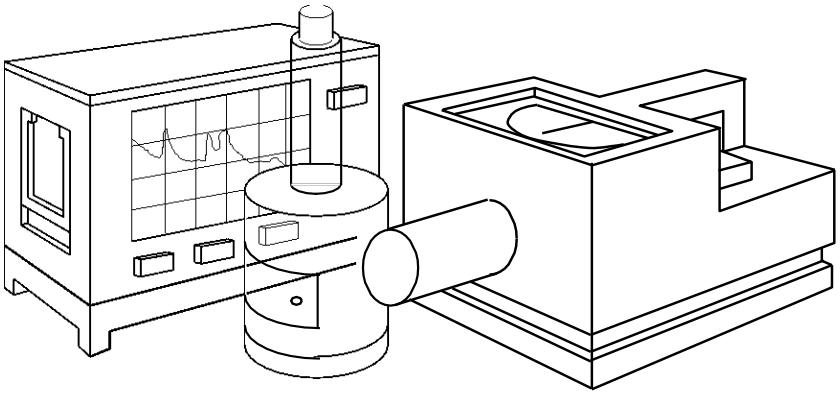
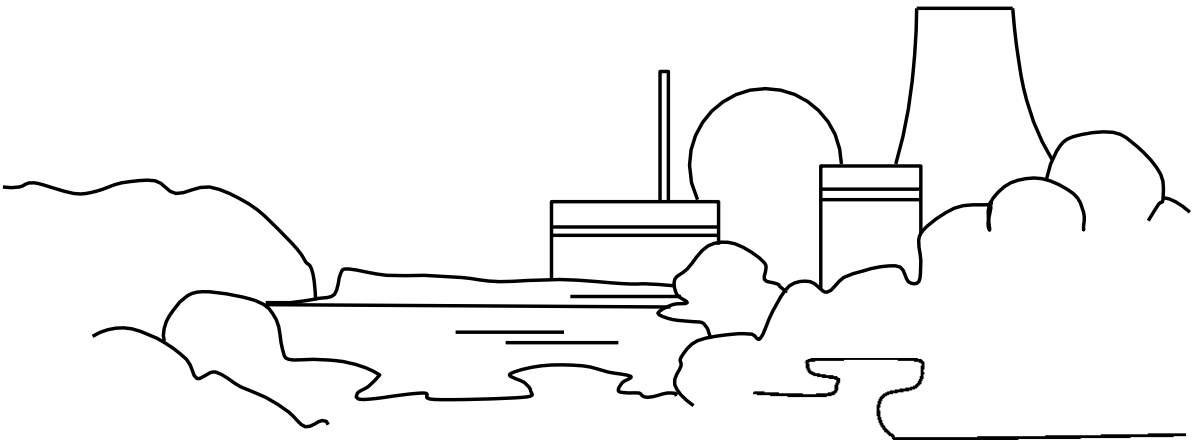
TECHNICAL UNIVERSITY
DRESDEN
Institute of Power Engineering
Training Reactor



Reactor Training Course

Experiment

"Activation and Decay of Radioactive Nuclides"



Instruction for
Experiment "Activation and Decay of Radioactive Nuclides"

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1. Introduction

In the year 1896, the French physicist Henry Becquerel noticed an unknown radiation emitted by uranium salts that resulted in the blackening of a photo plate. Further work by Becquerel, along with Pierre and Marie Curie found the radioactivity of thorium and eventually lead to the discovery of the chemical elements polonium and radium. However, only the first artificially induced nuclear reactions successfully pioneered by Ernest Rutherford by bombardment of nitrogen nucleons with α-particles, made possible the fabrication of artificial radionuclides with various properties. Since then, particularly in the second half of the 20th century, the significance of applied radioactivity methods has risen enormously.

Currently, artificial radioactive isotopes are being produced in any desired quality and quantity, mostly in nuclear reactors by the irradiation with neutrons originating from nuclear fission. Furthermore, advanced radiation measurement technologies are now an inherent part of science, technology and medical applications. Typical examples are the radiation-based measurements of thickness and of fluid level, as well as radiographic investigations, medical irradiations and radioactive tracer applications. However, these methods exhibit some characteristic drawbacks as well. As such, specific safety precautions are necessary and need to be thoroughly applied and controlled in order to prevent severe radiation damages.

The purpose of the experiment to be conducted in this session is to demonstrate the fundamentals of the production of radioactive isotopes in nuclear reactors and to show some of their basic properties as well as their appropriate handling. Therefore, selected materials will be activated in the reactor and subsequently, the decay of these materials will be measured. In one more part of the experiment, an unknown material will be irradiated and identified subsequently by regarding its decay curve and determination of its half-life. The latter experiment exemplifies one of the many possibilities offered by applied radioactivity.

2. Fundamentals of the Experiment

2.1. Important Terms Regarding Radioactivity

The chemical elements of the periodic table are characterised by a specific atomic number (number of protons) and the associated number of electrons in the atomic shell. In addition to protons, the atomic nucleus includes neutrons. Both neutrons and protons are termed nucleons. For any chemical element with its characteristic numbers of protons, atomic nuclei may exist that include a varying number of neutrons. These nuclei are called isotopes of this element. They appear at the same place in the periodic table and exhibit the same chemical properties, but different atomic masses. For most elements there are several isotopes that can or cannot be radioactive, respectively.

The term nuclide is used for any arbitrary atomic nucleus, characterised by both, its atomic and its mass number. If a nuclide is radioactive, it is termed a radionuclide. A radioactive isotope is termed radioisotope.

To summarise, radionuclides are radioactive nuclei of any chemical element of the periodic table. On the contrary, radioactive isotopes are invariably associated with a specific chemical element.

Thus, $^{28}_{13}$Al and $^{66}_{29}$Cu are two radionuclides, whereas $^{28}_{13}$Al is a radioisotope of aluminum and $^{66}_{29}$Cu is a radioisotope of copper.

