FYSC12/FKFN20: Nuclear Physics and Reactors, HT18

Instructions for KF3: α-decay lab

Administrative details

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Guest instructor: Anton Såmark-Roth

KF3 dates: Oct. 9-12, 2018 (Tues.-Thurs.)

Lab times/location: 8:30-15:15; coffee break 10:00-10:15; lunch break 12:00-13:15 (approximate)

Make-up lab policy: attend on a different day of the week, but notify the instructor; for serious emergencies, it is negotiable depending on the circumstance

Attending the introduction lecture and signing to acknowledge the safety orientation on September 24 is mandatory to participate in KF3!

Preparation and resources

K. S. Krane, Introductory nuclear physics; chapter 6.5 (short section on α decay only), 7.1 up to Eq. 7.6, chapter 7.4, 8.1-4

Comprehensive database for all nuclear properties: https://www.nndc.bnl.gov

Bring your laptop with a programming environment (python, C++, MATLAB, etc) for calculations; one machine may be shared between partners

Introduction

An alpha decay is one of the three most common decay modes of unstable atomic nuclei. It is an emission of a ^{4}He nucleus from an atomic nucleus, usually from a heavy element. In this lab we will measure the kinetic energies of the α particles from different species and gain some understanding of the nuclear structure and α-decay radiation principles.

The learning outcomes are:

- Assembly and optimization of experimental setup
- Statistics and error propagation
- Principles of Si surface barrier semiconductor detector for α particles
- Kinematics of α decays
- Comparison of Bethe-Bloch energy loss equation to experimental data
- Identification of α-decay chain of ^{228}Th to ^{208}Pb and the nuclear shell effects

Background

During the alpha decay, the excess binding energy of the mother nucleus is distributed as follows:

- E_α: The kinetic energy of the emitted α particle
- The recoil kinetic energy of the daughter nucleus
- (optional) excitation energy of the daughter nucleus, which may then de-excite by γ rays

The total output energy from the decay is called Q (Eq. 8.3 in Krane). Note that the formulae in section 8.2 in Krane assume that the daughter nucleus is not placed in an excited state during the decay. If the excitation energy is included, then Eq. 8.7 is revised to

$$\mathbf{E}_{\alpha}^{i} \approx (\boldsymbol{Q} - \boldsymbol{E}^{i})(\mathbf{1} - \frac{\mathbf{4}}{\boldsymbol{A}})$$

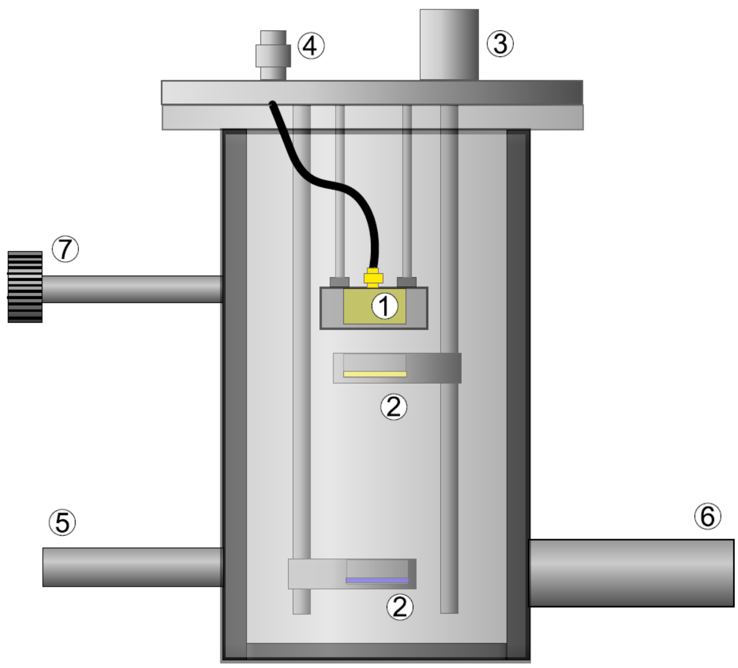
where E^i is the excitation energy in the daughter nucleus, and *A* is the mass number of the parent nucleus. We can calculate the velocities of the outgoing particles and determine whether they can be treated classically.

