressing the deposited energy per unit mass of the absorbing matter is called the absorbed dose

$$D = \frac{\mathrm{d}\epsilon}{\mathrm{d}m},$$

its dimension is $\mathrm{J\,kg^{-1}}$ and its unit is gray (Gy). In addition to the absorbed dose, it is also useful to know the distribution of the deposited energy along the particle's path. This property of radiation is expressed by the linear energy transfer

$$L = \frac{\mathrm{d}\epsilon}{\mathrm{d}x}.$$

Obviously, if the radiation has a short range (as is the case, for example, of α radiation), all the energy is absorbed along a short path, and hence the linear energy transfer is large.

Mechanisms of ionizing radiation energy loss

Ionizing radiation, consisting of a stream of charged particles, loses its energy by colliding with molecules and atoms in the environment. In doing so, electromagnetic interaction with electrons occurs, resulting in ionization and excitation. The linear energy transfer for charged particles is a

[3]Ionization is the formation of an ion by the release of an electron from the atomic electron cloud; the ionization energy is the energy required to release the electron.

[4]Excitation of atoms means the transition of electrons in atomic shells to higher energy levels, in molecules also an increase in the frequency of vibration of atoms in the molecule or acceleration of the rotation of the molecule.

complex function of the charge number Z of the particle, the number of electrons per unit volume of the absorbing material n, the velocity of the particle v and the ionization energy of the atoms and molecules of the material. In very simplified terms, we can write

$$L \sim \frac{Z^2 n}{v}. \tag{1.5}$$

Massive charged particles (α particles) penetrate matter only with difficulty, the α radiation has only a short and sharply defined range. The particle's ionization ability remains roughly the same throughout the particle's path, only dropping rapidly to zero near the end of the path. The sharp drop in ionization ability occurs when the particle slows down enough to capture electrons from the surroundings and becomes a neutral helium atom. The range of the α radiation emitted from radioactive nuclides is only a few centimetres in the air; a 10 cm layer of air absorbs the radiation completely. In liquids and solids, the completely absorbing layer is tens of micrometers thick.

The linear energy transfer of β radiation is generally smaller than that of α radiation. This is due to the smaller charge of the electron compared to the charge of the helium nucleus and the fact that at a given energy the electron velocity is significantly higher. For this reason, β radiation has a greater penetration and range in the environment. In gases (depending on the energy of the radiation), the range is a few meters, β radiation at low energy is similar to α radiation in its short range. The absorption curve of β radiation has an exponential form as described by empirical relationship

$$I = I_0 \mathrm{e}^{-\mu d}, \tag{1.6}$$

where I is the radiation intensity, d is the thickness of the absorbing layer and μ is the linear absorption coefficient depending on the material electron density and the radiation energy.

For the linear absorption coefficient we can write $\mu = \mu_m \rho$, where ρ is the material mass density and μ_m is the mass absorption coefficient, which is a constant for a given radiation type and energy spectrum. The absorption of β radiation is also contributed to a lesser extent by the formation of bremsstrahlung – braking (X-ray) and Cherenkov radiation.

Radiation γ does not have the ability to directly ionize the environment by electromagnetic interaction, as is the case of particles carrying an electric charge. It ionizes indirectly by the effect of secondary electrons, which are created when γ radiation passes through the matter by three processes, depending on the energy of the photons.

If the energy of γ radiation is less than 0.1 MeV, the radiation interacts mainly with electrons in the inner atomic orbitals. In doing so, all the energy of the photon is transferred to the electron, the photon is absorbed and the electron is released from the atom as a so-called photoelectron. Due to the filling of vacancies with electrons from higher orbitals, the photoeffect is accompanied by the production of characteristic X-rays.

At an energy of 0.1-2 MeV, γ radiation interacts mainly with weakly bound outer orbital electrons by Compton scattering. The photon transfers only part of its energy to the electron and releases it from the atomic electron cloud as a Compton electron. In this way, the photon interacts with the atoms with reduced energy and altered direction until its energy is reduced so much that it is absorbed in the photoeffect.

