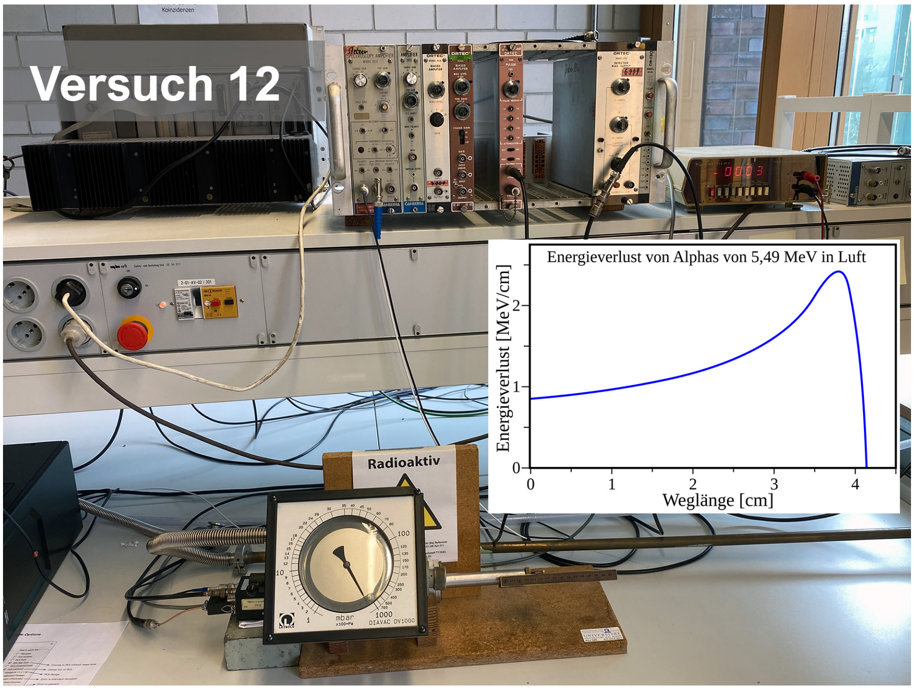
Experiment 12

Alpha Spectroscopy



Advanced practical lab course

at the institute of nuclear physics

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Contents

1 Introduction

When charged, heavy particles (e.g. α-particles or heavy ions) move through matter at high speed, they release their energy in many collisions with the atoms. There is a special feature here: the slower they become, the greater the energy transferred (known as the Bragg curve). At GSI, this behavior is used, for example, in the irradiation of tumors.

In this experiment, alpha radiation from a mixed source with three isotopes is measured with a surface barrier counter. The aim is to investigate the radiation of the three isotopes. For this purpose, energy spectra are recorded in order to determine the ranges and Bragg curves of the radiation. You will learn about alpha decay and gain an insight into the functioning of semiconductor detectors, the technical processing of signals and data analysis on the computer.

On the day of the experiment, you will be guided through the experiment by means of three tasks. Tasks 1 and 2 mainly deal with the characterization of the experimental set-up and Task 3 then examines how alpha radiation behaves in air.

What you need to know to carry out the experiment: The necessary prior knowledge for this experiment covers three areas: the theory of alpha decay, the energy loss of charged particles in matter and how semiconductor detectors work. The topics are briefly introduced in the following subsections of section 2.

But more knowledge is needed to carry out the experiment, which you should acquire yourself in a small literature search. Therefore, please carefully prepare beforehand the topics given at the end of each subsection for the experiment day. There are two books which are particularly recommended for this literature search: *Particle Detectors: Fundamentals and Applications* [1] and *Particles and Nuclei* [2]. Both are available as PDF files in the university library (as of January 2023).

After studying these topics, you should be able to answer the following questions, among others:

- How are the alpha particles produced that are investigated in this experiment?
- Which property of alpha particles can be measured with this experiment?
- Does this property have a constant value or is it different for each particle?
- How do the particles generate a signal in the semiconductor detector and how is the signal read out?
- What measured values (signal values) do you expect?
- What are the main sources of measurement inaccuracies?
- What is a histogram?
- What information is contained in the spectrum that is recorded on the computer?
- How do you obtain the observable you are looking for from the spectrum (e.g. energy loss per distance)?
- What happens when there is air in the apparatus?

2 Theoretical Background

2.1 Alpha Decay

Alpha particles are identical to helium nuclei (${}^{4}_{2}\mathrm{He}^{2+}$), i.e. they consist of two protons and two neutrons. The binding energy of the nucleons of such alpha particles is high compared to nuclei of similar size and is approximately 7 MeV per nucleon. The typical kinetic energy of alpha particles, which originate from natural decays of radioactive isotopes, is in the range of $3 - 8$ MeV [2], further properties can be found in Table 1.

Mass m_α	3727.3 MeV$/c^2$
Mass number A	4
Atomic number Z	2
Binding energy B	28.3 MeV

Table 1: Properties of α-particles.