Radioactivity is the feature of particular nuclei which can change their nucleus composition without any exterior influence. Whether or not this change occurs spontaneously depends on the stability of the nucleus, which is, among others, a function of the ratio between its number of protons and its number of neutrons. This is why for different isotopes of one chemical element some may be radioactive, while others are not. Radioactive nuclei exhibit an energy abundance, which they may release by emission of radiation and accompanying nucleus transformation (decay). These nuclei are unstable. Radiation emission cannot be controlled or manipulated by exterior influences.

The rate of nucleus transformations can be measured and is used as a means to quantify its radioactivity. According to the SI standard (Système International d'Unités), use of the unit Becquerel is mandatory:

1 decay/s = 1 Bq

In some cases, the historical unit 1 Curie (Ci) can still be found that was established based on the decay of 1 g of radium-226 ($1\ Ci = 3.7 \times 10^{10}$ Bq), but is not used anymore.

The most important radiophysical characteristics of radionuclides, crucial for allocating their potential application, are the following:

a) Type of the emitted radiation:
- α-emitter (emission of $^{4}_{2}He$ nuclei)
- $ß^{+}$-emitter (emission of positrons)
- $ß^{-}$-emitter (emission of electrons)
- γ-emitter (emission of electromagnetic radiation)

b) Energy of the emitted radiation:
In nuclear physics the measuring unit electron volt (eV) has been established particularly for radiation energy. 1 eV is the energy gained by an electron traversing an acceleration voltage of 1 V, thus:

$1\ eV = 1.602 \cdot 10^{-19}$ J as $1\ V = 1.602 \times 10^{-19}$ W·s

c) Half-life:
The decay of radioactive nuclides results in the production of new nuclides, which can be either stable or radioactive. The half-life $T_{1/2}$ denotes the time after which exactly half of the original amount of the radioactive material still exists, while the other half has decayed. The half-life is constant and characteristic for every radionuclide.

2.2. Production of Radioactive Nuclides

Radioactive nuclides originate from stable nuclei due to nuclear reactions if the resulting nucleus exhibit abundant energy, which is released either by radiation emission or emission of a particle. The material to be irradiated is called the target. Protons, neutrons, deuterons, alpha particles or gamma quants are commonly used as bombarding species.

Mostly, the following nuclear reactions are used for the production of artificial radioactive nuclides:

a) Exchange reaction: the bombarding particle x penetrates the target nucleus, leading to the emission of a different particle y. If x and y are differently charged, a transformation of the chemical element occurs.

b) Capture reaction: The bombarding particle x is absorbed in the target nucleus. The abundant energy is being released as electromagnetic γ-irradiation.

c) Fission reaction: By bombardment with neutrons or high-energy charged particles, atomic nuclei, particularly heavy ones, are being split in two different pieces of similar masses. This continuously occurs as a chain reaction in nuclear reactors. In this case, the production of radionuclides (radioactive waste) is not desired.

The mechanism of nuclear reactions can be assessed in two steps: In the first step, the bombarding particle is being absorbed in the nucleus. The binding energy of the bombarding particle is released and, additionally, its kinetic energy is transferred to the target nucleus. Thereby, a highly instable, highly excited temporary nucleus is being generated (compound nucleus). In the second step, this compound nucleus relaxes within a very short time ($<10^{-17}$ s) by emission of either a particle or a γ-quant or by splitting.

Nuclear reactions are represented by the following reaction equation

$$x + A \rightarrow C^* \rightarrow B + y \qquad \text{or shorter, } A(x,y)B$$

with the bombarding particle x, the target nucleus A, the temporary compound nucleus C*, the nucleus B remaining after the reaction and the particle y emitted due to the decay.

An example of such a nuclear reaction is the following:

$$^{14}_{7}N + ^{4}_{2}\alpha \rightarrow ^{18}_{9}F^* \rightarrow ^{17}_{8}O + ^{1}_{1}p \qquad \text{resp.} \qquad ^{14}N(\alpha,p)^{17}O$$

In a nuclear reactor, radioactive nuclides are essentially produced by capture of thermal neutrons. Thermal neutrons have a mean energy of 0.025 eV, being equivalent to a speed of 2200 m/s at room temperature.

The capture reactions with thermal neutrons occur as follows:

$$n_{th} + ^{M}_{Z}A \rightarrow ^{M+1}_{Z}A^* \rightarrow ^{M+1}_{Z}A + \gamma \qquad \text{resp.} \qquad ^{M}_{Z}A(n_{th},\gamma)^{M+1}_{Z}A$$

with the mass number M and the atomic number Z. The same element A thus remains, but a different isotope is created which mass number M is by one higher than that of the original isotope. Since the proton/neutron ratio changes, the created isotopes are usually radioactive.

For the materials used in the experiment, aluminum and copper, the following representations are applicable:

$$^{27}_{13}Al(n_{th},\gamma)^{28}_{13}Al$$

Natural copper consists of 2 different isotopes, $^{65}_{29}Cu$ (30.9%) and $^{63}_{29}Cu$ (69.1%). Both isotopes are being activated as follows:

$$^{65}_{29}Cu(n_{th},\gamma)^{66}_{29}Cu \qquad \text{resp.} \qquad ^{63}_{29}Cu(n_{th},\gamma)^{64}_{29}Cu$$

2.3. Decay of Radioactive Nuclides

Stability and instability of an atomic nucleus depend on its respective composition, determining the type and rate of its decay. The most important properties of a radionuclide can be found in tables for any isotope. These are (as already mentioned): type of emitted radiation, energy of emitted radiation and half-life.

A graphical decay scheme provides a good overview (Fig. 1). It illustrates the type of radiation, the respective loss of energy, the change of the atomic number as well as the relative probabilities of possible decay paths.

In the decay scheme, vertical distances represent changes in energy. Horizontal shifts represent a change of charge, which are positive in case of a shift to the right (i.e. transformation to a chemical element with a higher atomic number e.g. by nuclear electron emission), and negative in case of a shift to the left (i.e. transformation to a chemical element with lower atomic number e.g. by nuclear emission of a ß⁺-particle). The energy levels of the nuclei are represented by horizontal lines. The amount of energy change is indicated at the right of the energy levels either in units of keV or MeV.

