IIA8

Modul Atom/Nuclear Physics

Half-life

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1.1 Preparation questions

- What is meant by ionizing radiation? What types of ionizing radiation exist? What dangers arise from the different types of ionizing radiation? How can one protect oneself?
- What is an isotope? What is meant by isotopic abundance? Why must this be taken into account in this experiment?
- What is meant by the term half-life? How can the half-life of a given nuclide be changed?
- How can a short or a long half-life be determined?
- How does a counter tube work? What is meant by the response sensitivity of a counter tube?
- What is a background count rate? Why is it important to know this?

1.2 Introduction

Atoms whose nuclei contain the same number of protons but a different number of neutrons are called *isotopes*. All atomic species of the same isotope have the same atomic number and therefore represent the same element. The number of neutrons and thus also the mass numbers of the isotopes vary. Chemically, isotopes behave almost identically.
Potassium is a chemical element with the atomic number 19. This means it has 19 protons in its nucleus. In the Earth's crust, potassium is among the ten most common elements and occurs in many minerals.
There are several isotopes of potassium: ^{39}K is stable, ^{38}K has a half-life of about eight minutes, while ^{40}K has a very long half-life. The number preceding the element's symbol is the mass number. For example, the radioactive ^{40}K has a mass number of 40. The difference between the mass number and the atomic number corresponds to the number of neutrons; for ^{40}K, that would be 21. In the literature, the half-life of ^{40}K is given as $T_{1/2} = 1.27 \cdot 10^9$ years. This is shorter than the age of our solar system and is therefore, by definition, not considered stable. This experiment is intended to illustrate what is meant by the term half-life and to address the question of how such a long half-life, like that of ^{40}K, can be measured.

1.3 Theory

1.3.1 Activity and decay law

The *activity* A of a radioactive substance containing N atoms is the number of nuclear decays per time interval t. It is given in the physical unit Becquerel [Bq], where 1 Bq corresponds to one nuclear decay per second. The following applies:

$$A(t) = -\frac{\mathrm{d}N(t)}{\mathrm{d}t}. \tag{1.1}$$

The *decay constant* λ indicates the probability per time interval that an atomic nucleus will decay. Therefore, the activity A of a substance containing N atoms at time t can be expressed as

$$A(t) = \lambda \cdot N(t). \tag{1.2}$$

By integrating equation 1.1, the decay law follows:

$$N(t) = N_0 \cdot e^{-\lambda t}. \tag{1.3}$$

Here, N_0 is the number of atoms of the radionuclide at time $t = 0$. The activity is proportional to the number of radioactive atoms in the sample. Therefore, the activity follows the same decay law as N. From equations 1.1 and 1.2, together with $A_0 = \lambda \cdot N_0$, it follows directly that

$$A(t) = A_0 \cdot e^{-\lambda t}.$$

Note that the magnitude of a source's activity does not directly indicate its toxic effect on living organisms. The radiation from radioactive decays is differently harmful depending on the type (alpha, beta, or gamma radiation) and the kinetic energy.

1.3.2 Half-life

The radioactive decay of a given radionuclide proceeds exponentially, as shown in equation 1.3. The *half-life* $T_{1/2}$ is the period of time in which the amount and thus the activity of a given radionuclide are reduced by half due to decay. This means:

$$N(t = T_{1/2}) = \frac{N_0}{2}. \tag{1.4}$$

According to equation 1.3, we also have:

$$N(t = T_{1/2}) = N_0 \cdot e^{-\lambda \cdot T_{1/2}}. \tag{1.5}$$

Setting equations 1.4 and 1.5 equal yields:

$$\frac{N_0}{2} = N_0 \cdot e^{-\lambda \cdot T_{1/2}}.$$

This can be solved for the half-life $T_{1/2}$. The relationship between the half-life and the decay constant is given by:

$$T_{1/2} = \frac{\ln(2)}{\lambda}. \tag{1.6}$$

With equation 1.2, one directly finds:

$$T_{1/2} = \frac{\ln(2)}{A} \cdot N. \tag{1.7}$$

This means that during one half-life, half of the atomic nuclei transform into another nuclide while emitting ionizing radiation. The half-life is a fixed, characteristic quantity for each nuclide and cannot be altered.
The exact moment at which an individual atomic nucleus decays cannot be predicted. Only the probability of a transformation per time interval can be given by the decay constant λ. The probability that a given nucleus decays within the first half-life is 50%, within the first two half-lives $50\% + 25\% = 75\%$, and so on.

