Laboratory Work No. 1.
Induced radioactivity

The aim of this assignment is to gain an understanding of induced radioactivity, achieved by means of irradiating the given stable isotope with thermal neutrons. The half-life of the created radioactive isotope is evaluated using two methods: by registering the decreasing intensity of β^- decay, and by analyzing the recreated plot of the amount of activated nuclei as a function of activation time.

Contents

1. Basic definitions. Radioactivity

An atomic nucleus is a bound state of neutrons and protons, commonly (but not necessarily) found at the center of an atom. A given *isotope* is defined by the number of neutrons N and number of protons Z, and denoted as ${}^{A}_{Z}\mathrm{X}_{N}$, where $A = N + Z$ is its mass number, aka the total number of all neutrons and protons (collectively called the nucleons), and X is the chemical element. Note that the amount of protons Z is the same as the element's atomic number in the periodic table of chemical elements, which is why using the shorter ${}^{A}\mathrm{X}$ notation is as acceptable. For example, when dealing with isotope ${}^{9}\mathrm{Be}$, beryllium is the fourth element in the periodic table so $Z = 4$, and $N = A - Z = 9 - 4 = 5$, so this is beryllium isotope ${}^{9}_{4}\mathrm{Be}_{5}$.

A great part of matter that surrounds us, as well as matter we ourselves are made of, is comprised of stable nuclei. However, a small fraction of matter exists that is made up of radioactive nuclei, i.e. nuclei undergoing certain changes in structure known as *radioactive decay*. Radioactivity was discovered in 1896 by Becquerel and independently by Marie Curie. Becquerel noticed that minerals containing uranium caused a blackening of the photographic plate wrapped in non-transparent black paper. The rays causing this blackening were shown to be produced by specific atoms and, after the discovery of an atomic nucleus in 1911, were attributed to the changes in atomic nuclei rather than atoms as a whole.

2. Natural radioactivity

Unstable or radioactive nuclei undergo structural changes resulting in emission of one or several particles. More specifically, radioactivity is the spontaneous emission of particles from unstable atomic nuclei as they decay into other nuclei or lower energy states of the same isotope. Naturally this process happens of its own accord without external interference, hence the term "natural radioactivity" or simply "radioactivity" unless mentioned otherwise. Most common types of radioactive decay include α decay, β decay, γ decay and spontaneous fission.

The tendencies of various isotopes towards specific types of radioactive decay can be most conveniently illustrated on the chart of nuclides, otherwise known as the $N-Z$ diagram (Fig. 1). To date, around 3500 isotopes have been discovered, each shown with a square corresponding to a specific composition

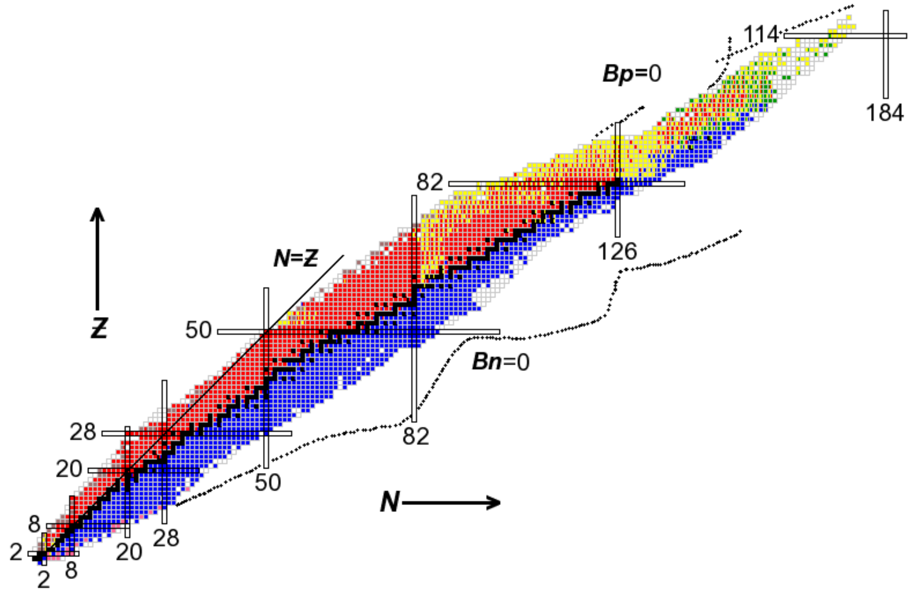

Figure 1. Chart of nuclides

of N neutrons and Z protons. Different theoretical estimates suggest that around 3000 more isotopes could potentially be discovered, predominantly in the region of heavy neutron excess ($N >> Z$). Affinity of different isotopes to specific types of radioactivity is shown with different colours. Squares painted in black correspond to stable isotopes. These nuclei form a line known as the valley of (β) stability. Stable isotopes are characterized by an energetically favourable relation between the numbers of neutrons and protons. Deviating from this relation results in an excess of neutrons or protons, and the corresponding nuclei are prone to one of the 3 types of β decay: β^- decay, β^+ decay and electron capture, all of which produce nuclei with a more balanced neutron-to-proton ratio.