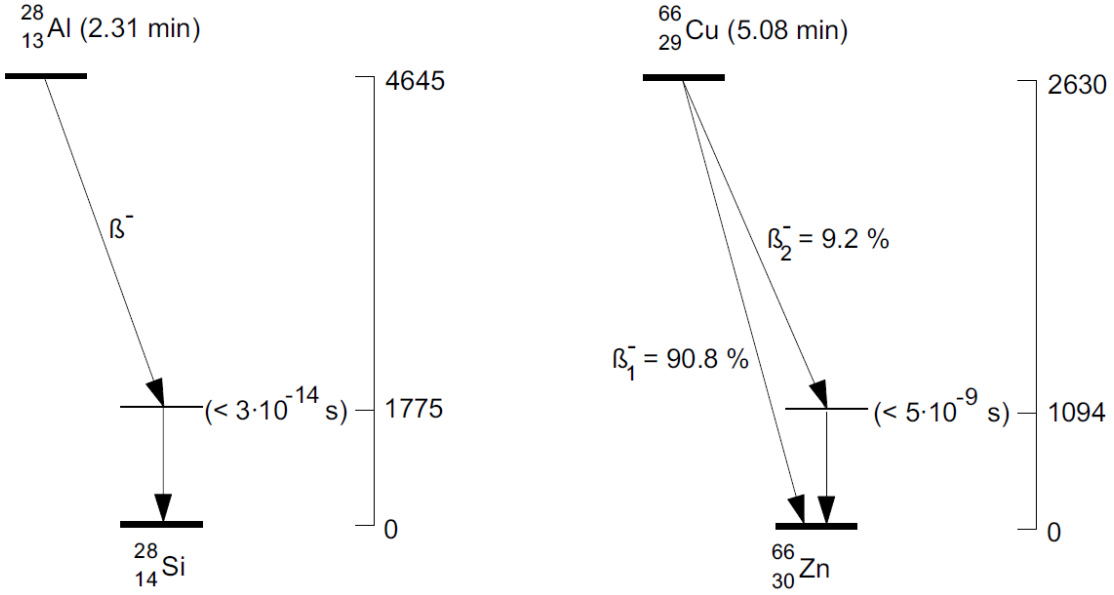


Fig. 1, Examples of decay schemes (for $^{28}_{13}Al$ and $^{66}_{29}Cu$)

2.4. Mathematical Description of the Production and Decay of Radionuclides

Initially, the number of capture reactions per time and volume units occurring in the activation material need to be quantified. The number of activations per second occurring in a cubic centimeter of sample material is called the activation rate **R** and can be determined according to the following equation:

$$R = N \cdot \sigma \cdot \Phi \qquad \textbf{(1)}$$

with **N** being the number of atomic nuclei per cm^3 in the activation material. N can be determined according to:

$$N = N_L \frac{\rho}{AG} \qquad \textbf{(2)}$$

with the LOSCHMIDT constant $\mathbf{N_L} = 6.025 \times 10^{23}$ mol^{-1}, the density ρ, and the atomic mass **AG** of the activation sample.

The microscopic cross section σ is an expression for the probability of the occurrence of a nuclear capture reaction of a neutron. σ may be understood as the interaction area of a nucleus facing the incident neutron. However, this area is not equivalent to the geometric cross section of the nucleus, it can be orders of magnitude bigger or smaller. If a neutron hits this area, a nuclear reaction occurs. Since σ is related to the facing area of a nucleus, it is measured in units of 10^{-24} cm^2. This unit is called the barn and is abbreviated with b ($1b = 10^{-24}$ cm^2). The exact value of σ is determined through evaluation of the probability of the nuclear reaction which is, among others, a function of the velocity (i.e. the energy) of the incident neutron.

A cross section exists for any type of nuclear reaction. Thus, in addition to cross sections for activation (i.e. neutron capture) reactions, cross sections can be defined e.g. also for elastic or inelastic scattering or fission. Finally, the total cross section is the sum of all partial cross sections associated with all possible nuclear reactions.

The product $N \cdot \sigma$ is called macroscopic cross section Σ. In contrary to σ its unit is a reciprocal length, and the reciprocal value of Σ is the mean free path **l** of a neutron in the sample material.

$$\Sigma = N \cdot \sigma \qquad l = 1/\Sigma \qquad \textbf{(3)}$$

Φ is the neutron flux density that accounts for the number of neutrons crossing an assumed area of 1 cm^2 per second at the place of irradiation, i.e. the measuring unit for the neutron flux density is thus $1/(cm^2 \cdot s)$.

In the core of a thermal nuclear research reactor, the neutron flux density is on the order of 10^7 $cm^{-2}s^{-1}$) for zero-power reactors and about 10^{13}–10^{15} $cm^{-2}s^{-1}$ in more powerful research reactors.

In order to calculate the number of radioactive nuclei that exist after the irradiation time t_{irr} it would be wrong simply to multiply the activation rate R with t_{irr}, because in the same time when new activations occur already previously activated nuclei can decay. Thus, it is necessary to take into account both, creation and decay of radioactive nuclei simultaneously.

First, the pure decay behaviour of an existing activated nuclide will be discussed.

K shall be the number of existing radioactive nuclei in a sample. The activity **A** is defined as the number of decays occurring in a time unit, which is thus equivalent to the decrease of existing radioactive nuclei K per time unit dt. Atomic decay reactions are distributed statistically, and consequently, the activity is proportional to the number of existing nuclei K:

$$A = -\frac{dK}{dt} = \lambda \cdot K \qquad \textbf{(4)}$$

This is the differential equation of the radioactive decay with the decay constant λ, which is associated with the half-life $\mathbf{T_{1/2}}$ as:

$$\lambda = \frac{\ln 2}{T_{1/2}} \qquad \textbf{(5)}$$

The solution of the differential equation (4) by separation of variables yields the well known decay law

$$K(t) = K_0 \cdot \exp(-\lambda \cdot t) \qquad \textbf{(6)}$$

with K_0 being the number of radioactive nuclei at the beginning (here: for $t_{decay} = 0$ at the end of irradiation).