The mass number of the nucleus decreases by four units during alpha decay, the atomic number by two units. If X denotes the parent nuclide and Y the daughter nuclide, ΔE the energy released during decay, and if mass numbers A are written at the top and atomic numbers Z at the bottom as usual, the following applies to alpha decay in general [9]:

$$ {}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\mathrm{He}^{2+} + \Delta E $$

As with any radioactive decay, alpha decay releases a well-defined amount of energy. According to $E = mc^2$, it corresponds to the mass that is lost as a mass defect through the process. This energy manifests itself as the kinetic energy of the alpha particle and the daughter nucleus; in some cases, part of the energy can also initially remain as an excited state of the daughter nucleus and then be decayed as gamma radiation. The kinetic energy is distributed between the two particles in the inverse ratio of their masses. The alpha particles emitted by a given nuclide therefore only have very specific values of kinetic energy, i.e. their energy spectrum is a line spectrum, unlike in beta decay, for example. This spectrum is characteristic of the respective radionuclide. Its measurement can therefore be used to determine this nuclide. [9]

Before the decay takes place, the alpha particle is attracted to the nucleus by the strong interaction, but at the same time electrically repelled due to charges of the same name. The stronger nuclear force has a short range, while the weaker electrostatic repulsion has a long range. The potential therefore forms a kind of barrier, the Coulomb barrier (see Fig. 1). The wall is higher than the kinetic energy available to the alpha particle. According to classical physics, the alpha particle would therefore be stably bound in the nucleus; however, it can leave it by means of the quantum mechanical tunnel effect. The probability per time span for this can be very small. It determines the half-life of the decay. The observed relationship between the half-life and the energy of the emitted alpha particles is described by the Geiger-Nuttall rule, see also the Gamow theory. [9]

In this experiment, the α-particles are emitted from a mixed source composed of ${}^{239}\mathrm{Pu}$, ${}^{241}\mathrm{Am}$ and ${}^{244}\mathrm{Cm}$. Figure 2 shows the measured decay spectrum of this mixed source. In addition to the main decay channels, one can see some extra secondary processes, which can be identified by the decay diagrams of Figure 3.

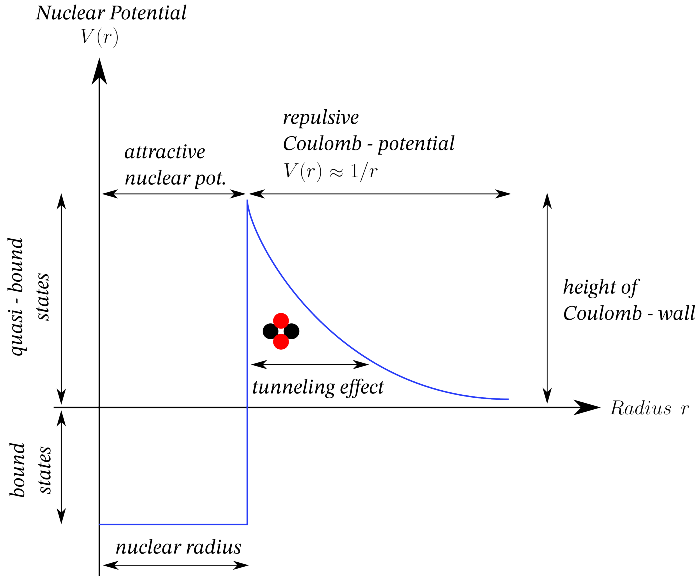


Figure 1: Coulomb wall. Model potential for an alpha particle, which is composed of the short-range nuclear potential approximated by a potential well and the long-range Coulomb potential. [10]

Topics for preparation

- Binding energy of atomic nuclei, mass defect
- Nuclide map, stability of nuclei
- Distance square law
- Line spectrum of alpha decay
- Properties of nucleons
- Gamow theory of alpha decay, Gamow factor, lifetime, potential of the atomic nucleus, tunnel effect