1.3.3 Partial half-life

If several competing (parallel) decay modes k of a nucleus are possible, with $k = 1, ..., n$, and decay mode k occurs with probability α_k, then the decay constant of decay mode k is called the partial decay constant λ_k. The total decay constant λ is the sum of the partial decay constants λ_k as follows:

$$\lambda = \lambda_1 + \lambda_2 + ... + \lambda_n = \sum_{k=1}^{n} \lambda_k \qquad \text{mit} \qquad \lambda_k = \alpha_k \cdot \lambda. \tag{1.8}$$

The sum over all possible occurrence probabilities α_k is by definition equal to one:

$$\sum_{k=1}^{n} \alpha_k = 1.$$

Furthermore, the partial half-life for *one* individual decay mode $T_{1/2,k}$ is, analogously to equation 1.6, given by:

$$T_{1/2,k} = \frac{\ln(2)}{\lambda_k}. \tag{1.9}$$

From equations 1.8 and 1.2, it follows that:

$$T_{1/2,k} = \frac{\ln(2)}{\alpha_k \cdot \lambda} = \frac{\ln(2) \cdot N}{\alpha_k \cdot A}.$$

With equation 1.7, this yields:

$$T_{1/2,k} = \frac{T_{1/2}}{\alpha_k}.$$

This can be rewritten as:

$$T_{1/2} = \alpha_k \cdot T_{1/2,k}.$$

Substituting equation 1.9 gives:

$$T_{1/2} = \alpha_k \cdot \frac{\ln(2)}{\lambda_k}. \tag{1.10}$$

Analogously to equation 1.2, the partial activity A_k, i.e., the number of decays through the kth decay mode, can be given by:

$$A_k(t) = \lambda_k \cdot N(t).$$

Thus, equation 1.10 can be written as:

$$T_{1/2} = \alpha_k \cdot \frac{\ln(2)}{A_k} \cdot N. \tag{1.11}$$

To determine the half-life, various correction factors must now be considered. The following subsections provide an overview.

1.3.4 Solid angle correction

The radioactive source emits radiation in all directions — upwards, downwards, to the left, etc. The detector is located at a certain distance above the source. It therefore covers only a small solid angle — only the radiation emitted upwards in the direction of the detector can be measured. The purpose of the solid angle correction is to extrapolate from the measured solid angle Ω to the total emission.
The solid angle Ω is defined as the surface area of a right circular cone (light gray in Figure 1.1) whose apex coincides with the center of the sphere. The angle θ is the half opening angle at the cone's apex. The solid angle is then given by

$$\begin{aligned}\Omega &= \int_0^{2\pi} \int_0^{\theta} \sin(\theta')\,\mathrm{d}\theta'\,\mathrm{d}\phi = \int_0^{2\pi} \mathrm{d}\phi \int_0^{\theta} \sin(\theta')\,\mathrm{d}\theta' = 2\pi \cdot \int_0^{\theta} \sin(\theta')\,\mathrm{d}\theta' \\ &= 2\pi \cdot (1 - \cos(\theta)).\end{aligned} \tag{1.12}$$

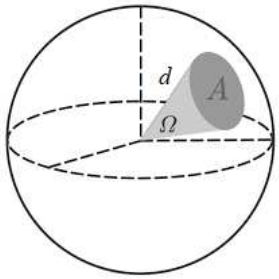

Figure 1.1: Imagine the radioactive source located at the center of a sphere, emitting in all directions. The detector is placed at a distance d from the source. The entrance window of the detector has an area A. Then the solid angle Ω is given as the surface area of the cone whose apex is at the position of the source.

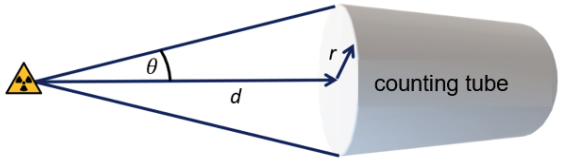

Figure 1.2: The counting tube is located at a distance d from the source, which is positioned at the apex of the cone. The half opening angle is θ. The opening window of the counting tube has a radius r and thus an entrance area $A = \pi \cdot r^2$.