Isotopes with an excess of neutrons (also known as neutron-rich isotopes and shown in blue on Fig. 1) typically undergo β^- decay that goes as follows:

$$^{A}_{Z}\mathrm{X} \rightarrow \;_{Z+1}^{\;\;A}\mathrm{Y} + e^- + \tilde{\nu}_e. \tag{1}$$

Here, e^- is an electron and $\tilde{\nu}_e$ is an electron antineutrino. On the level of elementary particles, this decay can be rewritten as:

$$n \to p + e^- + \tilde{\nu}_e, \tag{2}$$

where n and p are a neutron and proton, both remaining in the nucleus. Note that the electron created in the decay is not emitted from an atomic orbital – rather, it does not exist at all before the decay, and is only created along with the antineutrino as one of the neutrons in the nucleus turns into a proton. Essentially, this decay results in a decrease of N by 1 and an increase of Z by 1, creating an isotope that is either stable or lays closer to the valley of β-stability (in which case another β decay takes place, so on and so forth). The anti-neutrino created in this process is an electrically neutral particle that can only take part in weak nuclear interactions (see lab. work №14 for more details). While the corresponding processes are typically heavily suppressed in probability, this particle makes its presense known, for example, through the energy distribution of β decay electrons, also known as their spectrum. Electrons created through β decay demonstrate a wide range of energies, which due to laws of energy and momentum conservation can only happen in decays with 3 or more products. This particle will not be measured in this task, however, due to the mentioned extremely low chances of its interaction with matter (or, relevantly, registering equipment used in the task).

Similarly, if a given isotope is proton-rich, i.e., it has an excess of protons, β^+ decay may take place (nuclei shown in red on Fig. 1). The reaction on nuclear and particle levels goes as follows:

$${}^{A}_{Z}\mathrm{X} \to {}_{Z-1}^{\;\;A}\mathrm{Y} + e^+ + \nu_e, \tag{3}$$

$$p \to n + e^+ + \nu_e, \tag{4}$$

where e^+ is a positron (an antiparticle to the electron), ν_e is an electron neutrino. Alternatively, a different type of β decay, the electron capture, may also take place. In this case, an electron from one of the atomic orbitals, typically closest to the nucleus, is consumed by the nucleus in the following process:

$$ {}^{A}_{Z}\mathrm{X} + e^- \to {}_{Z-1}^{A}\mathrm{Y} + \nu_e, \text{ or} \tag{5} $$

$$ p + e^- \to n + \nu_e. \tag{6} $$

The resulting nucleus ${}_{Z-1}^{A}\mathrm{Y}$ in both β^+ decay and electron capture is, once again, either stable or is closer to the valley of stability.

The other two mentioned types of radioactivity, α decay and spontaneous fission, are typical for heavier isotopes. They are discussed in detail in tasks №2 and №15, respectively, and do not concern the current task.

An attentive student will notice that the chart does not show any nuclei undergoing γ decay. This has to do with the fact that the chart shows the decay modes for the ground states of various isotopes. γ decay, on the other hand, is typical for nuclei in excited states. Similar to how atoms in excited states are able to release energy by emitting photons, transitioning to lower energy states as a result, atomic nuclei are also able to undergo such a process. While the created photons in case of atoms are in the X-ray frequency range, the radiation in case of atomic nuclei is of higher energy, in the γ radiation range, hence the created particles bearing the name of γ quanta. The process of γ decay (also known as γ transition) then reads:

$$ {}^{A}_{Z}\mathrm{X}^* \to {}^{A}_{Z}\mathrm{X} + \gamma, \tag{7} $$

where the asterisk denotes an excited state and γ stands for the γ quantum – a quantum of electro-magnetic field. This is the only type of decay that does not change the composition of the nucleus and rather just its energy state.

3. Radioactive decay law

One of the key features of any radioactive decay is the spontaneous or probabilistic character of the phenomenon. This means that it is not possible to give an accurate prediction when a given unstable nucleus is going to decay.

It is possible, however, to describe the rate of this process for a large sample of nuclei.

Let λ be the probability of a single nucleus to decay in a span of a single second. If a given radioactive sample contains N nuclei and each nucleus decays independently of others, then in an small time window $\mathrm{d}t$ this amount should change by $\mathrm{d}N$ equal to

$$\mathrm{d}N = -\lambda N \mathrm{d}t. \tag{8}$$

The minus sign shows that the amount of nuclei decreases with time. Solving this differential equation for $N(t)$ yields the well-known *radioactive decay law*:

$$N(t) = N_0 e^{-\lambda t}. \tag{9}$$

Here, $N(t)$ is the amount of nuclei that remain at the moment of time t, N_0 is the amount of nuclei at the initial moment of time $t = 0$. The probability λ is called the *radioactive decay constant*. This value is different for different isotopes. The greater the value of λ, the quicker the given isotope decays.