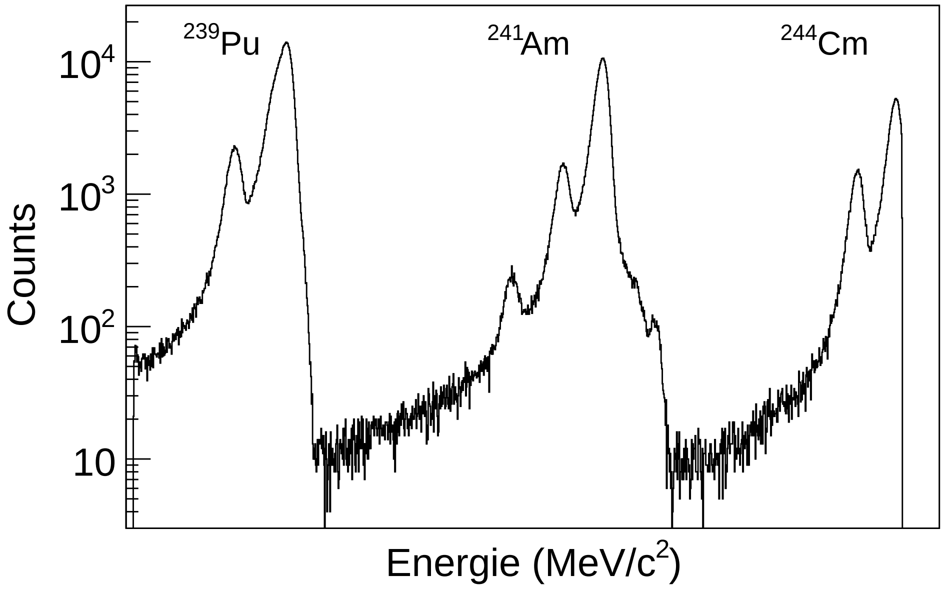


Figure 2: Measured decay spectrum of the mixed source used in the experiment.

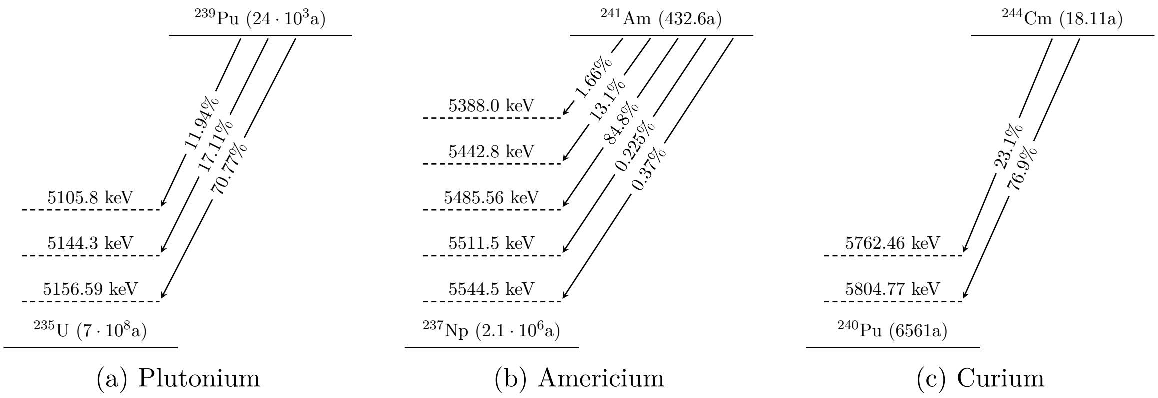


Figure 3: Decay diagrams of the alpha emitters.
Taken from: Pu [5], Am [6], Cm [7]

2.2 Interaction of charged particles in matter

When passing through matter, alpha particles essentially lose their energy through ionization and excitation of the atoms in the material. As they are significantly more massive than the electrons of the material ($m_\alpha \approx 8000\ m_e$) with which they interact, they pass through the material without major deflections. The average energy loss per path length is described by the Bethe-Bloch formula [1]. It depends on the properties of the medium as well as the charge and velocity of the particle.

$$\left\langle -\frac{dE}{dx} \right\rangle = K \frac{Z}{A} \frac{z^2}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} \right) - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \tag{1}$$

- $K = 4\pi N_A r_e^2 m_e c^2 = 0.307$ MeV cm^2/mol mit $r_e \approx 2.8$ fm.
- z charge number, $\beta = v/c$ velocity of the projectile particle.
- Z atomic number and A mass number of the medium.
- I: average excitation potential of the atoms.
- T_{max}: maximum possible energy transfer to a shell electron, which is $\approx 2 m_e c^2 (\beta\gamma)^2$ in a central collision.
- δ: density correction, which is important at high energies.

The shape of the mean energy loss is shown in Figure 4. For low particle velocities, the curve is approximately proportional to $1/\beta^2$. This means that the slower the particles become, the greater their energy loss per distance traveled. This results in the shape of the Bragg curve, which can be seen in Figure 5.

Typically, alpha particles from nuclear decay have a kinetic energy of approximately $E_{kin} =$ 5 MeV, i.e. a momentum of $p = \sqrt{2\ m\ E_{kin}} = 195$ MeV$/c$ and it is $p/mc = 0.052$; they move at around 5% of the speed of light. This makes them considerably slower than e$^+$/e$^-$ from β decays or neutron radiation, for example.