The third mechanism is the formation of pairs. It occurs when a photon of γ radiation penetrates close to an atomic nucleus and its energy is greater than 1.02 MeV (the value corresponding to twice the rest energy of the electron). In this case, the photon is converted into an electron-positron pair in the electromagnetic field of the nucleus. Positrons, after their creation, annihilate by interaction with electrons to form two γ photons.

The secondary electrons produced during the absorption of γ radiation by the above mentioned mechanisms deposit their energy to the matter by ionization and excitation processes in the same

way as described for β radiation. Because γ radiation has a high penetrating ability, the secondary electrons are distributed much more sparsely along the path of the radiation, the linear energy transfer is therefore small and the range of the radiation is large (high energy γ radiation penetrates air up to the distance of several kilometres). The attenuation of a γ beam as it passes through matter is governed by the relation (1.6), where the coefficient μ includes the probabilities of the three interaction mechanisms, and therefore depends on the proton number of the absorbing matter and the energy of the photons of the γ radiation.

Instead of the experimentally unavailable range, the penetration of γ radiation is expressed in terms of the so-called half-value thickness, which is the thickness of the material that attenuates the initial intensity of the radiation by one half. From the relation (1.6) and the condition $I = I_0/2$ we easily obtain the relation for the half-value thickness

$$d_{1/2} = \frac{\ln 2}{\mu}. \tag{1.7}$$

Half-value thickness for air is 35 m for radiation with energy 0.1 MeV, and 90 m for radiation with energy 1.0 MeV.

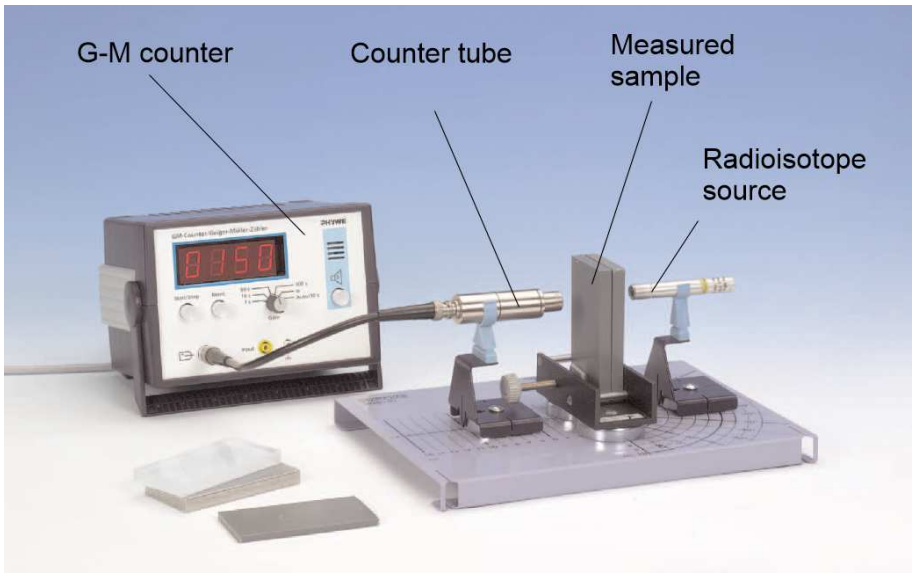

Figure 1.1: Experimental set-up.

1.3 Procedure

1.3.1 Before starting the measurement

Since, in addition to radioisotope radiation, Geiger-Müller (G-M) counter detector also registers the radioactive background, it is necessary to know its level for correction. Before requesting radioisotope sources, measure the radioactive background level N_{back} as the number of pulses registered over a longer time interval (e.g., 4 minutes).

1.3.2 Measurement of β-radiation absorption

1. Use the ^{90}Sr radioisotope source (activity 74 kBq), place it in the holder in the axis opposite the detector tube of the G-M counter at a distance of about 25 mm from the tube edge, and

remove its plastic protective cover. **Remove and replace the protective cover very carefully!**

2. Choose some absorbing material (plexiglass, FR-2 hard-paper, aluminium – the thin samples) and test the counting rates for different thicknesses of the absorbing material. With too thick layer of improperly chosen material, the detector does not register the radioisotope source radiation, but only the background radiation and the measurement is meaningless.

