Alpha Decay and Spontaneous Fission

Laboratory Exercise in Nuclear Physics

Note: Before attending the laboratory exercise, make sure you read the radiation safety information!

This laboratory exercise consists of three parts:

- Spectroscopy of an unknown alpha source.
- A measurement of the fragment energies from spontaneous fission of ^{252}Cf.
- A measurement of the energy loss of alpha particles in air as a function of air pressure.

Preparation: Read K.S. Krane, chapter 8 (alpha decay), chapter 13 (fission), and paragraphs 7.1 (Interactions of radiation with matter, the section about heavy charged particles) and 7.4 (semiconductor detectors). In the laboration a triple α-source containing the radioactive isotopes ^{244}Cm, ^{241}Am and ^{239}Pu will be used for energy calibration of the instrumentation. Calculate the $Q-$values of the alpha decays for these isotopes using e.g. the table of nuclear properties found at the Brookhaven National Laboratory website: http://www2.bnl.gov/ton/. Deduce the kinetic energies of the emitted α-particles from the $Q-$values.

Alpha Decay

Alpha decay involves the spontaneous emission of an alpha particle from an atomic nucleus. The alpha particle consists of two protons and two neutrons and is the same species as the nucleus of a helium (^{4}He) atom. These four nucleons have their origin in the nucleus X before the decay (the mother nucleus) and the nucleus is therefore transformed into a nucleus X' (the daughter nucleus) of another basic element according to the relation:

$$ {}^{A}_{Z}X_N \rightarrow {}^{A-4}_{Z-2}X'_{N-2} + \alpha, \tag{1}$$

where α is the alpha particle, N is the number of neutrons, Z is the number of protons, and $A = N + Z$ is the mass number.

Several naturally occurring isotopes decay by alpha emission. Figure 1 shows the four *radioactive series*, illustrating the chains of some heavy elements decaying by subsequent alpha- and beta particle emission. The half-life of the single isotopes in the chains varies over several orders of magnitude. Radioactivity from these isotopes is often found when measuring background radiation near or under ground, since ground minerals can contain uranium or thorium. These elements are also often found in small quantities in house building materials. The inert gas radon can escape the minerals, thereby making the air in an insufficiently ventilated room radioactive.

The alpha decay phenomenon has been utilised in a large number of applications. Examples include smoke detectors, power sources in unmanned spacecrafts and in cardiac pacemakers, and material analysis methods, e.g. the Rutherford backscattering technique.

Spontaneous Fission

For a limited number of heavy isotopes another decay mode, *spontaneous fission*, is strong enough to compete with alpha and beta decay. In this process, the nucleus separates into two large parts. Usually, a small number of neutrons are also released in the process.

If we compare the binding energy of a nucleus unstable to spontaneous fission to the binding energies of some typical fission fragment nuclei (e.g. see table in K.S. Krane, Appendix C), we immediately see that an substantial amount of energy is released as a result of the separation. This energy appears as kinetic energy of the two fission fragments and the emitted neutrons. The reason why the initial nucleus lives for some time before fissioning is the existence of a large Coulomb barrier that must be overcome via tunnelling in order for fission to occur.