In the next step, it shall be calculated how the production of radioactive nuclides during irradiation occurs. For that purpose, the decay law needs to be coupled with the activation reaction rate. Thus, in the decay differential equation one term has to be added that accounts for the constant additional supply of radioactive nuclei, which is the activation rate R:

$$\frac{dK}{dt} = -\lambda \cdot K + \Sigma \cdot \Phi \qquad \textbf{(7)}$$

In this case, the initial condition is K(t=0) = 0, which signifies that no radioactive nuclei exist before irradiation. The solution of this differential equation is:

$$K(t) = \frac{\Sigma \cdot \Phi}{\lambda} [1 - \exp(-\lambda \cdot t)] \qquad \textbf{(8)}$$

According to equation (4), A(t) = 8 · K(t), which can be introduced in equation (8), it can also be written in terms of the activity:

$$A(t) = \Sigma \cdot \Phi \cdot [1 - \exp(-\lambda \cdot t)] \qquad \textbf{(9)}$$

As obvious from this equation, the term in brackets approaches to 1 for continuing irradiation. Thus, a limiting maximum value for the activity exists, which is called the saturation activity $\mathbf{A_s}$:

$$A(t \rightarrow \infty) = A_s = \Sigma \cdot \Phi \qquad \textbf{(10)}$$

That means, when the saturation activity A_S is attained, the rate of nucleus production is equal to the rate of nucleus decay. It can easily be shown that after an irradiation time equivalent to 5 half-times of the activation material, the obtained activity already accounts for 97% of the saturation activity. In most applications, it is thus not useful to extend irradiation beyond this duration.

Now, time periods are introduced to label the time regimes during irradiation and activity decay. t_{irr} should be the irradiation time and t_{decay} the time of activity decay after end of irradiation. The number of radioactive nuclei at the end of the irradiation period can be calculated according to equation (8):

$$K(t_{irr}) = \frac{\Sigma \cdot \Phi}{\lambda} [1 - \exp(-\lambda \cdot t_{irr})]$$

To determine the number of active nuclei during the activity decay period, this expression has to be inserted as K_0 in equation (6). The number of active nuclei after irradiation is thus

$$K(t_{decay}) = \frac{\Sigma \cdot \Phi}{\lambda} [1 - \exp(-\lambda \cdot t_{irr})] \cdot \exp(-\lambda \cdot t_{decay})$$

and, finally, in terms of the activity

$$A(t_{decay}) = \Sigma \cdot \Phi \cdot [1 - \exp(-\lambda \cdot t_{irr})] \cdot \exp(-\lambda \cdot t_{decay}) \quad \textbf{(11)}$$

The time behaviour of the activation process and the subsequent radioactive decay after the end of irradiation is presented in Fig. 2.

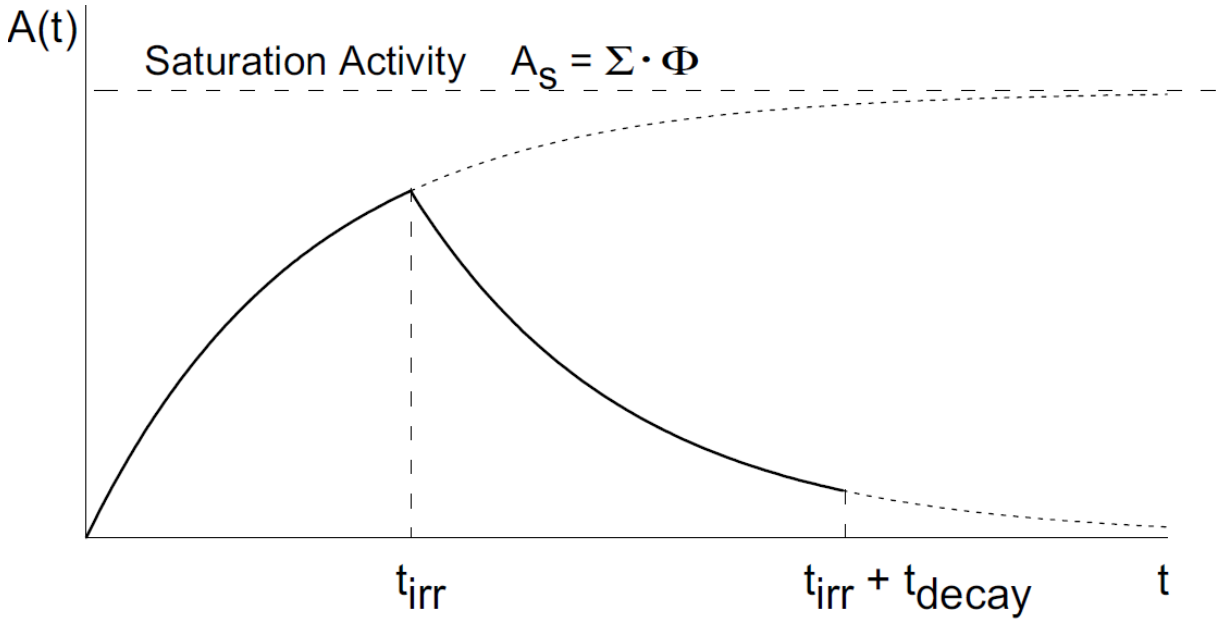


Fig. 2, Time dependence of the activation and the decay of a radionuclide

2.5. Neutron Self-Absorption

For calculation of the reaction rate in the material to be activated, equation (1) can only be applied accurately, if the neutron flux density does not decrease within the sample. However, this is the case in most applications as shown schematically in Fig. 3. The figure has to be understood in a way that the incident neutrons impinge perpendicularly on the plate from the left. If solely absorption and no scattering reactions take place the following relation for the decrease of neutron flux density is applicable:

$$\Phi(x) = \Phi_0 \cdot \exp(-\Sigma \cdot x) \qquad \textbf{(12)}$$

with **Σ** being the macroscopic cross section for absorption and **x** the distance from the plate surface.