   Adjust the position of the counter tube and the source, **you must not change it during the measurement**.

3. For each absorber layer thickness (including zero), measure the number of pulses registered by the G-M counter.

   Note that the decay of radioactive nuclei is governed by statistical laws, so that pulse counting must be carried out for a sufficiently long interval. Since β radiation is absorbed in matter quite rapidly, conduct individual measurements (depending on the material and its thickness) for about 10 seconds to 2 minutes. In the case of absorbing materials with higher densities, the measured values may be close to the natural radioactive background; in these cases it is not worth continuing the measurements.

   If you conduct individual measurements for different intervals, the values obtained must be converted to a single time interval before processing, see Note 1.3.6.

1.3.3 Measurement of γ-radiation absorption

Measurement of the γ-radiation absorption is done in the same way as for the β-radiation, except that:

- use the ^{60}Co source (activity 74 kBq), place it in the holder in the axis opposite to the detector tube of the G-M counter at a distance of about 45 mm from the edge of the counter tube,
- use thicker samples of absorbing material (lead, iron, aluminium, concrete),
- pulses should be counted for at least one minute.

1.3.4 Absorption of α-radiation

- Using the ^{241}Am source, check that you can completely block the α radiation even with a thin layer of absorbing material (e.g., a sheet of paper).
- Due to the short range of α-radiation, the plastic cover of the input of the counter tube must be removed. **Remove and replace the protective cover very carefully!**

1.3.5 After the measurement

Carefully place the protective cover on the counter tube and give back the radioisotope source(s) to the lab instructor.

1.3.6 Notes on the processing of measured data

Since the intensity of the radiation decreases exponentially with the thickness of the absorption layer and is proportional to the pulse counting rate, the linear absorption coefficient is most conveniently calculated by approximating the measured values corrected for the radioactive background (d_i, $N'_i - N'_{\text{back}}$) with exponential function

$$N' = A\mathrm{e}^{kd},$$

where the absolute value of the calculated coefficient k represents the linear absorption coefficient[5] μ.

All read pulse counts must be converted to the same (but otherwise arbitrary) interval Δt_0 – preferably the one for which you took the most measurements. Thus, if you have read N_i pulses in the i-th measurement for the interval Δt_i, the following will apply

$$N'_i = N_i \times \frac{\Delta t_0}{\Delta t_i}.$$

The pulse counting rate is a random variable following the Poisson distribution for which the variance is equal to the mean value. The estimate of the standard deviation (standard uncertainty) of the readout converted to the interval Δt_0 can therefore be calculated as its square root, i.e.,

$$\sigma'_i \approx \sqrt{N_i} \times \frac{\Delta t_0}{\Delta t_i}.$$

For the calculations and plotting the graphs, you can use the *Universal tool for plotting graphs* at (*https://planck.fel.cvut.cz/praktikum/*).

1.4 Appendix – Geiger-Müller counter

The Geiger-Müller counter represents a gas ionization detector. The counter tube has a cylindrical shape, with a conductive film on the inner wall forming the cathode and a thin wire in the axis of the cylinder forming the anode. The tube is filled with a suitable gas, and a DC voltage is applied to the electrodes, usually 400-2000 V, depending on the type of detector. When a particle of radiation enters the detector, it ionizes the gas and creates many positive ions and electrons along its path. These move rapidly towards the respective electrodes, the gas filling becomes conductive for a short time and a current pulse is generated which is registered. The electrons are so accelerated in the strong field of the anode that they cause further ionization and amplify the current pulse. During the collection of ions and electrons, when current is passing through the tube, it is not possible to register another particle. This interval is called the dead time.