Value τ called *mean lifetime* is sometimes used instead of λ (most commonly in particle physics). Mean lifetime represents the average time a particle exists before decaying and can be calculated as:

$$\tau = \frac{\int_0^\infty tN(t)\mathrm{d}t}{\int_0^\infty N(t)\mathrm{d}t} = \frac{1}{\lambda}. \tag{10}$$

Radioactive decay law can then be rewritten simply as

$$N(t) = N_0 e^{-t/\tau}. \tag{11}$$

Perhaps one of the most intuitive characterestics, most commonly used in nuclear physics, is the half-life of a nucleus, denoted as $T_{1/2}$. The value of $T_{1/2}$ refers to the time it takes for half of the nuclei in a sample to decay. The definition imposes the radioactive decay law in the following form:

$$N(t) = N_0 \cdot 2^{-t/T_{1/2}}. \tag{12}$$

It follows that half-life is related to the mean lifetime and radioactive decay constant via a logarithm:

$$T_{1/2} = \tau \ln 2 = \frac{\ln 2}{\lambda}. \tag{13}$$

$T_{1/2}$ (or τ or λ) is one of the fundamental characterics of atomic nuclei and can be found in the corresponding tables of nuclear properties compiled for known isotopes.

The defining property of any radioactive sample is its activity (or total activity) A. Activity describes the amount of nuclei decaying every second. For a pure sample comprised of a single radioactive isotope, activity is simply

$$A(t) = \left|\frac{\mathrm{d}N}{\mathrm{d}t}\right| = \lambda N(t) = \lambda N_0 e^{-\lambda t}. \tag{14}$$

The SI unit of activity is the becquerel (symbol Bq), which defined as 1 decay per second, or just s^{-1}. An older non-SI unit of activity, the curie (Ci), is sometimes also used; it is equal to $3.7 \cdot 10^{10}$ decays per second.

4. Induced radioactivity

In contrast with natural radioactivity that takes place "by itself", *induced radioactivity* (also called artificial or man-made radioactivity) takes place when a previously stable material is turned into radioactive after receiving a dose of radiation. The process in which radioactive isotopes are created, is called *activation*. The method was discovered in 1934 by Irène Joliot-Curie and Frédéric Joliot-Curie, for which they shared the 1935 Nobel Prize in Chemistry in 1935.

The amount of activated (radioactive) nuclei one obtains in the process of activation, depends on the amount of atoms in the irradiated target, activation time and the cross section of the nuclear reaction in which the analyzed radioactive isotope is created.

The *cross section* σ is a measure of the probability that a specific nuclear reaction takes place as two particles collide. Let us consider a beam of particles with flux j describing how many particles pass the unit area in a unit of time ($[j] = [\text{time}]^{-1}[\text{area}]^{-1}$). If we direct the beam at some target, some of these particles would interact with the atoms of the target. The amount of these interactions taking place per time unit $\frac{\Delta N}{\Delta t}$ is proportional to the amount of atoms in the target N_{targ} and the initial flux j:

$$\frac{\Delta N}{\Delta t} = \sigma j N_{\text{targ}}, \tag{15}$$

where the proportionality coefficient σ is the cross section. We note from this definition that the cross section is expressed in units of area, although in nuclear and particle physics, a non-SI unit of barns (b) is more commonly used: $1\,\text{b} = 10^{-28}\,\text{m}^2 = 100\,\text{fm}^2$. The name "cross section" becomes more clear if we replace each nucleus of the irradiated matter with a target of area equal to the cross section of the nucleus. In that case, the sum target area is equal to $N_{\text{targ}}\sigma$ and the probability of interaction of the beam with the target is expressed with the formula above. In practice, however, the real cross section coincides with the cross section of the nucleus only in a few particular cases. The cross section of different nuclei varies in the range of $10^{-24} \div 10^{-25}$ cm^2, whereas the cross section of various nuclear reactions can take a value anywhere between 10^{-20} cm^2 (e.g. thermal neutron capture) and 10^{-30} cm^2 (e.g. nuclear excitations via γ-quantum absorption). In the general case of neutron absorption, σ depends strongly on the energy of the neutrons in the beam.

Let us obtain the formula for activation that shows how many radioactive nuclei exist in the sample after it was irradiated for the duration of time t. Suppose we construct an experiment, in which we use a particle beam with flux j directed at a target with a number of atoms (or nuclei) in the target