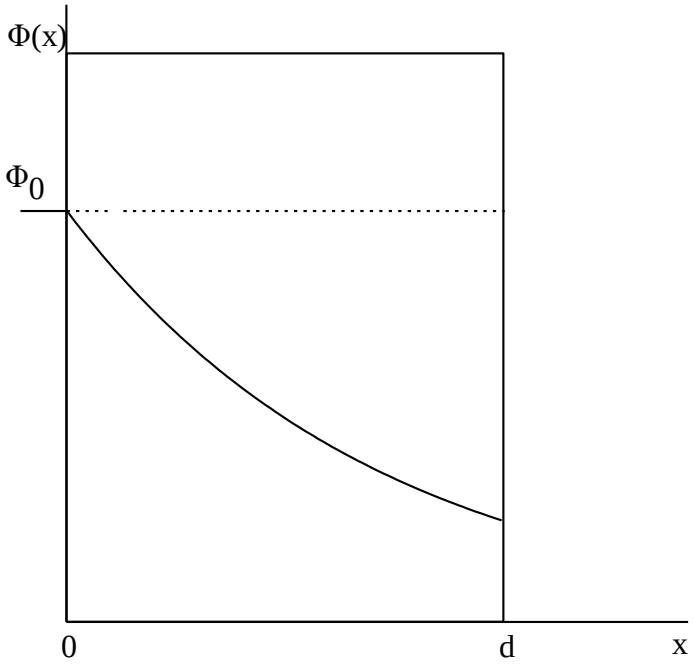


Fig. 3, Decrease of neutron flux density inside of a neutron absorbing material of thickness d (neutron self-absorption)

Such absorptions always occur during irradiation experiments since the extent of the irradiated samples is never infinitesimal small in any direction. Furthermore, calculation of the shielding effect for irradiation applications usually proves to be even more complicated than equation (12) suggests since the incident neutron flux exhibits a non-homogeneous angular distribution. Also, the sample shape may differ from easily describable geometries such as flat plates.

In general, it can be concluded that neutron self-absorption effects are significant if

a) The macroscopic cross section is high and/or
b) The samples are very thick.

3. Generic Safety Measures for Experiments at Training Reactor AKR-2

The AKR-2 is operated with an operation license according to the German Atomic Energy Act and must respect the rules of the Radiation Protection Ordinance.

The reactor is located inside a controlled area where the following rules are mandatory in general:

- Any visitor has to show a valid ID card for identification in case of first entry,
- Minimum age of participants in the exercises is 16 years,
- Pregnant women are not allowed to work at the reactor,
- Visitors have to wear lab overcoats and overshoes inside the controlled area,

- Visitors have to wear personal electronic dosimeters provided by reactor staff,
- Visitors must NOT eat, drink, smoke inside the reactor hall,
- If leaving the controlled area, visitors must check that not any contamination on hands and shoes is detected,
- All visitors are required to follow the instructions of the reactor staff.

It is required that visitors confirm this instruction by their signature in the reactor logbook.

In all experiments, the rules of the ALARA principle must be respected. Ambient dose rates for gamma rays as well as for neutrons must be measured by suitable mobile devices available at the reactor site.

In some experiments, irradiation of samples will be carried out in the horizontal experimental channel no. 3, which goes immediately through the graphite reflector tangentially to the reactor core. The cover plate in front of the irradiation channel and the inserted radiation shielding plugs must be removed. At the open channel, radiation dose rates for both, neutrons and gamma rays must be determined and discussed with the supervisor with respect to radiation protection limits and measures. Wipe tests on surfaces inside the irradiation channel have to be carried out and evaluated immediately, in order to guarantee that no contamination is detectable.

If necessary, further safety rules that apply for the exercise will be given by the operating staff.

4. Experimental Procedure

4.1. Choice of Materials to Be Activated

As mentioned above, three radiological properties are decisive for the choice of materials for irradiation: the type of emitted radiation, the radiation energy and the half-life of the radionuclide. Additionally, other practical issues can influence the choice such as easy handling, temperature resistance, availability, solubility, and low toxicity.

In the experiment carried out here disc-shaped samples of 1 mm thickness and approximately 30 mm diameter of two different materials will be activated: aluminum and copper. Its densities are 2.70 g/cm^3 and 8.92 g/cm^3, respectively. The masses of the samples are engraved on the discs in the unit of grams [g]. A third sample of unknown material is to activate, too, and to identify on base of the measured half-life (simple kind of neutron activation analysis (NAA)).

Necessary data for activation and analysis of aluminium and copper are summarised in Table 1. As obvious from Table 1, two isotopes with different half-lives are being activated in the copper sample. This has to be considered while evaluating its decay curve.

Chemical element	Nuclide to be activated	Fraction in element	$\sigma(n_{th},\gamma)$	Activated nuclide	$T_{1/2}$	Emitted radiation of the nuclide
Al	$^{27}_{13}Al$	100 %	0.215 b	$^{28}_{13}Al$	2.3 min	2.87 MeV β^- 1.78 MeV γ
Cu	$^{63}_{29}Cu$	69.1 %	4.3 b	$^{64}_{29}Cu$	12.8 h	0.57 MeV β^- 0.66 MeV β^+ 1.35 MeV γ
	$^{65}_{29}Cu$	30.9 %	2.1 b	$^{66}_{29}Cu$	5.1 min	2.63 MeV β^- 1.5 MeV β^- 1.04 MeV γ

Table 1, Activation and decay data for aluminium and copper

4.2. Start of the Reactor and Activation of the Samples

The safety check of the reactor has to be made and the reactor needs to be started. It should reach criticality at a power of 2 W.

Irradiation will be carried out in the horizontal experimental channel no. 3, which goes imme-diately through the graphite reflector tangentially to the reactor core. The cover on the irradiation channel and the inserted radiation shielding plugs have to be removed. At the open channel, radiation dose rates for both, neutrons and γ-rays have to be determined and discussed with the supervisor with respect to radiation protection measures.