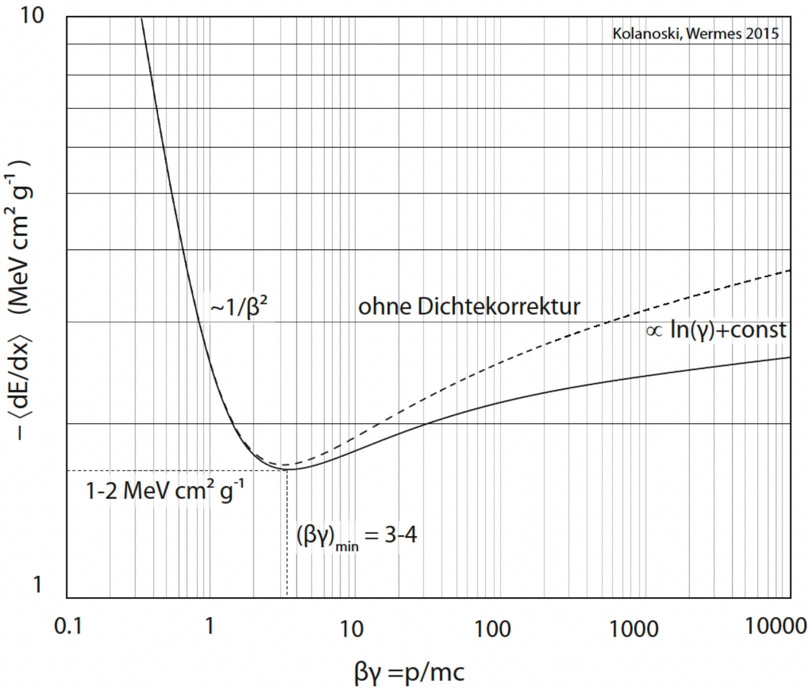


Figure 4: Graph of the average energy loss of charged particles in matter as a function of p/mc. [1]

Topics for preparation

- Energy loss of charged particles in matter
- Bethe-Bloch curve
- Bragg peak
- Radiation range and shielding
- Energy straggling

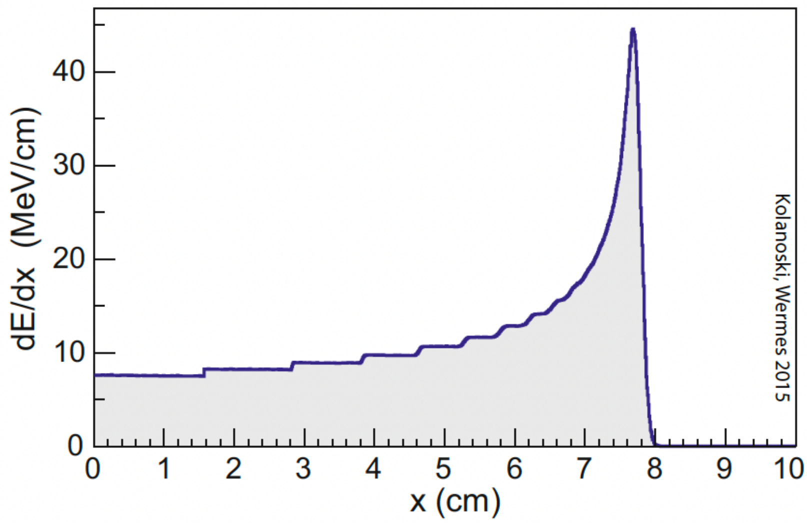


Figure 5: Bragg Peak. Energy loss per distance traveled as a function of the distance already traveled. Here using the example of protons in water. [1]

2.3 Semiconductor detectors

In principle, all particle detectors are suitable for detecting alpha radiation, for example for radiation protection purposes. However, the radiation must be able to reach the inside of the detector, the sensitive volume; a counting tube must have a sufficiently thin foil window for this. For precise measurements, for example to determine the energy spectrum of the radiation, the radiation source and detector must be in the same vacuum. A semiconductor detector is usually used for this. [9]

Basically, silicon semiconductor detectors are relatively large p-n semiconductor diodes with a very thin entrance window for charged particles, which offers minimal energy loss. They are operated in the reverse direction so that free charge carriers are sucked out of the sensitive volume (depletion zone) of the diode by an applied voltage. Figure 6 shows the structure of the detector used in this experiment.

When a charged particle, such as an alpha particle, enters the detector, it loses a small part of its energy at the thin entrance window. The majority of its energy is deposited in the depletion zone by ionization of the silicon atoms. The number of electron-hole pairs generated by this process is proportional to the energy of the incoming particle. The free charge generated by the ionization is extracted from the electrodes and collected by the capacitors of the preamplifier connected via the connector. The collected charge results in a voltage pulse, which is determined by the capacitance of the preamplifier and the amount of charge and rises within up to 100 ns. The amplitude of the voltage pulse is proportional to the energy of the measured alpha particle and can be further processed for evaluation using a multichannel pulse height analyzer (MCA).