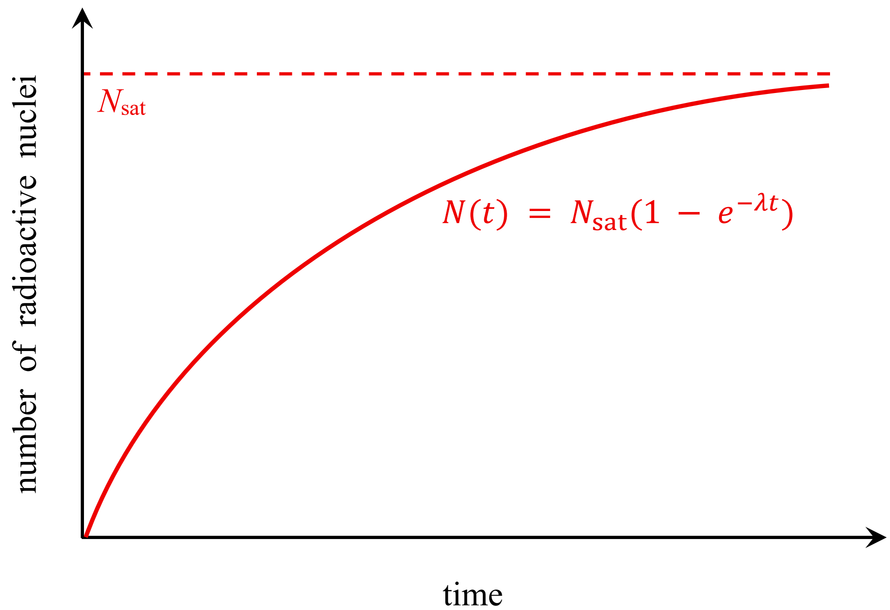

Figure 2. Activation curve

N_{targ}, and a specific reaction with cross section σ takes place as it gets irradiated. The amount of radioactive nuclei generated as a result increases according to formula (15). At the same time, these nuclei undergo a radioactive decay at the rate dictated by their decay constant λ, and their amount decreases at every moment by $\mathrm{d}N$ from (8). The two processes of activation and decay take place simultaniously, and the resulting differential equation reads:

$$\mathrm{d}N = \sigma j N_{\mathrm{targ}} \mathrm{d}t - \lambda N \mathrm{d}t, \text{ or} \tag{16}$$
$$\frac{\mathrm{d}N}{\mathrm{d}t} = \sigma j N_{\mathrm{targ}} - \lambda N. \tag{17}$$

If we impose the initial condition of $N(0) = 0$ (no radioactive nuclei were present at the start of activation), solving this differential equation for N gives

$$N(t) = \frac{\sigma j N_{\mathrm{targ}}}{\lambda}(1 - e^{-\lambda t}) = N_{\mathrm{sat}}(1 - e^{-\lambda t}). \tag{18}$$

Here, $N_{\mathrm{sat}} = \frac{\sigma j N_{\mathrm{targ}}}{\lambda}$ denotes the amount of radioactive nuclei obtained in the saturation limit. Indeed, if we let the activation process run indefinitely, the formula suggests we are not able to reach any arbitrarily large number of radioactive nuclei – rather, there is an upper limit of N_{sat} that cannot be crossed, as seen on Fig. 2. This happens because the rate at which radioactive nuclei are generated in the activation process, $\sigma j N_{\text{targ}}$, is constant (in the approximation that a very small amount of the target nuclei are activated relative to N_{targ}), while the rate at which they decay, λN, increases as the amount of radioactive nuclei N increases. Eventually those two rates equal out: the same amount of radioactive nuclei appear and decay, and their overall amount N stops raising further on. This saturation takes place after approximately 4 to 5 half-lives of the radioactive isotope obtained during activation.

Activation can take place under radiation comprised of various particles, such as protons, neutrons, electrons, etc. In modern experiment and practical applications, neutron activation is the main form of induced radioactivity. The reason is that unlike, for example, protons, neutrons are not charged and no Coulomb repulsion takes place as neutrons approach the target nuclei. In 1935 Enrico Fermi found out that the induced activity of the target irradiated by neutrons, increases many times over if the neutron generator is surrounded by hydrogen-containing materials, such wax. This happens because neutrons quickly lose a significant portion of their energy when colliding with objects of similar mass – in this case, the nuclei of hydrogen: protons, after which their velocity approaches the thermal velocity range (hence the term "thermal neutrons"). Furthermore, chaotic collisions of neutrons with wax may result in their deflection backwards and crossing of the target several times, while the cross section of neutron capture is inversely proportional to neutron velocity.

When a nucleus with mass number A captures a free neutron, it enters an intermediate state called "compound nucleus" – a nucleus with mass number $A + 1$ in an excited state that quickly releases the excess energy in one of several ways, such as by emitting one or several γ-quanta or by undergoing α decay, β decay or fission, etc. This excited state usually lasts for about 10^{-12} s, though sometimes it may endure for minutes, hours or even years. If its mean lifetime is greater than a nanosecond, the state is called metastable or isomeric. States with the same amount of neutrons and protons but in different energy states that live for this long are called nuclear isomers and are of great interest in modern science.

Neutrons can be typically produced in neutron generators based on (α, n) or (γ, n) reactions (in (x, y) notation, x is the incoming and y the emitted particle in the nuclear reaction). For example, a mix of beryllium powder with a small amount of some α emitter such as polonium can pose as a convenient source of neutrons. Neutrons produced in this way range from 0 to 13 MeV in energy.