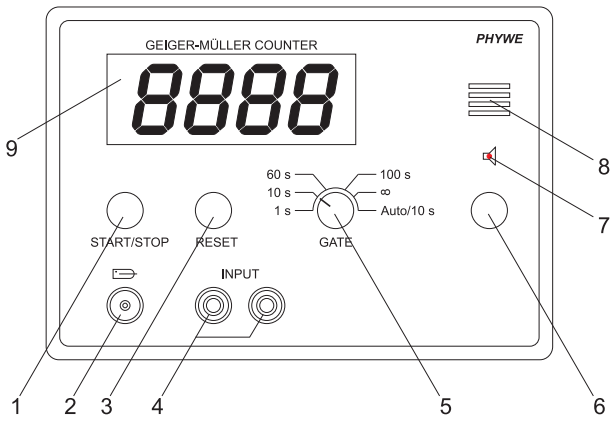

Figure 1.2: G-M counter Phywe.

The detection tube of the used G-M counter is filled with a mixture of argon and neon, its dead time is about 100 μs. The tube housing transmits quanta of γ radiation and β particles with sufficient energy, the probability of detection is: 20 % for 0.73 MeV, 60 % for 1.01 MeV, 85 % for

[5] Its unit will correspond to the unit in which you enter the thicknesses d_i. For example, if they are in cm, you get μ in cm^{-1}.

1.37 MeV and 95 % for 1.7 MeV. Low-energy electrons and α particles unable to pass through the tube cover are detected through a thin mica window, from which the plastic cover must be **very carefully** removed.

G-M counter control – Fig. 1.2

1. The **START/STOP** button is used to start the counting, if it is pressed during the measurement before the set interval has elapsed, the counting is interrupted and the number of pulses remains on the display. In this case, a new measurement can only be started after pressing the **RESET** button.

2. BNC connector for connecting the shielded cable of the detection tube.

3. The **RESET** button is used to reset the counter.

4. Input terminal **INPUT** is used for reading TTL signal.

5. Rotary switch for setting the reading interval and operating mode. Individual measurements for a fixed interval of **1 s**, **10 s**, **60 s** and **100 s** are started by pressing the **START/STOP** button. After the selected time limit is completed, the reading remains on the display. If you then press the **START/STOP** button again, the reading will continue from the previously measured value. To count from zero, you must first press the **RESET** button.

   In the ∞ position, the counter reads continuously between two consecutive presses of the **START/STOP** button. Press the **START/STOP** button again to start another reading, new pulses will be added to the original value. When the value 9999 is reached, the counter stops.

   In the **Auto/10s** mode, after pressing the **START/STOP** button, the measurement is repeatedly started from zero for 10 s. After this interval has elapsed, the reading is displayed on the display for some time.

6. The speaker button switches the audio signalling of the read pulse off and on. The on state is indicated by LED.

7. LED indicating the loudspeaker switched on.

8. Loudspeaker.

9. Display showing the read values.

1.5 Appendix – Safety considerations regarding handling of radioisotope sources

- Radioisotope sources used for experiments in the laboratory are so-called *insignificant sources of ionizing radiation*. The equivalent absorbed dose rate at any distance within 0.1 m from the surface of the source is less than 1 μSv/hr, which allows working with the sources and staying near them *without any time limitation*.

- Higher dose may occur in the case of a serious mechanical damage to the source. It is therefore forbidden to dismantle the cover of the source.

- At the end of the measurement, or when not in use, the source must be stored in its protective container.
- If the experimenter discovers mechanical damage to the source, he/she shall immediately report this fact, as well as any suspected leakage of radionuclide, to the lab instructor. Until his/her decision, the source must not be manipulated in any way.
- The individual radioisotope sources will be handed over to you by the lab instructor upon request, **the last used source should be handed over to the lab instructor before leaving the laboratory**.

1.6 Appendix – Mass density of absorbing materials

Material	ρ [kg/m^3]	Material	ρ [kg/m^3]
paper	852	glass	2370
lead	11340	aluminium	2690
iron	7860	concrete	2350
plexiglass	1119	hard paper	1390

1.7 References

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