Semiconductor detectors can be used in a wide energy range, namely for electrons with about 20 keV up to heavy ions with 200 MeV. Their efficiency in the active volume is close to 100%, while the proportionality of charged particle energy to pulse height is constant over a wide range. In this experiment, a silicon semiconductor detector will be used for α-particle spectroscopy.

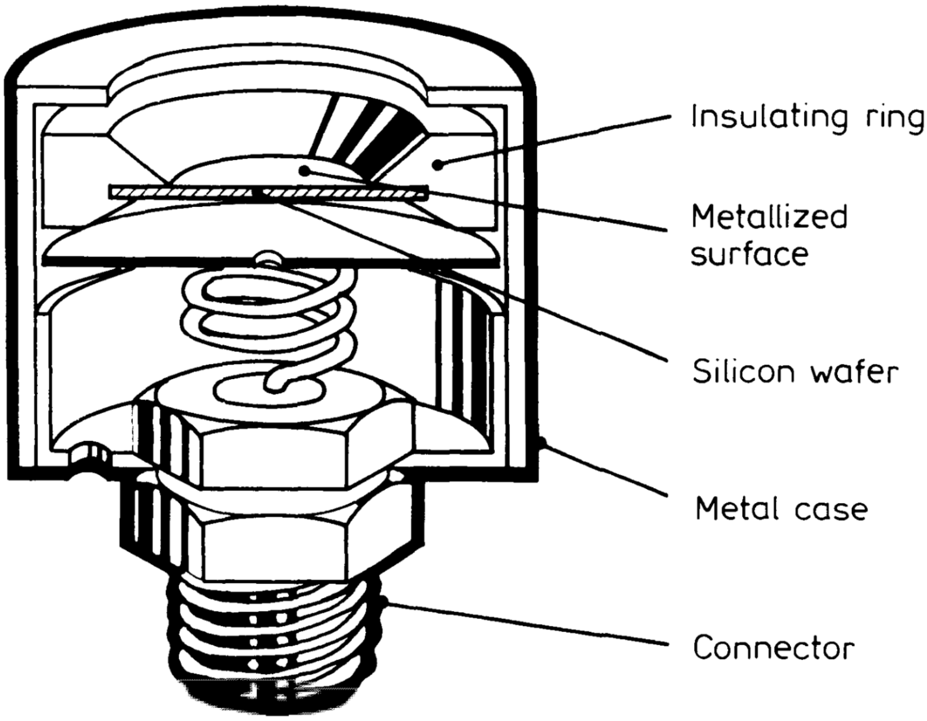


Figure 6: Structure of the surface barrier layer counter [3].

Topics for preparation

- Semiconductors, doping, diode, p-n junction, diffusion voltage
- Energy deposition, formation and recombination of charge carriers
- Energy resolution of the semiconductor detector
- Thermal noise, energy per electron-hole pair
- Poisson statistics, Fano factor (see [1, Kap. 17.10.2])

3 Experimental Setup

The experimental setup consists of the following components:

- Radiation source
- Semiconductor detector
- Vacuum container with pressure gauge,
  inlet (to let the air in) and outlet (for vacuum) valves
- Vacuum pump
- Preamplifier and main amplifier
- Power supply unit with external voltage measuring device
- Multi-channel pulse height analyzer (MCA) inside the PC
- PC with MCA software

Figure 7 shows the experimental setup schematically, photos can be seen in Figure 9. The surface barrier counter and the alpha radiation source are located in an airtight metal cylinder. The source can be moved in the cylinder along one spatial axis in order to change the distance between the source and detector. At the minimum adjustable distance, the source does not touch the detector. In fact, determining this minimum distance is part of the experiment.

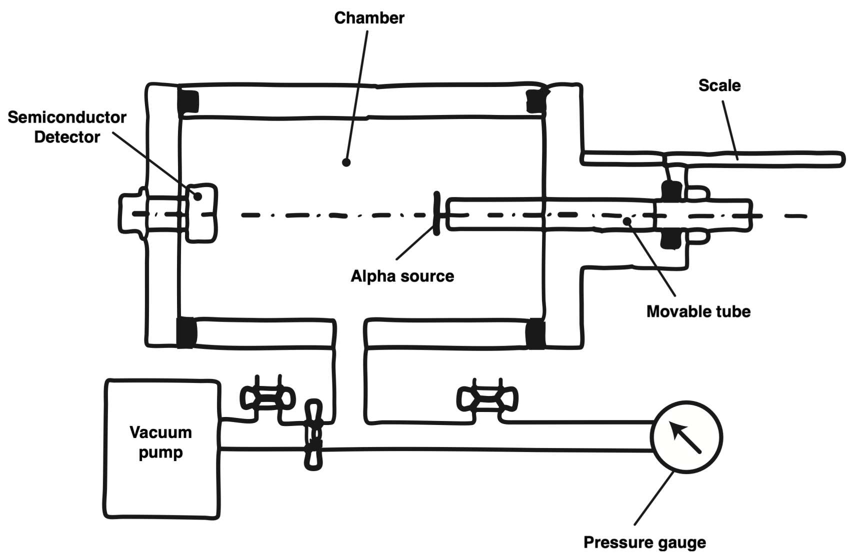


Figure 7: Schematics of the experimental setup.