Usually α decays of heavy nuclei form a decay chain of subsequent daughter nuclei also emitting α particles. However, the decay chain may involve alternative modes, such as β decays. How can β decays compete with α decays in certain nuclei? This can be explained with a nuclear shell model description of the Z ~ 82 species.

We will also measure the range and energy loss of α particles in air and compare the experimental results with the Bethe-Bloch formula (Eq. 7.3 and 7.4 in Krane).

Experiment method and planned schedule

The main apparatus for alpha decay spectroscopy is shown below.



The components are:
1. Si surface barrier detector
2. Slots for radioactive specimen
3. Knob to switch samples
4. Signal output/preamplifier power supply interface
5. Pipe connected to vacuum pump
6. Pipe connected to barometer
7. Vacuum valve

Additional equipment and materials to be used in this lab are:

- Preamplifier box
- Crate containing signal amplifier/shaper and preamplifier bias power supply modules
- Barometer for pressure reading of the vacuum chamber
- Roughing pump
- Multichannel analyzer (MCA) by Ortec
- Data acquisition (DAQ) PC with Maestro to read out MCA data
- Oscilloscope to see amplified signals
- ^{241}Am α source for energy calibration
- ^{228}Th α source for spectroscopy measurements

Activities for detector setup and energy calibration

1. Review Fig. 7.23 on page 220 of Krane and connect the cables in the right places for the setup to work. Use the unipolar output channel and set the baseline correction scheme to “blr”. Connect the output of the amplifier to the oscilloscope rather than the MCA for now.
2. Place the ^{241}Am source inside the vacuum chamber for energy calibration. Try to get it reasonably close to the detector, in order to collect enough statistics quickly.
3. Turn on the vacuum pump. It takes a long time to reach the maximum vacuum, but measurements can begin immediately.
4. Raise the high voltage to 80 V and look at the scope. Do you see any signals? If so, connect the amplified signal output cable to the MCA.
5. Open the Maestro application on the DAQ PC and collect data for 1 minute. Adjust the gain on the amplifier and the range setting of the MCA so that the peak is positioned near the middle of the spectrum. Use the software tools to determine the centroid of the distribution. Take note of the FWHM also.
6. Clear the energy spectrum in Maestro and increase the high voltage to 90 V. Collect new data. What changes do you see?

7. Repeat step 6 with increments of 10 V up to 120 V. Record each set of measured values (centroid and FWHM). What do you notice? Did the peak positions change? How about FWHM?
8. Use the centroid channel value at 120 V to calibrate the system in Maestro ("Calibrate" button). The main peak has a literature E_α value of 5486 keV. Note that the FWHM value is also calibrated in energy.

Procedure for ^{228}Th source measurement

1. Evacuate the vacuum chamber by turning off the roughing pump and opening the valve.
2. Lift the lid of the vacuum chamber and with the 241Am source with a 228Th source. As it is likely to be weak, place it as close to the detector as possible.
3. Place the lid back on the chamber and start the roughing pump again.
4. Start a new data acquisition run in Maestro. Leave the setup to collect statistics over the lunch break.
5. (After lunch) Stop the data acquisition and turn off the roughing pump. Record each visible and intense peak's energy and FWHM values.

Procedure for α energy loss measurement in air

1. Open the lid and switch the ^{228}Th sample with the ^{241}Am source. Place the source about 1 cm from the detector, and well centered.
2. Using a ruler, measure the closest distance between the surface of the source and the surface of the detector. This will be quite imprecise, so provide reasonable uncertainties.
3. Without turning on the roughing pump, close the lid and measure the energy spectrum for 120 s of live time. This limit can be set on Maestro. Record the peak energy of the distribution.
4. Open the lid and move the source approximately 0.5 cm away from the detector.
5. Repeat steps 2-4 until the distance is 4.5 cm, while keeping the live time fixed at 120 s.

