Praktikum für Fortgeschrittene
Institut für Kernphysik
Technische Universität Darmstadt

Experiment 2.3: α spectroscopy with a semi-conductor detector

Praktikum für Fortgeschrittene
Institut für Kernphysik
Technische Universität Darmstadt

Johan Emil Larsson

(Dated: April 29, 2025)

I. KEY GOALS

This lab exercise concerns itself with the study of the radioactive process of α decay. The students will measure several properties of the decay of ^{241}Am using a surface barrier diode made of silicon. The students are expected to describe the basic properties of α decay, interactions of charged particles with matter, working principles of semiconductor detectors and the electronics used to treat and digitize the raw signals.

II. READING MATERIALS

This exercise was devised using the following books:

- Krane, K. S. (1988) "Introductory nuclear physics." New York: Wiley. Chapters 1-8
- Knoll, G. F. (2000) "Radiation detection and measurement." 3rd ed. New York: Wiley. Chapters 1-4, 11, 16, 18
- Griffiths, D. J. and Schroeter, D. F (2018) "Introduction to quantum mechanics." Third edition. Cambridge: Cambridge University Press. Chapter 10

Alternatives to these sources from the previous version of this exercise sheet are listed on the last page.

III. PREREQUISITE KNOWLEDGE

Before starting the lab exercise we will discuss for one hour the following topics.

α **decay:** The basic physics of α decay. Q-values. Gamow's theory of α decay. Modification of the Coulomb barrier due to angular momentum. The α emitter ^{241}Am, its half-life, Q-value and α particle energies.

Interactions of charged particles with matter: The Bethe-Bloc formula. Bragg curve. Range.

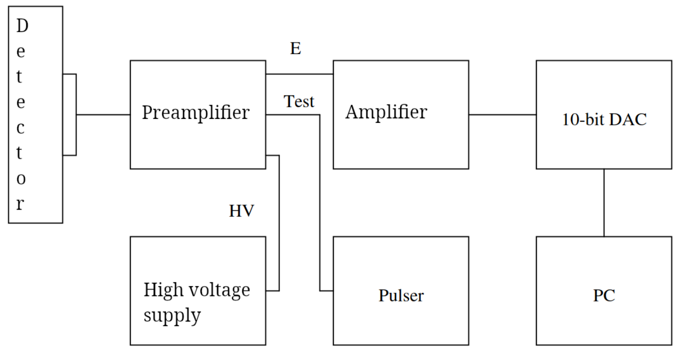

FIG. 1. Schematic of the electronics used to complete the experiment.

Semi-conductors: The band gap model. Charge carriers. Conductance. Doping.

Semi-conductors as radiation detectors: p-n diode. Depletion zone. Reverse biasing. Fano factor. Sources of noise. Detector resolution. Electrical potential and fields in a semiconductor. Surface barrier diode.

Electronic chain: Charge-sensitive pre-amplifier. Main amplifier and pulse shaping.

IV. EXPERIMENT

A. Setup

The instructor will install the detector in the vacuum chamber, and help connect the required electronics. The α source is a ^{241}Am source sealed behind a thin window and placed on an extendable rod allowing us to vary the detector-source distance. The source is installed by the instructor in front of the detector. Turn on the vacuum pump and wait for a good vacuum. Note the pressure in the chamber.
Describe the setup using a figure or annotated figure in the report.

B. Check the raw signal from the detector

1. How does the raw amplifier signal from the detector look like when it is not biased? Why do you get signals even when the detector is not biased?
2. Increase the bias voltage slowly while watching the baseline of the signal. What happens to the baseline as the bias is increased? What is happening?
3. Connect the detector to the amplifier. How does the output look like?
4. Repeat this exercise once the detector is fully biased. Change the coarse gain, fine gain and the shaping time of the amplifier. How does this impact the signal?

NOTE: Do not change the gain or shaping time after the energy calibration is done in step D!

C. Biasing the detector

Starting with 0V bias voltage, in steps of 1V until 10V and then in steps of 5V until 50V, measure the spectrum as a function of voltage for a fixed time of 1 minute. Always change the bias voltage slowly, maximum 0.5V/s. Plot the number of counts, the mean energy and the standard deviation of the spectra as a function of voltage. What does this tell you about the depletion layer of the detector? What is the saturation voltage of the detector and what does this imply?

- **Hint:** make sure when calculating the means and standard deviations, that you are excluding the noise at the beginning of the spectrum.
- **Hint:** no energy calibration is needed for this sub-task.

D. Calibration of the detector

When you measure a spectrum with the ADC, we obtain a histogram of the number of counts in each bin. The bin numbers scale linearly with the energy of the signal. We therefore want to obtain the calibration coefficients to relate the bin number ch to the energy E in units of keV: $E = a \cdot ch + b$.

1. With the detector fully biased, try changing the parameters of the amplifier and observe how the spectrum changes. What is the ideal parameter for the shaping time of the signal? What observable do you need to check to optimize this parameter?
2. Connect the pulser and inject electrical pulses in the test input of the preamplifier.
3. Change the pulse amplitude such that it overlaps with the strongest known α line of ^{241}Am.
4. Attenuate the signal by a factor 2 and take data for 2-3 minutes.
5. Then set the attenuation to a factor of 5 and take 2-3 minutes more of data.

A spectrum with three peaks with known energies is now obtained. A fit of the three data points to the equation above can be used to calibrate the spectrum.