In the current task, a plutonium-beryllium neutron generator is employed with activity around 10^6-10^7 neutrons/second. Plutonium isotope ^{239}Pu (its half-life $T_{1/2} = 24$ thousand years) undergoes alpha decay (emitting alpha particles – nuclei of helium isotope ^{4}He). α particles have a very low penetration depth and cannot escape the generator, instead reacting with beryllium and producing neutrons. This chain of reactions can be explicitly written as:

$$^{239}_{94}\mathrm{Pu} \rightarrow {}^{235}_{92}\mathrm{U} + \alpha, \tag{19}$$

$$^{9}_{4}\mathrm{Be} + \alpha \rightarrow {}^{13}_{6}\mathrm{C}^* \rightarrow {}^{12}_{6}\mathrm{C} + n. \tag{20}$$

Neutrons then react with the material chosen for activation.

5. Experimental setup

In this work, a plutonium-beryllium neutron source with an output of $10^6 - 10^7$ neutrons/s is used. To slow the neutrons down to thermal velocities, the neutron source is placed in a wax block reinforced with cadmium and lead. The assignment involves irradiating aluminium samples in form of solid swords. The swords are inserted into grooves located at a distance of several centimeters from the neutron source, in a block of plexiglass. The position of the swords is thus strictly fixed relative to the neutron source if the same groove is used for activation. Up to 8 swords can be irradiated simultaneously. The grooves have numbers. The scheme of the neutron source

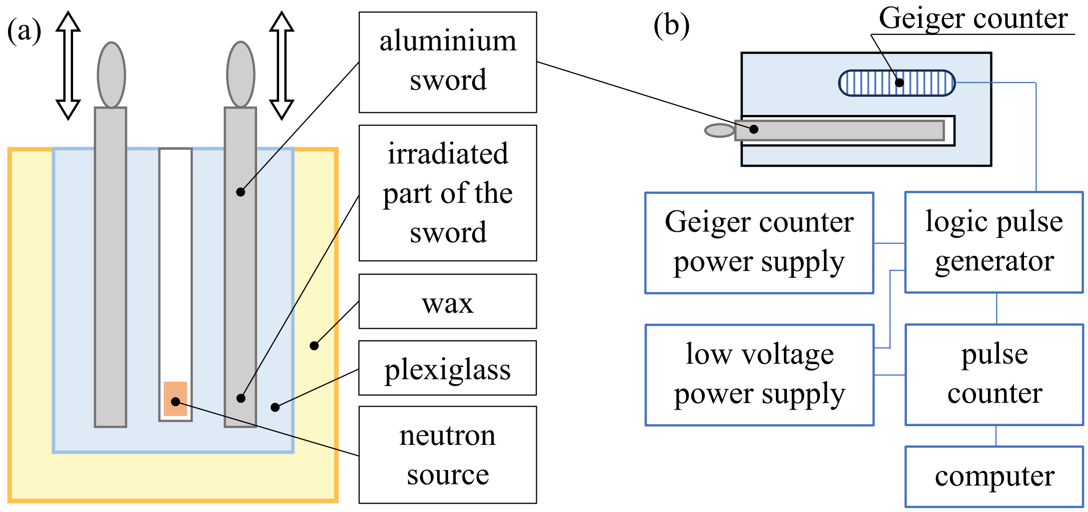

Figure 3. Experimental setup: (a) the scheme of the neutron source, (b) the diagram of the detector

is depicted on Fig. 3(a).

The following nuclear processes take place when stable aluminium isotope ^{27}Al is irradiated with neutrons:

$$
\begin{aligned}
&{}^{27}_{13}\mathrm{Al} + n \to {}^{28}_{13}\mathrm{Al}\\
&{}^{28}_{13}\mathrm{Al} \to {}^{28}_{14}\mathrm{Si}^{*} + e^{-} + \tilde{\nu}_e\\
&{}^{28}_{14}\mathrm{Si}{*} \to {}^{28}_{14}\mathrm{Si} + \gamma
\end{aligned}
$$

As can be seen, neutron activation of ^{27}Al results in creation of radioactive isotope ^{28}Al that undergoes β^{-} decay and a subsequent γ-transition (the simplified spectra of all the relevant isotopes are illustrated on Fig. 4). The induced β-activity is measured using a Geiger–Müller counter with wall thickness of 0.065 g/cm^2. To reduce the background influence, the counter is reinforced on all sides with lead. The sword is inserted in the groove of the lead casing and is always positioned in the same way relative to the Geiger counter. The diagram of the whole detecting system is shown on Fig. 3(b).