The mixed source has an active area with a diameter of about 7 mm and is covered by a gold layer, which is about 2 µm thick (see Figure 10b). However, the covering of the radioactive material does not provide protection against contamination on contact. Hence, the source must be considered open and special licensing requirements and precautions must be taken into account (see section 4.1).

The preamplifier is attached to the semiconductor detector directly outside the vacuum container. The entrance window of the detector can be seen in figure 10a. The preamplifier has several connections:

- Operating voltage supply, connected to the rear of the main amplifier.
- Signal output, connected to signal input of the main amplifier.
- External voltage input, connected to the power supply unit.
- Connection option for a pulser. Not connected.

The wiring of the experiment is shown in figure 8 and figure 11 shows a picture of the main amplifier as well as the voltage supply unit.

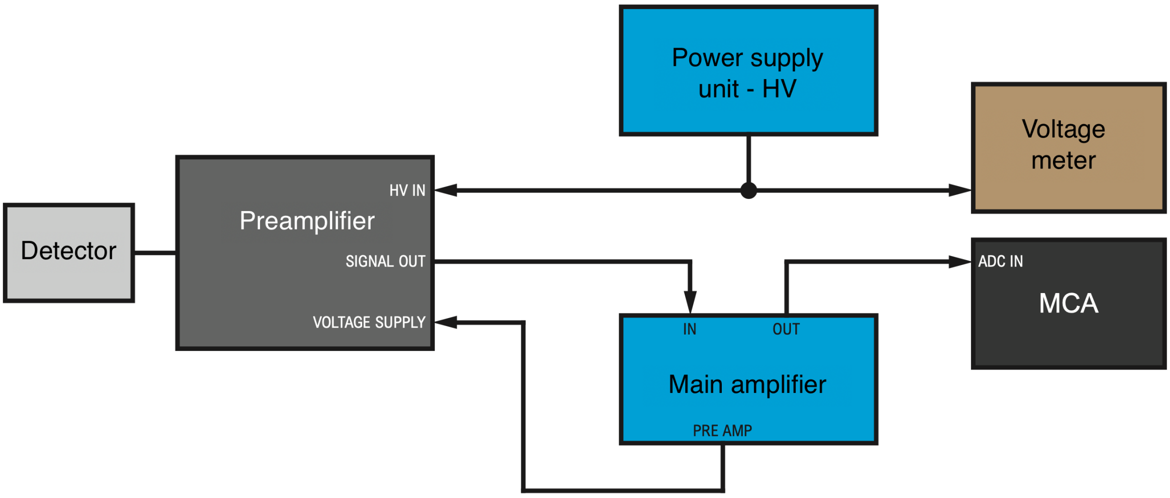
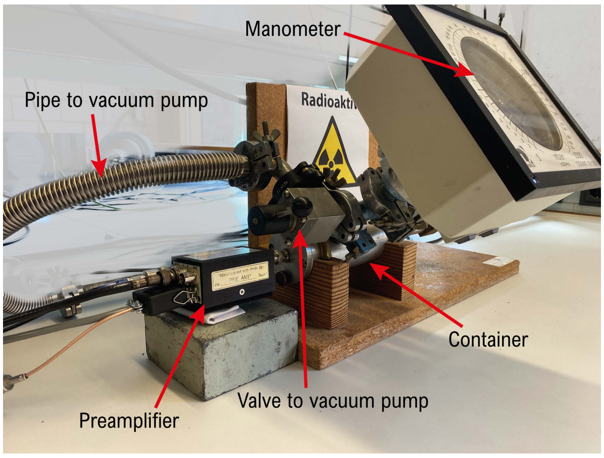
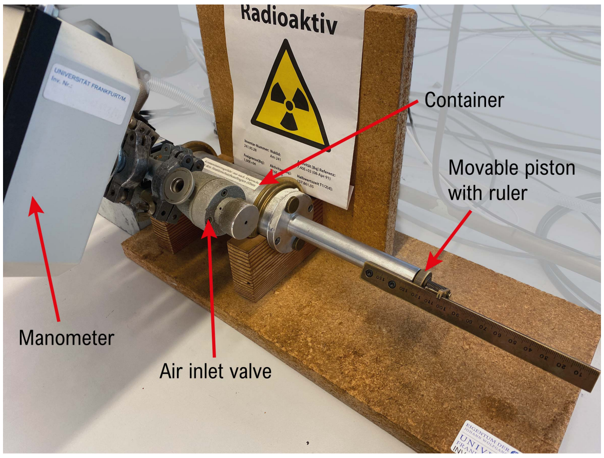


Figure 8: Schematics of the wiring of the experiment.