From Equation 1.12, for a counting tube with window radius r and distance d from the source, under the assumption $r \leq d$ and using the relation

$$\cos(\theta) = \frac{\text{Adjacent}}{\text{Hypotenuse}} = \frac{d}{\sqrt{d^2 + r^2}},$$

where the hypotenuse is determined using the Pythagorean theorem, one directly obtains

$$\begin{aligned}\Omega &= 2\pi \cdot \left(1 - \frac{d}{\sqrt{d^2 + r^2}}\right) = 2\pi \cdot \left(1 - \frac{d}{d \cdot \sqrt{1 + \left(\frac{r}{d}\right)^2}}\right) = 2\pi \cdot \left(1 - \frac{1}{\sqrt{1 + \left(\frac{r}{d}\right)^2}}\right) \\ &\approx \pi \cdot \left(\frac{r}{d}\right)^2. \end{aligned} \tag{1.13}$$

For the last approximation, a Taylor expansion was used. For small x it holds that

$$\frac{1}{\sqrt{1+x}} \approx 1 - \frac{1}{2} \cdot x \qquad \text{with} \qquad x = \left(\frac{r}{d}\right)^2.$$

Thus, the solid angle Ω is obtained. The solid angle of a unit sphere is $\Omega_E = 4\pi$, which can be found from Equation 1.13 when integrating from 0 to π instead of 0 to θ in the second integral. The solid angle correction factor f_W is therefore calculated as

$$f_W = \frac{\Omega}{\Omega_E} = \frac{\Omega}{4\pi} = \frac{1}{4} \cdot \left(\frac{r}{d}\right)^2. \tag{1.14}$$

1.3.5 Dead time correction

The dead time τ of a detector refers to the time interval immediately following the detection of a particle, during which the detector is not yet ready to register another particle. As a

result, if two or more particles arrive in quick succession, only the first one is detected. Let s be the count rate and τ the dead time. The fraction of events lost due to the dead time must correspond to the fraction of the total dead time relative to the measurement duration. This yields the correction factor f_τ for the dead time as

$$f_\tau = 1 - s \cdot \tau. \tag{1.15}$$

The dead time of the PHILIPS counting tube in the form used for this experiment is approximately $\tau = 190, \mu s$.

1.3.6 Backscatter correction

Due to scattering at the shielding lead wall, particles can enter the counting tube that originally had completely different directions. This effect is particularly relevant for beta radiation. The magnitude of the backscatter factor f_R depends on the wall thickness and the material of the surroundings, i.e., the wall of the measurement chamber. Saturation is reached when the wall thickness of the measurement chamber is approximately one third of the maximum range of the beta radiation in the corresponding material. The range of beta radiation in lead is on the order of one millimeter, while the lead wall thickness is about 2 centimeters. Therefore, it is reasonable to assume that saturation is reached.

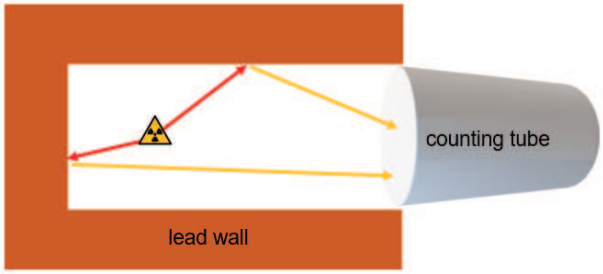

Figure 1.3: Beta radiation can be scattered at the lead wall of the measurement chamber and enter the counting tube indirectly. In this way, the counting tube will register more events than it would if the lead wall were not present.

In this experiment, the wall of the measurement chamber is made of lead for shielding purposes. The saturation value for the backscatter factor in lead is $f_R = 1.8$. For iron, the saturation value of the backscatter factor would be 1.5, and for aluminum 1.3.

1.3.7 Self-absorption correction

Self-absorption occurs in thicker samples. It is possible that beta particles are shielded by the sample material itself, as shown in Figure 1.4. The self-absorption correction factor f_S depends on the sample material (here KCl) and the thickness h of the sample. It is calculated as

$$f_S = \frac{1}{\mu \cdot h}. \tag{1.16}$$

Here, μ is the mass absorption coefficient, which depends on the material. For beta particles from ^{40}K with an energy of $1.311, \mathrm{MeV}$, it is $\mu = 0.0115\,\mathrm{cm}^2/\mathrm{mg}$. The quantity h is the areal density in $\mathrm{g/cm}^2$ of potassium in the measurement dish.