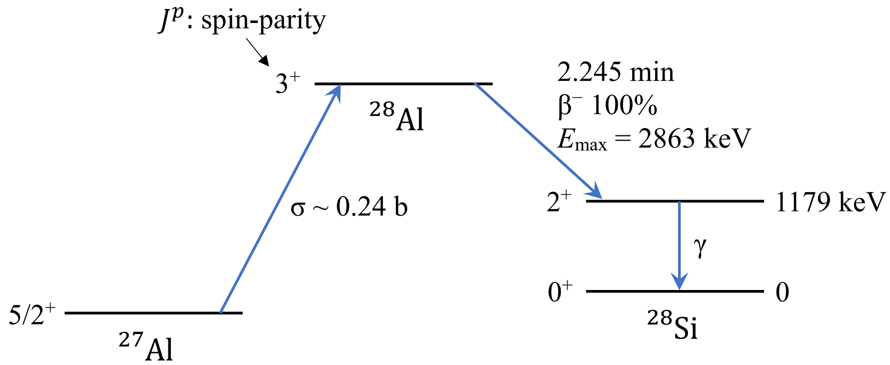

Figure 4. Simplified spectra of the isotopes created in the process of aluminium activation

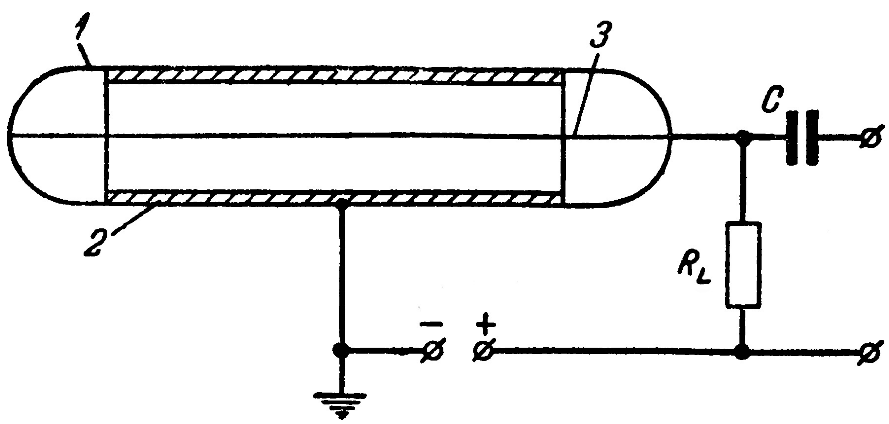

Figure 5. Gas-discharge counter, its construction, and typical wiring. 1 — glass tube; 2 — metal cylinder (cathode); 3 — wire (anode).

5.1. Operating Principle of the Geiger–Müller Counter

The Geiger counter belongs to a broad group of gas-filled detectors, which, due to their high sensitivity to various types of radiation, relative simplicity, and low cost, are widely used for radiation detection. Such a detector consists of a gas-filled volume with two electrodes. A constant voltage is applied to the electrodes. The operating voltage depends on the gas pressure, which may vary over a wide range for different detector operating modes.

Particle detection occurs as follows. A fast particle entering the counter ionizes the gas. The electrons and heavy positive and negative ions produced by the ionizing particle move in the electric field and undergo multiple collisions (elastic and inelastic) with gas molecules. The average drift velocity of electrons and ions is proportional to the electric field strength and inversely proportional to the gas pressure. The resulting current is mainly due to electrons, as their mobility is three orders of magnitude higher than that of heavy ions. The voltage pulse across the resistor R_{L} is amplified and sent to the recording apparatus.

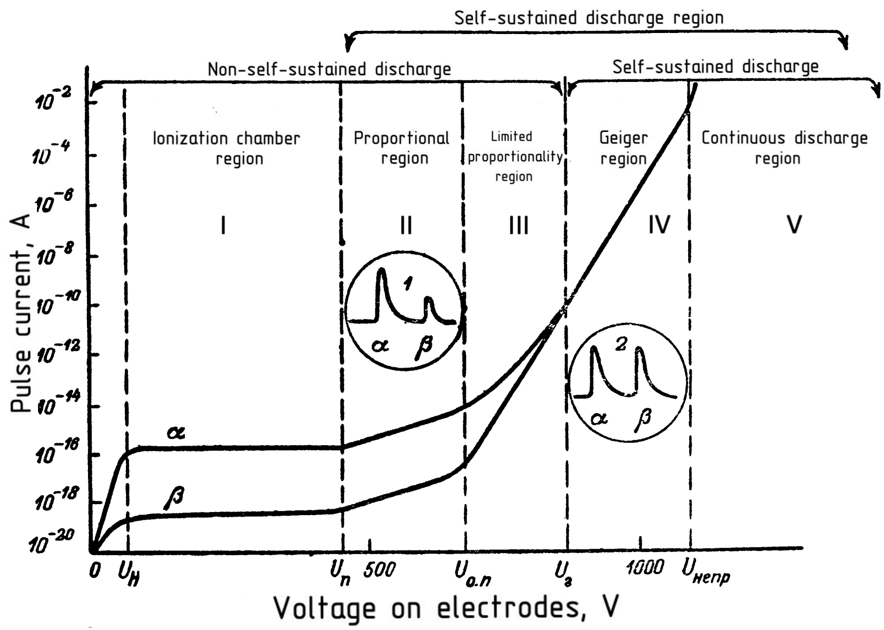

Figure 6. Voltage-current characteristic of a typical gas-discharge counter in different operating modes. The shape of pulses from α- and β-decays is schematically shown.