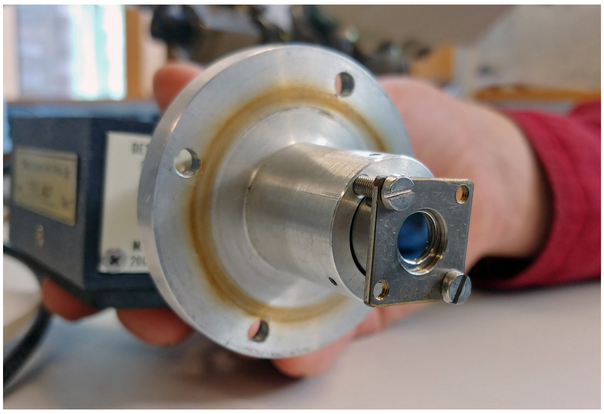


(a) View from the left.



(b) View from the right.

Figure 9: The experimental setup.



(a) The semiconductor detector.

(b) The radiation source with golden surface.

Figure 10: Interior views of the vacuum container.

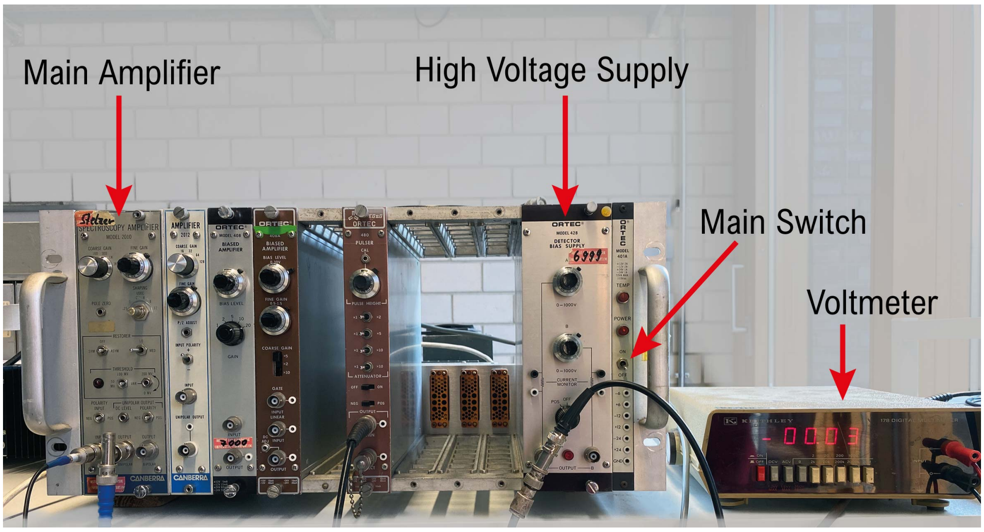


Figure 11: Electronics in the "Ortec-Crate".

4 Experimental procedure and evaluation

4.1 Warning notices

Eating and drinking is prohibited in the laboratory.

The radiation source used emits radioactive alpha radiation. It is weakly sealed and partially open. Radiation protection requires special safety measures for such sources. For this reason, the source has been permanently installed in the apparatus so that no radioactive material can escape from it into the room and no contact with the source is possible. Therefore, the measuring apparatus must not be opened under any circumstances. The ventilation valve should remain open for as short a time as possible.

The maximum voltage on the semiconductor detector is 200 V. Always change the voltage slowly. Exceeding the voltage can destroy the detector.

Only make changes to the wiring when the power supply is switched off.

The detector is extremely sensitive to light, operation with high voltage applied outside the closed vacuum chamber would destroy it.

Do not open both venting valves of the vacuum piston at the same time.

Switch off the high voltage before venting.

4.2 Preparations

Go through this checklist together with the supervisor:

1. Check the wiring (see Figure 8);
2. Ensure that the power supply unit is set to 0 V;
3. Set the source to the smallest possible distance from the detector $r_{rel} = 0$ mm;
4. Evacuate the vacuum chamber;
5. Switch on Ortec-Crate;
6. Start MCA3 Software on the PC.

4.3 Task 1: Saturation voltage

The aim of the first task is to determine the saturation voltage of the semiconductor detector. The measurement is performed in vacuum at the smallest possible distance $r_{rel} = 0$ mm, and only for Plutonium.

a) At detector voltage $U_A = 0\ V$, acquire a histogram with at least 8000 counts. Determine

- the peak position μ [ADC Channels];
- the half-width $FWHM$ [ADC Channels];
- and the counting rate Z [1/s]

of the Plutonium peak using a Gaussian fit in the software.

b) Repeat a) for the voltages $U_A = 8, 15, 20, 25, 30, 40, 70, 100$ V.

c) Plot the peak position μ, the count rate Z and the percent resolution

$$d_E = \frac{FWHM}{\mu} \cdot 100 \qquad [\%] \tag{2}$$

as a function of U_A.

d) Determine approximately the saturation voltage $U_{sat.}$ using the graphs. Select a voltage $U_{Det.}$ for your subsequent measurements. Explain your selection and the significance of the saturation voltage for using the semiconductor detector for α-particle spectroscopy.