Then the first sample can be inserted by using a manipulator. The depth of insertion is 1.25 m. At this depth, the sample is placed immediately next to the core of the reactor.

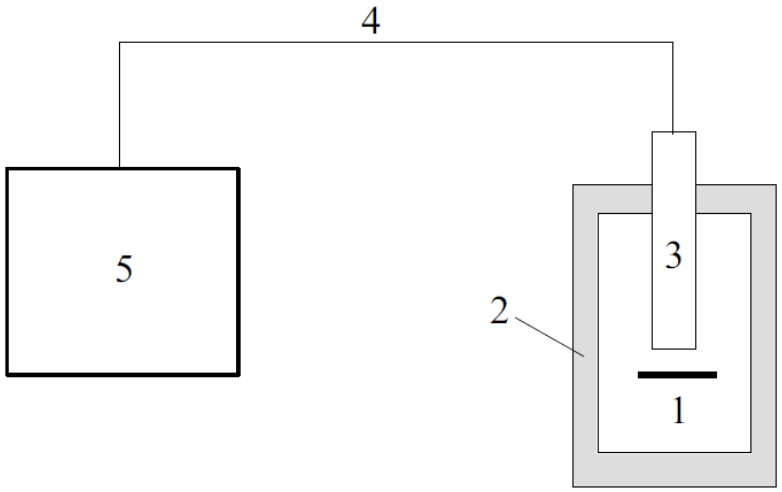
The half-lives of the activated isotopes of aluminum and copper account for only several minutes, which results in a steep decline of radioactivity after the end of irradiation. Therefore, the samples have to be irradiated one after another and immediately measured after the end of irradiation. The irradiation time for both samples is 10 min, respectively.

4.3. Evaluation of the Experiment

4.3.1. Description and Configuration of the Measurement Equipment

The γ -radiation of the activated Al and Cu nuclei has to be measured in dependence on decay time. For radiation detection a scintillator is available. Upon incident irradiation, flashes (scintillations) occur in the scintillator due to atomic interactions. These scintillations are converted into photoelectrons in a secondary multiplier phototube (so-called photomultiplier) by the photoelectric effect.

Between the cathode and the anode of the photomultiplier, several intermediate electrodes (so-called dynodes) are installed. Between each two dynodes, a part of the high-voltage of the photomultiplier is applied. Therefore, the incident electrons are accelerated in such a way that they sputter more electrons in the next dynode (collision ionisation). Thus, the photomultiplier serves to convert scintillations into electric current and voltage signals amplifying them with very low noise. The voltage pulses are further amplified in a subsequent electronic amplifier and counted by a pulse counter. The measurement setup is shown schematically in Fig. 4.



1 Radioactive sample
2 Radiation shielding (lead)
3 Measuring head VA-S-50 with fotomultiplier and scintillator
4 Cable connection
5 Radiation measuring device 20046

Fig. 4, Experimental setup

The following parameters are set at the radiation measurement device:

Threshold (Pegel):	5.7 V
High-Voltage (Hochspannung):	-1140 V (5.70 at the potentiometer)
Amplification (Verstärkung):	22 dB
Measuring time (Messzeit):	6 s = 1×10^{-1} min
Channel width (Kanalbreite):	DIS

The main purpose of the lead shielding around sample and detector is not to shield radiation from inside the apparatus, but rather to absorb background noise from the exterior surroundings due to reactor operation. Without shielding, this background would result in a high number of noise pulses.

4.3.2. Measurement of the Radioactive Decay of Activated Samples

Before measuring the activated samples, the background radiation has to be measured 5 times during 6 s each, which of the average is calculated. Background radiation impinging on the shielded scintillator results in a continuous noise in the measurement signal that needs to be subtracted for evaluation of the underlying radiation of the activated samples.

The samples irradiated in the reactor are removed from the reactor channel after exactly 10 min of irradiation time and immediately put on the sample holder beneath the scintillator for radiation measurement. The time of the end of sample irradiation has to be exactly recorded and will be taken as the point of origin of the time of decay.

The number of pulses has to be measured for exactly 6s (preset at measuring device), respectively, after time increments of 0.5 minutes for 10 to 15 min after the end of irradiation. The measured time dependence of the count rate has to be illustrated in a graph, after background correction, both, on linear and logarithmic ordinate scale.

4.3.3. Determination of Half-Lives

The half-lives of the copper isotope ^{66}Cu and for ^{28}Al have to be determined based on the obtained decay curve. Subsequently, the decay curve and the half-life determined for the unknown activated material under investigation will help to identify the material and its composition. This will show the possibility of identifying unknown materials by NAA.

For every half-life calculation the error bars have to be estimated. Every measured count rate is subject of a statistical error. Statistical analysis based on the POISSON probability distribution show that the count rate of Z can be measured with a statistical error of $\Delta Z = \pm \sqrt{Z}$.

The thereby determined error bars should be included in the graph of measured values to illustrate the range of possible decay curves and of the half-lives that can be derived based on the measurements.

4.3.4. Calculation of the Neutron Flux Density at the Point of Irradiation

The relation between neutron flux density Φ at the point of irradiation in the reactor and the sample activity per volume at the end of irradiation is given through equation (9) if $t = t_{irr}$. For evaluation, the decay curve needs to be extrapolated to the point of origin $t_{decay} = 0$, equivalent to the activity at t_{irr}. The volumic activity obtained by equation (9) has to be still multiplied by the sample volume to obtain the total activity.

However, this value is not yet equivalent to the activity of the sample, but only proportionally related. The proportionality factor includes a geometry factor and the counting efficiency of the scintillator: Part of the emitted radiation from the sample is not counted in the detector because it is directed to the bottom or the sides without penetrating the scintillator (geometry factor), and not all of the emitted species that impinge on the scintillator cause a pulse (energy-dependent counting efficiency). Previously, this proportionality factor has been experimentally determined as $C \approx 0.01$.