E. Measure the spectrum of ^{241}Am

Disconnect the pulser, and measure the spectrum of ^{241}Am. Determine the energies and resolutions of the three strongest lines. Determine for how long time you need to acquire data for a good measurement. Measure the FWHM (full width at half maximum) of the peaks, assuming that the total width is

$$\Delta_{observed} = \sqrt{\Delta^2_{electric} + \Delta^2_{intrinsic} + \Delta^2_{statistical}}$$

estimate the intrinsic line width of the experiment.

- Measure the FWHM of the pulser line for the electric contribution $\Delta_{electric}$.
- Calculate the statistical contribution $\Delta_{statistical}$ from the number of electron-hole pairs created and the Fano-factor for silicon.
- Calculate the intrinsic line width value from the Gamow theory and the energy-time uncertainty principle - are they remotely close?
- Does the Gamow theory give a reasonable estimate of the lifetime? Why (not)?
- What other effect(s), not accounted for above, will contribute to the observed FWHM?

F. Measure the energy loss of α particles in air

1. Debias the detector, and let air back into the vacuum chamber.
2. Bias the detector again.
3. Measure the energy and resolution of the peak at the closest separation for 1 minute.

4. Increase the distance between the source and the detector in steps of 5mm, measuring the energy and resolution at each distance. For each measurement the number of counts in the peak should be the same as the first measurement, the measuring time therefore needs to be increased. You need a minimum of 5 points.

Plot the differential energy loss as a function of energy and fit a simplified Bethe-Bloc formula, assuming a non-relativistic α particle. Compare the energy loss with tabulated values. How close are you? Briefly discuss the potential sources of error. Additionally, plot the width of the peaks as a function of energy loss as well, what physical phenomenon is at play?

- **Hint:** The separation between the source and the detector is unknown. The rings on the α source have a separation of 5mm so all of your distances will be relative to the initial separation.

V. REPORT

The report must contain:

- a title page
- an introduction
- a theory section covering the basic physics that were discussed during the lab and during the preparations
- an experimental section describing how the data were acquired
- a results section presenting the results
- a discussion section were the results are critiqued and interpreted
- a short summary of the report

Additionally, the following must be observed:

- All values are given with physical units and, where relevant, experimental uncertainties.
- All figures are properly labeled and referenced. There is in general no need to use figures from outside sources, describe the physics in your own words and make your own figures if needed.
- All questions in the instruction sheet are addressed.

Lastly, the FP "Spielregeln" must also be adhered to. Available at `https://www.ikp.tu-darmstadt.de/lehre_kernphysik/praktika/f_praktikum/index.de.jsp`.

VI. USEFUL RESOURCES

- Data on ^{241}Am can be found from NNDC: `https://www.nndc.bnl.gov/nudat3/decaysearchdirect.jsp?nuc=241Am&unc=NDS`
- Energy losses and stopping powers can be found from NIST: `https://physics.nist.gov/PhysRefData/Star/Text/ASTAR.html`

These references are taken from the previous version of this exercise and can also be used for reference and studying.

1. **Semi-conductor physics:**
Lit.: Gerthsen, *Physik* (1982), pp. 710–718, 279, 706–710; Knoll, *Radiation Detection and Measurement* (1979), pp. 359–372; Geist, *Halbleiterphysik II* (1970), pp. 4–5, 19–24; Kittel, *Einführung in die Festkörperphysik* (1969), pp. 306–308, 358–359, 367–372, 386–391; Kuhn, *Halbleiter- und Kristallzähler* (1969), pp. 29–42, 47–50; Bertolini & Coche, *Semiconductor Detectors* (1968), pp. 11–25.

2. **Semi-conductors as radiation detectors:**
Lit.: Knoll, *Radiation Detection and Measurement* (1979), pp. 375–387; Czulius, Engler, Kuckuck, *Halbleiter-Sperrschichtzähler*, in: *Ergebnisse der exakten Naturwissenschaften*, Bd. 34, pp. 244–248, 251–255; Neuert, *Kernphysikalische Messverfahren* (1966), p. 266; Kuhn, *Halbleiter- und Kristallzähler* (1969), pp. 86–92; Bertolini & Coche, *Semiconductor Detectors* (1968), pp. 103–149.

3. **Energy resolution:**
Lit.: Knoll, *Radiation Detection and Measurement* (1979), pp. 372–375, 390–393; Neuert, *Kernphysikalische Meßverfahren* (1966), p. 292; Kuhn, *Halbleiter- und Kristallzähler* (1969), pp. 133–141; Bertolini & Coche, *Semiconductor Detectors* (1968), pp. 75–103.

4. **Time resolution:**
Lit.: Knoll, *Radiation Detection and Measurement* (1979), pp. 393, 390–393; Neuert, *Kernphysikalische Meßverfahren* (1966), pp. 297–299; Bertolini & Coche, *Semiconductor Detectors* (1968), pp. 243–279.

5. **Amplifiers:**
Lit.: Knoll, *Radiation Detection and Measurement* (1979), pp. 649–656, 614–628; Foh & Wien, *Vorlesungsskript: Physikalische Messtechnik* (Darmstadt 1969/70), pp. 39, 55–60; Valvo-Broschüre, *Halbleiter-Kernstrahlungsdetektoren* (1969), pp. 59–60; Tietze, Schenk, *Halbleiterschaltungstechnik* (1969); Bertolini & Coche, *Semiconductor Detectors* (1968), pp. 201–243.