4.4 Task 2: Calibration and offset distance

In this task, an energy calibration of the multi-channel analyzer is performed and the minimum adjustable distance r_0 (zero-distance) between detector and source is determined. The measurements take place in vacuum.

a) Set the power supply voltage to the value $U_{Det.}$ determined in task 1;

b) Record a reference spectrum with at least 12000 counts at $r_{rel} = 0$ mm.
Save a screenshot of the reference spectrum for your report.
Optional: Save the histogram as a `.txt` file. This allows you to repeat the calibration at home.

c) Calibrate the multi-channel analyzer in the software. To do this, determine the position of the three main maxima in the histogram by Gaussian fit and use the matching energies from Figure 3.

Perform the Gaussian fits again to obtain the calibrated values for positions [keV], half-widths [keV] and count rates [1/s].

d) Record at least 3000 counts at the relative distances $r_{rel} = 5, 10, 15, 20, 30$ mm and determine the calibrated positions, half-widths and count rates of the three main maxima by Gaussian fit.

e) *In the laboratory:* Plot the count rate as a function of the relative distance for Plutonium.

In the report: Plot the energy, percentage detector resolution and the counting-rate as a function of the relative distance for all isotopes.

f) Determine the zero-distance r_0 between sample and detector in order to be able to use the effective distance $r_{eff} = r_0 + r_{rel}$ for the next measurements. To do this, consider how the distance law

$$Z \propto \frac{1}{r_{eff}^2}, \tag{3}$$

where Z is the count rate in $[1/s]$, can be transformed and cleverly plotted to read the zero-distance directly from the y-axis intercept. Give the averaged result from the measurements of all three isotopes.

4.5 Task 3: Range in air

In the last part of the experiment, the differential energy loss of alpha radiation in air is determined.

a) Close the outlet valve of the vacuum chamber. Then slowly open the inlet valve until atmospheric pressure is established in the chamber. Then close the inlet valve again.

b) Determine at $r_{rel} = 0, 4, 8, 20, 24, 28, 32, 36, \ldots$ mm using a Gaussian fit:

- the calibrated peak position μ [keV];
- the calibrated half-width $FWHM$ [keV];
- the count rate Z [1/s];

for the main maxima of the three isotopes. If necessary, further increase the relative distance by 4 mm per step until the plutonium signal disappears at r_{max}. Then take three additional measurements at $r_{rel} = r_{max} - 2, r_{max} - 6, r_{max} - 10$ mm. Record at least 2000 counts for each measurement.

c) *In the laboratory:* Plot the α-energy $E \mathrel{\widehat{=}} \mu$ depending on the effective distance for Plutonium.

In the report: Plot the energy, the percentage resolution of the energy measurement, as well as the count rate depending on the effective distance for all three isotopes.

d) Determine approximately – by extrapolation with the eye – the range of the α-particles and their exit energy using the graph showing effective distance versus energy. What influences the uncertainty of the results the most?

Compare the results with the literature values in a table. Use the given exit energies and Geiger's empirical range law, which gives the range R [mm] depending on the exit energy E_0 [MeV] of the α-particles:

$$R = 3.1 \cdot (E_0)^{3/2} \tag{4}$$

Optional: If equation 4 is transformed and adjusted accordingly, it is suitable as a fit function for the data. This allows range and exit energy to be determined more accurately than can be determined by eye.

e) *In the laboratory:* Plot the differential energy loss as a function of the effective distance ($\Delta E/\Delta x$ vs. r_{eff}) for Plutonium.

In the report: Add the Bragg-Peaks of the other isotopes. Give an estimate of the energy loss close to the sample and explain what the maximum energy loss could be. Compare the three Bragg curves with each other.

f) Estimate the different contributions that go into the energy resolution. Consider the detector resolution from the vacuum and air measurements. Discuss the significance of the electronic noise, the statistical fluctuations in the number of electron-hole pairs (Fano factor), as well as the finite thickness of the source and the energy straggling.

When writing the report, also think about an error analysis and add corresponding error bars to the diagrams. Together with the protocol, submit your original measurement data as a neat `.txt`-file with appropriate comments so that the data can be assigned to the respective measurements. The structure of the protocol should be based on the following points:

- Theory section
- Execution and evaluation
  - What is to be measured and why?
  - What measurement results are expected?
  - How is the measurement carried out?
  - What was actually measured? How large are the measurement errors?
  - What can be learned from the measurement result? Were the expectations met? What are the sources of error?
- Conclusion

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