Fig. 6 shows the dependence of the output pulse amplitude on the applied voltage (assuming that the time constant $\tau = R_{\mathrm{L}}C$ is much larger than the charge collection time in the detector). Curves α and β correspond to different initial ionizations, higher for curve α. These curves are called the counter's voltage-current characteristics. Each curve can be divided into characteristic regions.

At low voltages two competing processes occur: charge collection at the electrodes and recombination of ions in the gas. Increasing the voltage increases ion drift velocity, reducing the probability of recombination.

In region I, nearly all charges produced in the detector are collected by the electrodes. This region is called the ionization chamber region. Detectors operating in this region are called *ionization chambers*.

At higher voltages, electrons produced by primary ionization are accelerated enough to ionize neutral gas atoms upon collision, producing secondary ions. This is called *gas amplification.* Initially, the pulse amplitude increases proportionally to primary ionization — the proportional region. In region II, so-called *proportional counters* operate.

The proportional region is followed by the limited proportionality region III.

Finally, in region IV, gas amplification becomes so large that the collected charge no longer depends on primary ionization. This is the Geiger region. The discharge remains triggered, i.e., it starts only after an ionizing particle passes through.

Further voltage increase leads to continuous self-sustained discharge (region V), which is unsuitable for particle detection.

In the Geiger counter, gas amplification is so high that secondary ionization reaches saturation. Near the threshold of this region, conditions for avalanche ionization occur only near the wire (e.g., in cylindrical counters at $V = 1000$ V, the field E at the cathode is hundreds of V/cm, and near the wire — $20000 \div 40000$ V/cm). Increasing voltage enlarges the avalanche region, and secondary ionization rapidly increases, forming an electron avalanche.

Thus, the counter undergoes a breakdown; the discharge covers the entire gas volume. Large voltage pulses appear on the anode, independent of primary ionization. Formation of even a single ion pair triggers a full discharge. In the Geiger region, the gas amplification factor reaches 10^{10}, and pulse amplitude amounts to several volts or tens of volts.

The detector geometry is chosen based on its operating conditions. A cylindrical counter consists of a metallic or metal-coated glass tube and a thin wire along the cylinder axis. The wire serves as the anode, the tube — as the cathode. End-window counters have an input window at the end. Counters are usually used for short-range particles, so the window is made of thin film.

Filling gases are usually special mixtures (e.g., Ar + HCl + HBr) with quenching additives to improve the detector's response time.

Geiger counters are highly sensitive to ionizing radiation. However, they cannot differentiate radiation types or energies, thus they measuring intensity only. An important feature is the counting plateau: the number of registered pulses is nearly independent of voltage, as each ionizing particle triggers an avalanche. Further voltage increase leads to spontaneous discharge.

The operating voltage is chosen in the middle of the plateau. Threshold voltage, plateau position, and length are specific to each counter and should be determined experimentally, usually ranging from several hundred to a thousand volts.

Geiger counters are simple, reliable, and efficient. Their sensitivity depends on particle penetration: only particles entering the active volume are detected, so wall or window thickness should not exceed particle range. Any particle producing at least one ion pair will almost certainly be detected.

To restore sensitivity after each registration, the gas must clear of heavy ions. During this *dead time*, the counter cannot register new particles. Geiger counters have relatively long dead times: 10^{-4}–10^{-3} s, and resolution does not exceed a few thousand counts per second.

Counters are also insensitive to γ-rays. Detection occurs only via secondary charged particles, produced in the counter walls, made of high-Z material. Detection efficiency is usually only 1–2%.

If a material with a high neutron cross-section is placed in the detector, neutron capture reactions produce detectable particles. Slow neutrons are often detected using boron trifluoride counters, where α-particles are produced in $^{10}\mathrm{B}(\mathrm{n}, \alpha)$ reactions. Fast neutrons are detected using hydrogen-rich detectors, where recoil protons produce the discharge.

6. Experimental Procedure

The half-life of isotope ^{28}Al is around 2.245 min. The goal of the assignment is to reproduce this value in 2 separate ways: by analyzing the radioactive decay curves and by recreating the activation curve.

Exercise №1. The radioactive decay curves.

The software on the computers connected to the Geiger counters allows to represent the decay data in convenient format and analyze it using mathematical tools such as Origin. While a single decay measurement is enough for the purposes of half-life evaluation in this manner, several decay measurements (around 5) will be required, both to make a more accurate estimate of $T_{1/2}$ and to recreate the activation curve in Exercise №2. As such, the steps for this task are:

1) Choose the time of individual measurements of the Geiger counter that will determine the step at which the dots on the decay curve will be spread apart. We recommend this time be set to around 15 seconds. This value will not be changing throughout the assignment.

2) Choose the activation durations t_i for measurements $i = 1..5$. Recall that the activation curve tends to the saturation limit after around 4-5 half-lives of the radioactive isotope. This means that to recreate this curve in Exercise №2, activation times should be picked in the interval of $[0,\ 5T_{1/2}]$ so as to provide information for the fitting procedure. We recommend that your first activation time t_1 be picked equal to $T_{1/2}/2$. After this, with each subsequent activation, keep increasing the activation time. The increasing order of t_i is chosen so as to minimise the residual induced radioactivity from previous measurements. For the last measurement, the activation time may be picked equal to 5 to 7 half-lives so as to obtain the saturation limit on the activation curve later.