Considering this information, equation (9) can be rewritten as

$$Z(t_{irr}) - n_0 = C \cdot V \cdot A(t_{irr}) = C \cdot V \cdot \Sigma \cdot \Phi \cdot [1 - \exp(-\lambda \cdot t)] \qquad \textbf{(13)}$$

$Z(t_{irr})$ is the measured count rate extrapolated for $t_{decay} = 0$.
n_0 is the background noise that has to be subtracted from the measured count rate.

Additionally, it has to be considered that in natural copper, the ^{65}Cu nuclei account for only 30.9% of the total. For calculation of the neutron flux density, equation (13) can thus be rewritten as:

$$\Phi = \frac{(Z(t_b) - n_0) \cdot AG}{C \cdot m \cdot 0.309 \cdot N_L \cdot \sigma \cdot [1 - \exp(-\lambda \cdot t_b)]} \qquad \textbf{(14)}$$

<u>Remark</u>: Of course, also the activated isotope ^{64}Cu contributes to the measured count rate as well. However, as calculated in question to ask no. 9, the contribution accounts for less than 10% of the total count rate and shall thus be neglected in the calculations performed in this task.

5. Radiation Protection

Handling of radionuclides requires particular protection and safety measures in order to exclude any danger to the health of the involved personnel and to prevent uncontrolled distribution of radioactive materials. To ensure strict compliance with radiation protection measures, every involved person has to get accustomed to the particular working technologies required when handling radioactive sources. This involves an extensive learning process to which any person needs to get accustomed to, who is frequently exposed to radionuclides.

For this experiment, the following rules need to be respected in particular:

1. Perform a wipe test in order to confirm that the irradiation channel is free of contamination.

2. Never stand right in front of the open irradiation channel. Approach the channel and insert the sample from the side.

3. When walking around the reactor, avoid passing the open irradiation channel.

4. Before performing the experiment, thoroughly plan the working steps to minimise the time of handling the activated samples.

5. Do not touch the activated sample bare-handed, but use a pincer or forceps. Wear gloves while handling the sample.

6. Questions to Answer

1. What does radioactivity mean?

2. What do the terms element, isotope, nuclide mean?

3. What is the difference between natural and artificial radioactivity?

4. What information is available from a decay scheme?

5. Which properties are decisive to select a radionuclide for a specific purpose?
   Discuss by using the example of a liquid level measurement of a storage container or the intake of a radioactive medicament as a tracer.

6. Determine the percentage of the saturation activity reached by a sample irradiated 2, 4, or 7 times its half-life. Derive for how long a nuclide should be irradiated for its activation.

7. Determine the probability for a thermal neutron to reach the center of a 1 mm thick copper or gold sample if it impinges perpendicular the probe surface.
   ($\sigma(n_{th},\gamma)$ for Au-197 = 98.7 b, ρ= 19.3 g/cm^3)

8. Which peculiarity of natural copper has to be considered when drawing the decay curve (elemental composition)?

9. Calculate the activity of both irradiated samples (copper and aluminum) after 10 minutes of irradiation with an estimated neutron flux density of $\Phi_{th} = 10^7$ cm^{-2}s^{-1}). Why is the count rate measured with the measurement equipment lower than the calculated value ?

10. Describe qualitatively the radiation detection process in a scintillator and a photomultiplier.

Protocol for Experiment
"Activation and Decay of Radioactive Nuclides"

Date:

1. Measurement of background radiation (5 measurements for 6 s each)

Number of measurement	Measured value

Average value (=N_0):

2. Determination of half-life

Decay time /min	Al: N_i	Al: $N_i - N_0$	Cu: N_i	Cu: $N_i - N_0$	X: N_i	X: $N_i - N_0$
0						
0.5						
1.0						
1.5						
2.0						
2.5						
3.0						
3.5						
4.0						
4.5						
5.0						
5.5						
6.0						

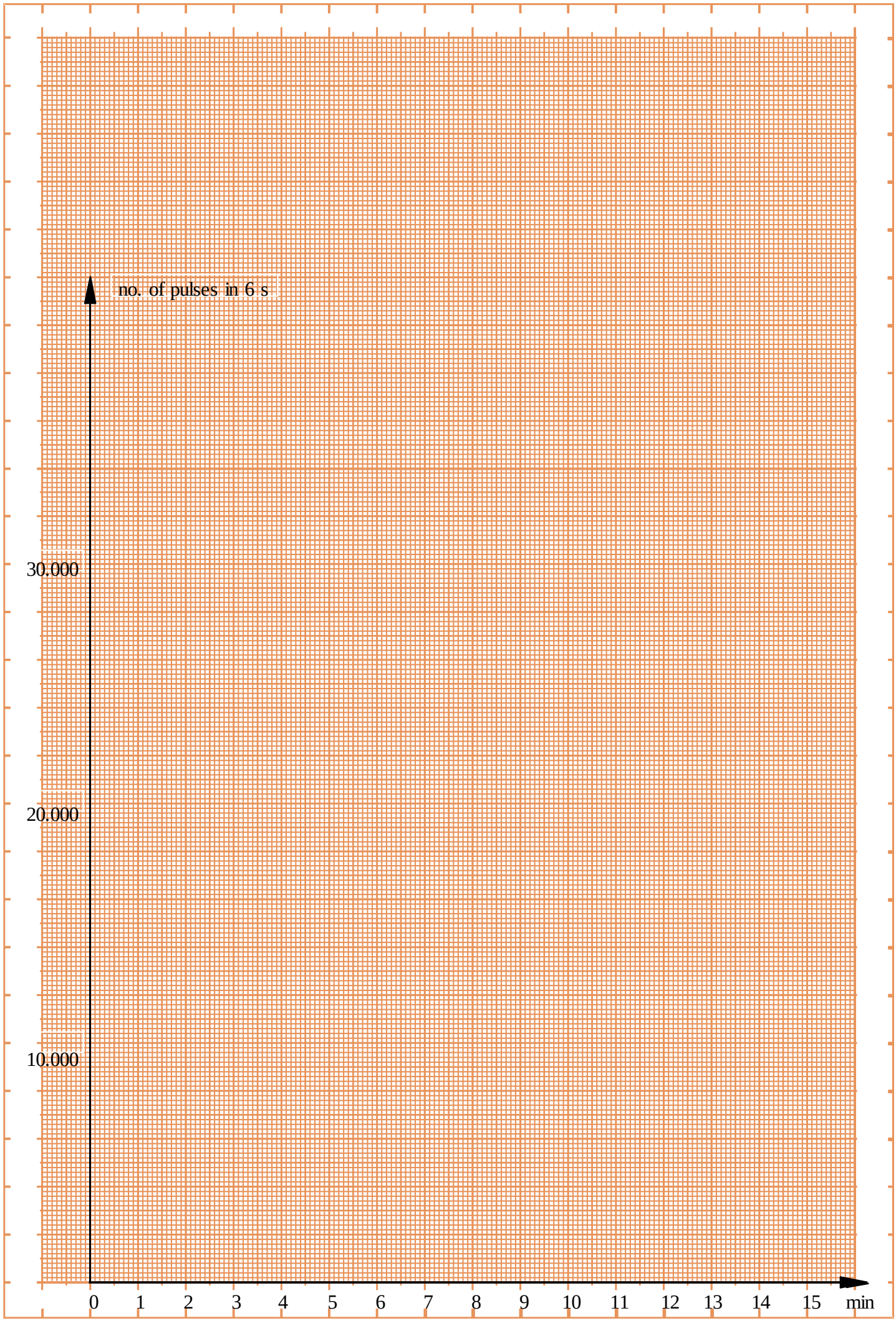
Decay time /min	Al: N_i	Al: $N_i - N_0$	Cu: N_i	Cu: $N_i - N_0$	X: N_i	X: $N_i - N_0$
6.5						
7.0						
7.5						
8.0						
8.5						
9.0						
9.5						
10.0						
10.5						
11.0						
11.5						
12.0						
12.5						
13.0						
13.5						
14.0						
14.5						