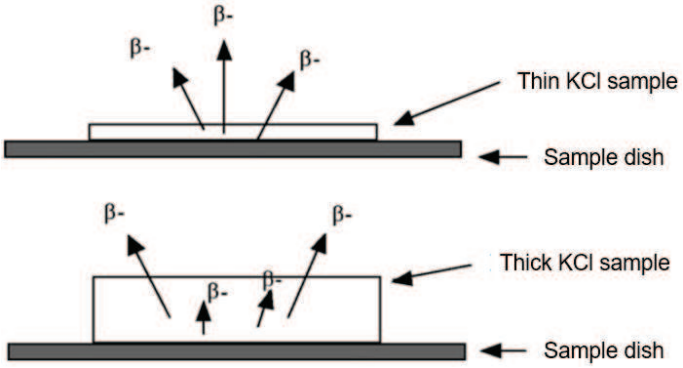

Figure 1.4: The upper image shows a thin KCl sample; the lower image shows a thicker KCl sample. Both samples emit beta particles. In the thicker sample below, self-absorption occurs, meaning that some beta particles are already shielded by the overlying KCl.

1.3.8 Absorption between source and counting tube

The space between the KCl sample and the counting tube is filled with air. Since the distance d between the sample and the counting tube is very small compared to the range of beta particles in air (several meters), absorption between the source and the counting tube can be neglected. The absorption correction factor is therefore $f_A = 1$.
If the sample were farther from the counting tube or if a medium other than air were present between the sample and the detector, the absorption correction factor f_A would have to be estimated accordingly.

1.3.9 Total correction factor

The combination of all correction factors is denoted by f. It holds that

$$f = f_W \cdot f_\tau \cdot f_R \cdot f_S \cdot f_A.$$

Here, f_W is the correction factor for the solid angle, f_τ the correction factor for the dead time, f_R the correction factor for backscattering, f_S the correction factor for self-absorption, and f_A the correction factor for absorption between the source and the counting tube.

1.3.10 Detector efficiency

A counting tube does not operate perfectly; even outside the dead time, not every particle entering the detector is registered. The efficiency ε of a counting tube depends strongly on the type of radiation. While for beta radiation an efficiency of about $\varepsilon \approx 0.99$ can be assumed, the efficiency for gamma radiation is on the order of $\varepsilon \approx 10^{-2}$.

1.3.11 Determination of the half-life

The experimentally measured count rate s is related to the activity A_k of the decay type k via the total correction factor f and the detector efficiency ε. The relation is given by

$$s = A_k \cdot f \cdot \varepsilon. \tag{1.17}$$

Here, A_k is the β-decay rate, f the total correction factor, and ε the detector efficiency. Solving for A_k gives

$$A_k = \frac{s}{f \cdot \varepsilon}. \tag{1.18}$$

From Equations 1.11 and 1.18, the half-life can finally be expressed as

$$T_{1/2} = \frac{\alpha_k \cdot \ln(2) \cdot N \cdot f \cdot \varepsilon}{s}. \tag{1.19}$$

1.4 Experiment

1.4.1 Experimental equipment

The following materials are required for this experiment:

Component	Quantity
PHILIPS counting tube	1
High-voltage power supply	1
Counter module	1
Cables	3
Measuring dish	1
Sample holder	1
Caliper	1
Scale	1
KCl sample	1
Rubber gloves	1
Rack for modules	1
Dosimeter	1
Safety goggles	1

The PHILIPS counting tube is enclosed in a lead geometry (see Figure 1.5). Below the counting tube is the measurement chamber, which can be opened by a lead door. During measurements, this lead door should always remain closed.

Figure 1.5: For determining the half-life of ^{40}K, a PHILIPS counting tube is used. It is encased in lead. At the lower section is the measurement chamber, into which the samples can be inserted.

1.4.2 Potassium

The decay scheme of ^{40}K is shown in Figure 1.6. There are three decay modes (so-called decay channels) for ^{40}K. Accordingly, for the three decay types $k = 1, ..., n$, one has $n = 3$. For clarity, let $\alpha_1 = \alpha_{\beta^-}$, $\alpha_2 = \alpha_{\mathrm{EC}}$, and $\alpha_3 = \alpha_{\beta^+}$. It holds that the β^--decay has a probability of $\alpha_{\beta^-} \approx 89\%$, electron capture (EC) has a probability of $\alpha_{\mathrm{EC}} \approx 11\%$, and the rare β^+-decay has a probability of $\alpha_{\beta^+} \approx 0.001\%$. The sum of all probabilities is one, as predicted by theory:

$$\sum_{k=1}^{n=3} = \alpha_{\beta^-} + \alpha_{\mathrm{EC}} + \alpha_{\beta^-} \approx 1.$$