Estimated timeline for the lab activities:

8:30 – 9:15 Introduction, detector setup and energy calibration with ^{241}Am source

9:15 – 10:00 Start ^{228}Th sample measurement; tutorial on surface barrier semiconductor detectors

10:15 – 12:00 (after coffee break) alpha decay theory and computational exercise to calculate energy loss of α's through matter via Bethe-Bloch equation

13:15 – 14:15 Check ^{228}Th sample measurement; build and verify decay chain to ^{208}Pb; compare experimental α energies to literature values; brief discussion of nuclear shell effects

14:00 – 14:45 Measure α particle's energy from the ^{241}Am source at different distances to the detector without vacuum to compare with theoretical calculations

14:45 – 15:15 Summary of the lab activities and guidance on lab reports

Analysis/discussion

Questions to be addressed from the measurements and the calculations:

- During detector calibration, why did the energy resolution improve as the bias voltage increased, even though the centroid position has not shifted?
- Compare the experimental energies of the peaks from the ^{228}Th source measurement with the literature values. How accurate was the 1-point energy calibration using the ^{241}Am source? Are there any systematic uncertainties in the method that need to be discussed?
- Plot the relative energy resolution (FWHM/E_α) versus E_α of the different peaks from the ^{228}Th sample. Can you suggest a good model to describe this relationship?
- Plot and compare the energy loss of the α particle from the ^{241}Am source in air at various distances with the Bethe-Bloch equation. Do they agree well? How many cm of air under standard pressure (1 atm) is needed to fully stop a more energetic 8.785-MeV α particle from ^{212}Po?
- On pages 195-196, Krane writes that Bethe-Bloch fails for heavy particles at very low energies due to the atomic electrons being captured by the slow-moving particle. Will this phenomenon increase or decrease dE/dx? How can we determine the magnitude of a correction term to account for this effect?

Reports, revisions and grading

The report should contain the following:

- A short introduction about alpha decays and the objectives of this lab
- The experimental method with enough details for the reader to be able to follow the procedures and reproduce the results – not in the same format as this lab manual. Describe the setup with words and pictures.
- List all the measurements with proper uncertainties in tables, graphs and histograms. Label the axes and units. Discuss the results by answering the questions listed above. All energy spectra should be calibrated, except the one with the ^{241}Am calibration source peak. For all figures (diagrams, tables, graphs, histograms, etc), you must make references to them at least once in the text.
- Describe the Bethe-Bloch formula used for energy loss/range calculations. List the special inputs (any non-constants) and any simplifying assumptions. Discuss possible

limitations of your model. In the appendix, provide the code you used to calculate the energy loss and range of α particles via the Bethe-Bloch equation.

Write in full sentences, unless you are providing a list of items.

One report per 2 students is encouraged. For lab sessions with an odd number of students, a 3-person group report is acceptable and preferred over a report written alone.

Suggested length: around 10 pages without counting the appendix for your code. Avoid small figures and small font sizes for the figure text.

Report file format: .pdf (use whatever typesetting software you prefer)

First lab report due date: within 10 working days after the lab

Submit your report on URKUND for plagiarism checks: joochun.park.lu@analys.urkund.se. Only one copy per group please.

Grading: the first version of the lab reports will be graded and returned with comments within 15 working days. Then you have several scenarios:

- You may choose to settle with the initial grade. Notify the instructor that you will not submit a revision, unless the instructor explicitly requests minor revisions.
- You may improve the lab grade by addressing the instructor's comments to report. Do NOT submit the revised versions on URKUND, because there will be many overlaps with the first version. There is no hard deadline for the second version. The final grade will be the average of the 2 reports, and it cannot be lower than the first grade.
- If your first grade was below 50%, then a sufficiently revised report must be submitted in order to pass the KF3 lab. You will receive either the average grade of the previous versions or 50%, whichever is greater.

A late submission of the first report will result in a maximum grade of 50%, regardless of a possible need to re-submit with revisions in the future.