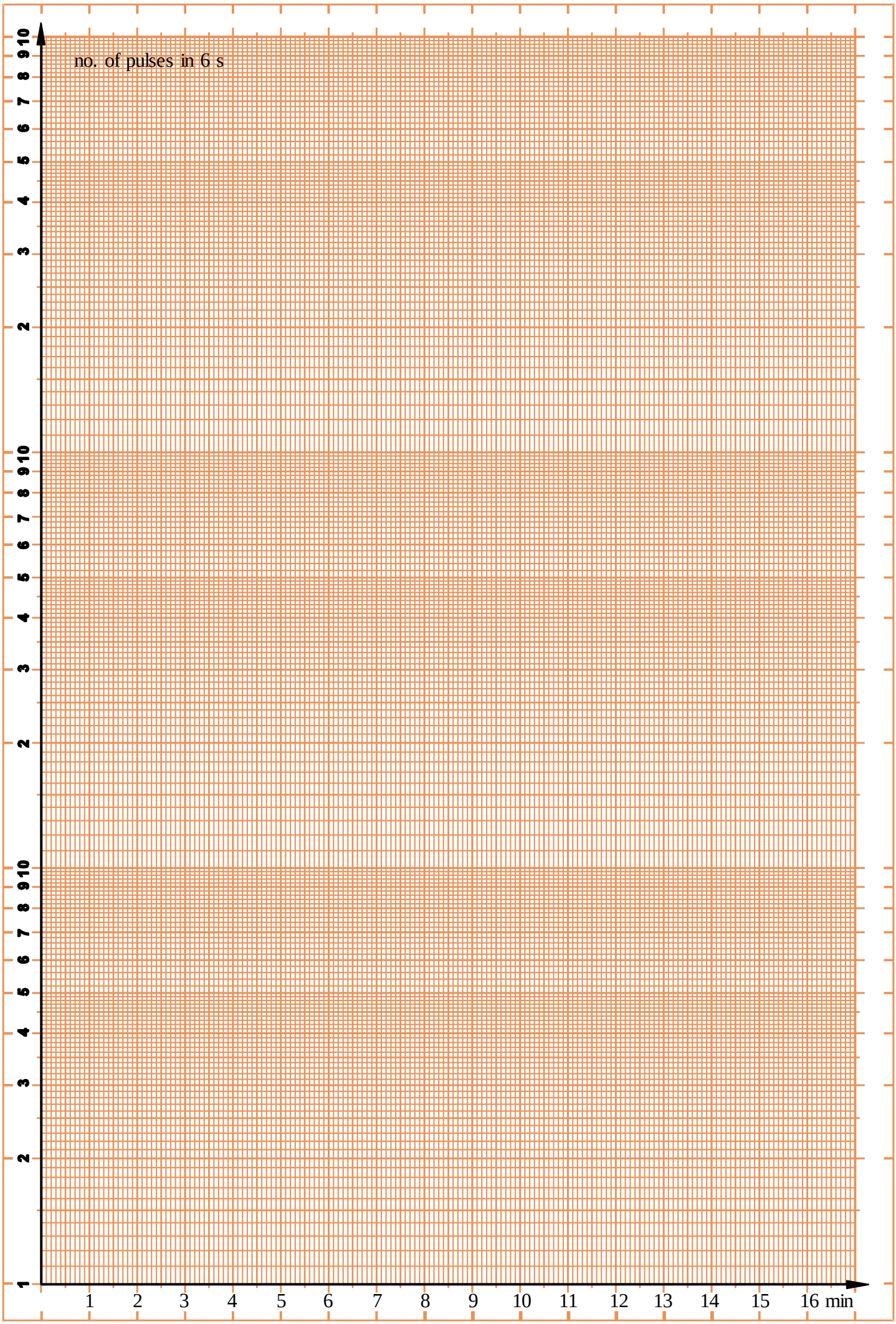
Results:

Half-life (Al):

Half-life (Cu):

Half-life (X):


no. of pulses in 6 s
30.000
20.000
10.000
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
min


no. of pulses in 6 s
1 2 3 4 5 6 7 8 9 10
1 2 3 4 5 6 7 8 9 10
1 2 3 4 5 6 7 8 9 10
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 min