3) Begin the neutron irradiation by carefully inserting the aluminium sword in the groove of the neutron source. Remember the groove number, as you will be inserting the sword in this same groove for the remainder of the assignment.

4) After elapsed time t_i, quickly but carefully pull the sword out of the neutron source and insert it into the groove of the Geiger counter. You

should immediately see the registered activity of the isotope on the screen. The activity should keep decreasing according to the radioactive decay law.

5) After activity reduced to sufficiently low values, save the data and use it to plot the corresponding decay curve using any data analysis tools such as Origin. Approximate the curve with the exponential function $Ae^{Bx} + C$. The C-term should be explicitly considered, as it allows to take into account the radioactive background that will inevitably add up to the measurements of the Geiger counter. Extract the value of B from the fitting procedure, and from it obtain the value of $T_{1/2}$ using the exponential decay law.

6) Repeat the steps 3–5 and obtain a number of estimates for the half-life of ^{28}Al. These values can be used to get the average value of $T_{1/2}$ along with a standard deviation σ for it.

Exercise №2. The activation curve.

Collected data from the previous exercise can be used to recreate the activation curve. The activity of the irradiated sample can be represented as a continuous function of time, first rising according to formula (18) as more radioactive nuclei are created in the process of activation, and then falling according the radioactive decay law (9). Of course, as the Geiger counter starts registering particles *after* activation is over, only the decreasing part of this function – the decay curve – is directly registered in experiment. However, the initial activity in the decay process is a point that also lies on the activity curve, and as such, can be used to plot it (see Fig. 7 for clarification). This is of course the reason why several such points corresponding to different activation times must first be obtained in Exercise 1, too. The steps for getting a second estimate for $T_{1/2}$ should become clear now.

1) Extract the values of the initial amount of registered particles N_i in each of the measurements performed in the previous exercise.

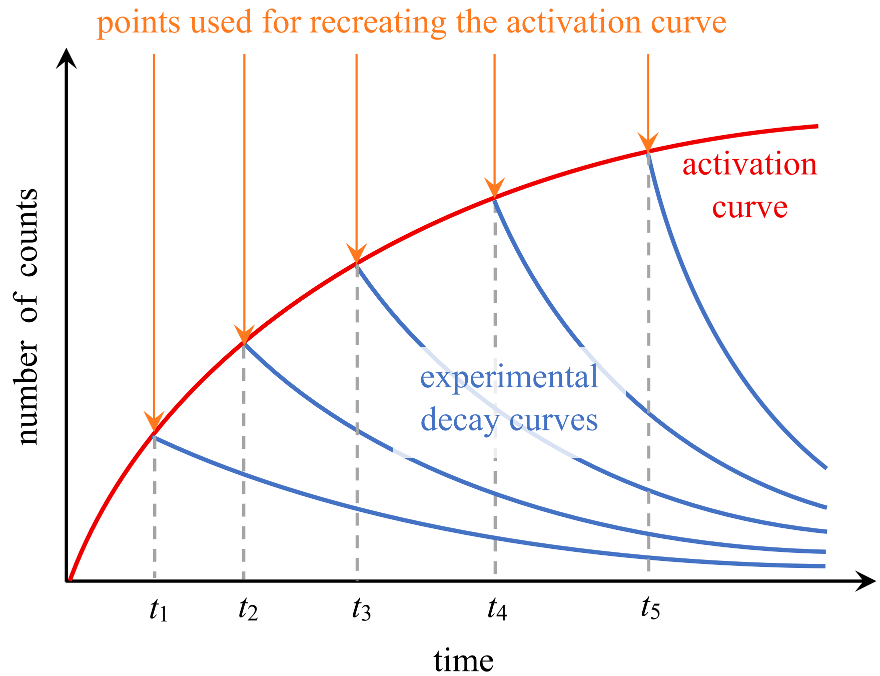

Figure 7. Activation and decay curves

2) Plot these values against the activation time t_i. Approximate the values of $N_i(t_i)$ using formula (18). If done correctly, the approximation should yield the value of λ, from which $T_{1/2}$ can be easily obtained.

The value of $T_{1/2}$ may differ by some tens of seconds from the tabulated half-life of ^{28}Al. This is normal, as deviations may arise from various factors, such the systematic errors related to the performance of the Geiger counter and the human factor of taking different time to pull out the sword from the neutron source and insert it in the counter.

To submit the work, provide:

1) all of the decay curves together with the obtained values of $T_{1/2}$ in each measurement;

2) an averaged half-life of ^{28}Al together with the standard error of this value;

3) the recreated activation curve and its fitting formula with values of all the parameters obtained in the fitting procedure;

4) a second estimate of $T_{1/2}$ obtained from analyzing the activation curve;

5) comparison of the two estimates for $T_{1/2}$;

6) conclusions from the experiment.