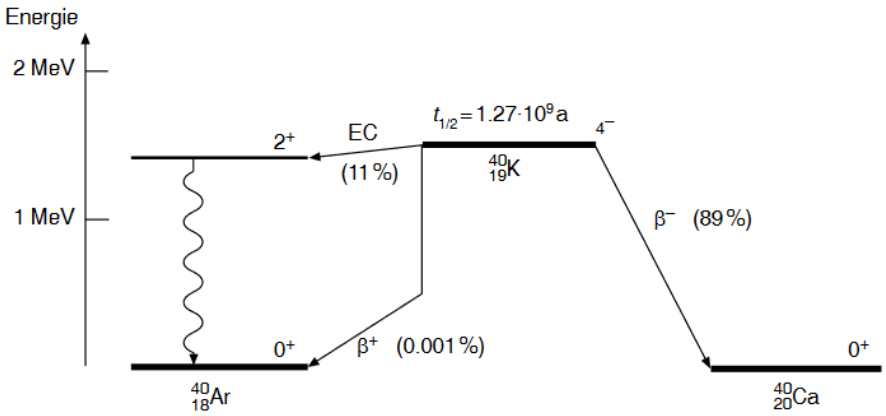

Figure 1.6: In the decay of ^{40}K, three processes compete with each other: the β^- decay to ^{40}Ca is the most probable with 89%, electron capture (EC) is the second most probable with 11%, and the β^+ decay to ^{40}Ar has a probability of only 0.001%. The excited state of ^{40}Ar produced by electron capture decays to the ground state via photon emission.

To calculate the number of ^{40}K nuclei N, both the chemical composition of the potassium salt KCl used and the natural isotopic abundance γ must be taken into account. For the radionuclide ^{40}K, this abundance is

$$\gamma_{^{40}\mathrm{K}} = 1.19 \cdot 10^{-4}.$$

This means that only one out of approximately $1/\gamma_{^{40}\mathrm{K}} = 8403$ potassium atoms is an atom of the isotope ^{40}K.

1.4.3 Counting tube

A counting tube is a cylindrical metal tube closed on both ends. It serves as the cathode, i.e., the negatively charged electrode. A wire with a diameter of about 0.1 mm runs along the cylinder axis and is led out of the tube at the rear (on the right in Figure 1.2) through an insulator. This wire acts as the anode. The diameter of the counting tube can be several centimeters.

The front base of the tube is equipped with a low-mass window that is therefore permeable to beta and gamma radiation. Mica, for example, can be used as the window material. This window is very delicate and must not be damaged under any circumstances.

The counting tube is filled with a gas. A noble gas is particularly advantageous as a filling gas because it allows especially short pulses to be produced.

A DC voltage is applied between the anode and cathode. When ionizing radiation enters, it produces free electrons in the gas filling, which are accelerated toward the anode by the electric field. Through collisions with other gas atoms, additional electrons are released, forming

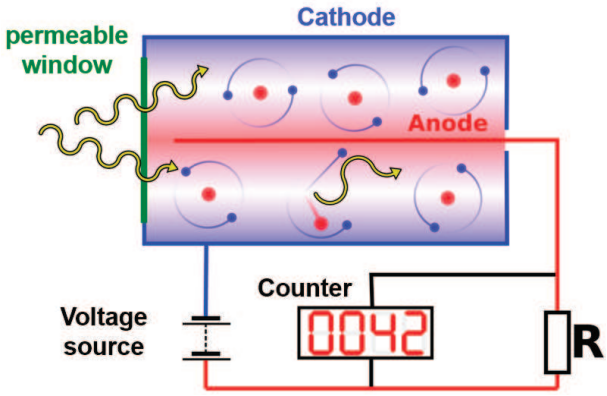

Figure 1.7: The counting tube is cylindrical. A wire runs along the cylinder axis. A voltage is applied between the cylinder (cathode) and the wire (anode). At the front is a permeable entrance window. The tube is filled with gas. Ionizing radiation causes an electron avalanche in the tube, which leads to a voltage change between the anode and cathode. This change can be measured across a resistor R and counted. The number of such pulses counted is proportional to the number of incoming particles.

electron avalanches containing up to a million electrons. This process is referred to as gas amplification. The resulting voltage change can be measured across the resistor R. A counter then registers these voltage changes as pulses.

1.5 High voltage and counter

The counting tube is powered by a high-voltage module supplying a high voltage of 580 V. This voltage must not be exceeded! The high-voltage module must be connected to the counting tube via the *GM Tube* (Geiger–Müller tube) connector and to the counter via the *Output*. To switch on the high voltage, first set the main switch on the right side of the rack to *ON*, and then set the switch at the bottom of the silver module (see Figure 1.8) to *ON* as well. The counter module is brown and located directly next to the high-voltage supply. At the top, in the *DISPLAY*, it shows the measured number of pulses (counts). However, these pulses are only counted while the *GATE* is open. This can be recognized by the red indicator light — if no light is illuminated above the word *GATE*, the gate is closed and the counter is inactive.
The duration for which this gate remains open corresponds to the measurement duration. For example, if you want to count the pulses over one minute, you must ensure that the gate remains open for one minute. This is done in the middle section of the counter under *TIMER*. Two digits light up in red there. Use the button *INC M* to change the left digit and *INC N* to change the right digit. Press each button repeatedly until the desired digit appears. The *DWELL* should remain set to *OFF*. Using the button *TIME BASE SELECT*, the indicator light should be set to *0.1 SEC*. The desired measurement time is then given by:

$$0.1\,\mathrm{s} \cdot \text{Left digit} \cdot 10^{\text{Right digit}}.$$

The *RESET* button resets the timer to zero. Then the measurement can be started with the *COUNT* button. After the measurement duration set in the *TIMER* has elapsed, the gate closes automatically and the result can be read on the *DISPLAY*. Afterwards, press the *STOP* button and reset the timer to zero again using *RESET*. A new measurement can then be started with *COUNT*, and so on.

Figure 1.8: The brown module on the left is the counter; the silver one on the right is the high-voltage supply for the counting tube. To switch on the high voltage, turn the main switch on the far right to *ON*, and then switch the high voltage to *ON* at the bottom of the silver module. A value of 580 V should be set. The output signal is to be connected to the counter. The dead time of the counting tube is approximately 190 μs.

Example: In Figure 1.8, the left digit in the *TIMER* is 6 and the right digit is 2. The counter is therefore set to a measurement time of

$$0.1\,\mathrm{s} \cdot 6 \cdot 10^2 = 60\,\mathrm{s}.$$

If a measurement is now started, the *GATE* remains open for exactly 60 seconds. After that, the display shows how many pulses the counter registered during these 60 seconds.

1.6 Experimental Procedure

The goal is to measure the specific activity of a potassium salt (KCl). Due to its low specific activity, thin sources cannot be used; instead, the β count rate s must be measured using an infinitely thick sample. From this, the half-life of ^{40}K can finally be determined. Use a measurement setup with a PHILIPS counting tube and proceed as follows:

- Switch on the high voltage. Note that this counting tube requires a voltage of 580 V, which must not be exceeded. The high voltage should be switched on at least 10 minutes before the start of the measurement to ensure stable results.
- Perform a background measurement without any source in the measurement chamber. The measurement duration should be 10 minutes.

- Ensure that the empty sample dish is inactive. You can verify this by placing the empty dish in the measurement chamber and measuring for 10 minutes. The resulting count rate should be similar to that of the background measurement.
- Weigh the empty sample dish using the most precise scale available. Also determine the possible filling height h of the dish using a caliper.
- Put on rubber gloves. Fill the previously weighed, inactive dish to the brim with KCl.

Figure 1.9: Potassium chloride is filled into the inactive sample dish up to the brim. Use a spatula for this purpose. Wear gloves and handle carefully to avoid spilling. The sample dish is then placed in a transparent sample holder.

- Determine the filled mass of the sample dish using the scale. Then place the dish into a transparent sample holder of suitable size.
- Determine the count rate of the ^{40}K sample. It should be positioned in an upper position within the measurement chamber as shown in Figure 1.10, but not at the very top. Measure the number of particles detected by the counting tube for 10 minutes.

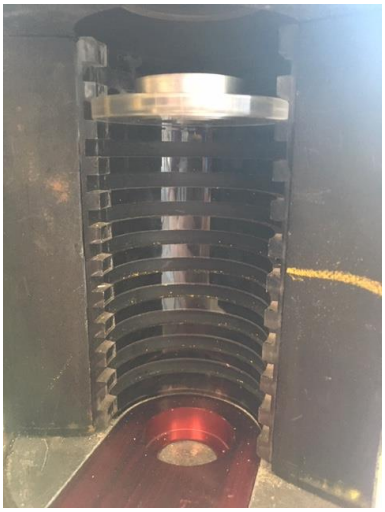

Figure 1.10: Place the transparent sample holder containing the filled dish in an upper position inside the measurement chamber. During the measurement, the lead door of the chamber must remain closed at all times.

- Carefully measure the distance d between the KCl sample and the entrance window of the counting tube, as well as the diameter of the counting tube window. *Caution:* The counting tube must not be touched under any circumstances!
- Determine possible γ emissions from the KCl by placing a very thick aluminum absorber above the KCl sample. The measurement time should again be 10 minutes. The trick is that beta particles cannot penetrate the absorber, meaning that all registered events must come from gamma radiation. Since this experiment only considers beta decay, any gamma contributions must be subtracted during data analysis.
- Carefully pour the KCl back into its storage container. Make sure nothing is spilled. It is especially important that no KCl is spilled in the measurement chamber — contamination risk!
- Clean the workspace thoroughly using disposable materials such as paper towels. Dispose of them afterwards in the specially marked bin for slightly radioactive waste.
- The workspace must be checked and confirmed as free of activity.
- Remove your gloves and wash your hands thoroughly.

1.7 Analysis

Complete the following tasks and document your results:

- Why is KCl more suitable than K_2CO_3 for determining the half-life of ^{40}K?
- Determine the count rates s from your three measurements. Note that the count rate has the unit s^{-1}.
- Correct the count rate of the KCl sample for background and γ emission. Why can you then be confident that the corrected count rate only represents beta particles?
  Hint: For example, if you measure a count rate of $100\,s^{-1}$, with a background of $20\,s^{-1}$ and a γ emission of $5\,s^{-1}$, the corrected beta count rate is $75\,s^{-1}$ after subtracting background and gamma contributions.
- Determine the number N of ^{40}K atoms in your sample dish.
  Hint: Remember that KCl consists of both potassium and chlorine, and consider the isotopic abundance of ^{40}K given in chapter 1.4.2. The Avogadro constant is $N_A = 6.022 \cdot 10^{23}\,\text{mol}^{-1}$, the molar mass of potassium is $M_{K-40} \approx M_{K-39} \approx 39.09\,\text{u}$, and one atomic mass unit is $1\,\text{u} \approx 1.66 \cdot 10^{-27}\,\text{kg}$. The molar mass of chlorine is approximately 35.45 u.
- Consider whether you can use the approximation formula 1.16 for the self-absorption correction in this evaluation, and justify your reasoning.
  Hint: The quantity $1/(\mu \cdot \varrho)$, with μ the mass attenuation coefficient and ϱ the density of KCl, can be regarded as the characteristic absorption length. The approximation formula 1.16 may be used only if the sample thickness (in cm) is much greater than the characteristic absorption length — this is referred to as an infinitely thick sample. Is that condition satisfied here?
- Determine the individual correction factors and calculate from them the total correction factor f for the count rate s, as well as the corrected count rate $s_{\text{korr}} = f \cdot s$.
- Using s_{korr}, calculate the half-life $T_{1/2}$ for ^{40}K with Equation 1.19.

- Estimate the systematic measurement errors for the count rate s, the distance d between the counting tube and the sample, the filling height h of the sample dish, and its radius r. From these, determine the systematic error of $T_{1/2}$.
- The decay of individual atoms in a radioactive substance occurs spontaneously and randomly in time. The resulting statistical nature of particle emission becomes noticeable particularly for weak samples or low count rates and follows a Poisson distribution. It follows that for a measured number of events c, the mean statistical error is $\Delta c_{\text{stat}} = \sqrt{c}$. Calculate the statistical error of the half-life $T_{1/2}$.
- Compare your result for the half-life of ^{40}K with the literature value given in Figure 1.6. Does your result agree with the literature value within the margin of error?

1.8 Literature

There are many excellent books on nuclear physics. A small selection is given here:

- B. Povh, *Kerne und Teilchen*, Springer Verlag, 2013
- H. Krieger, *Grundlagen der Strahlungsphysik und des Strahlenschutzes*, Vieweg+Teubner Verlag, 2007

Further material on radioactivity and radiation protection can be found on the AP course website. It is recommended to study these documents carefully in advance.