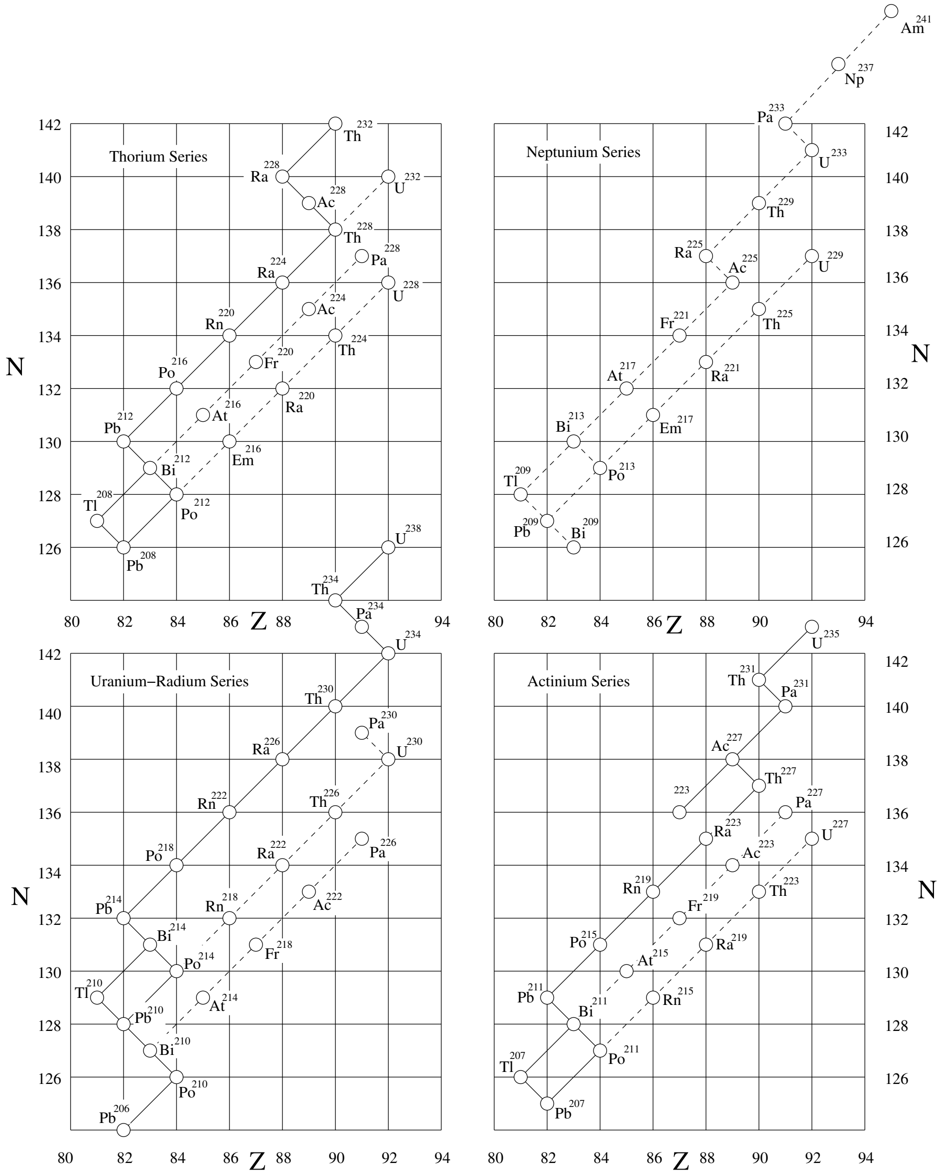

Figure 1: The four radioactive decay series of the heavy elements. Solid lines indicate naturally occurring decays, while dashed lines indicate decays from artificially produced radioactive isotopes.

The Interaction of Charged Particles in Matter

Rutherford performed pioneering work in the early twentieth century by studying the interaction of alpha rays with matter. This work, through the experiments carefully performed by Geiger and Marsden, eventually led to the discovery of the atomic nucleus. The problem on how charged particles interact with matter continued to be studied by Niels Bohr and others, and later the theory was developed by Hans Bethe and Felix Bloch. Thanks to these early efforts we have a good understanding today about how charged particles are decelerated when penetrating various materials.

When a charged particle at high velocity passes through a material it will slow down and change direction due to interactions with the surrounding atoms. The first effect is mainly due to inelastic scattering with atomic electrons in the material. The electric field of the incoming particle can interact with electrons several atomic distances from the particle trajectory and the electrons are thereby excited into a higher atomic orbit or completely detached from the atoms. If such a detached electron has high enough energy, it can interact with other electrons and excite or ionise the atoms. The electrons detached in such a subsequent interaction are called secondary electrons, as opposed to the primary electrons released by the interaction with the incoming charged particle.

The process responsible for the change in direction for the projectile is the elastic scattering against atomic nuclei in the material. This is a rare process which has only a small effect on the slowing down of heavy charged particles in matter. Other less common processes, such as nuclear reactions, can also occur depending on the energies and particles involved.

Since the deceleration of heavy charged particles in a material typically involves a large number of interactions, it is meaningful to introduce continuous quantities, such as the infinitesimal energy loss per travelled length in the stopping material: $\frac{dE}{dx}$.

A theory for the energy loss of charged particles in matter was developed by Bohr [**?**, **?**] around the same time as he developed his atomic model. The classical formula from this work reads:

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{4\pi z^2 e^4}{m_e v^2} N_e ln \frac{\gamma^2 m v^3}{z e^2 \hat{\nu}} \tag{2}$$

This formulation gives reasonable results for alpha particles and heavier ions, but does not work well for protons because of quantum effects. A proper quantum mechanical approach was made by Bethe, Bloch and others in the 1930s resulting in the *Bethe-Bloch formula*, the most well-known expression for calculating the energy loss of charged particles in matter:

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \frac{4\pi z^2 N_a Z\rho}{m_e c^2 \beta^2 A} \left[\ln\left(\frac{2m_e c^2\beta^2}{I}\right) - ln(1-\beta^2) - \beta^2\right], \qquad (3)$$

where $v = \beta \cdot c$ is the velocity of the particle, z is its proton number, Z, A, and ρ are the atomic number, atomic weight, and mass density of the material. N_a is Avogadro's number, m_e is the electron mass, and I is the mean excitation energy of the atomic electrons in the stopping material.

Modern calculations also include features like *shell corrections* and *density corrections* [**?**]. Today, the energy loss for ions in several materials can be calculated easily using existing computer software, e.g. the SRIM programme [**?**]. By dividing the stopping power by the density of the material, the mass stopping power, $\frac{1}{\rho}\frac{dE}{dx}$, is obtained. This is a useful quantity since the mass stopping power varies less between different materials than the linear stopping power.

The Experimental Setup

Since alpha particles and fission fragments have a limited range in air at normal pressure, we have to remove the air between the source and the detector. Two different vacuum chambers are used in the exercise. A schematic picture of the setup is drawn in figure 2. A mechanism for changing radioactive sources is mounted in the large chamber. In this way, we can choose between any of three different sources (and one empty position) without breaking the vacuum. In the small vacuum chamber (located in a NIM module together with the electronics) we can control the air pressure by adjusting a valve. You may open the small vacuum chamber (when it is at atmospheric pressure) and inspect the α source and the Si surface barrier detector. Be careful not to touch the surface of the α source! In both vacuum chambers we use the same type of surface barrier semiconductor (Si) detector. The energy signals from the Si detector are amplified and shaped by the preamplifier and main amplifier modules and subsequently digitised and stored by a multi-channel analyser (MCA) card residing in a PC . The *Maestro* software displays the energy data on the computer screen and can be used to analyse the spectrum.

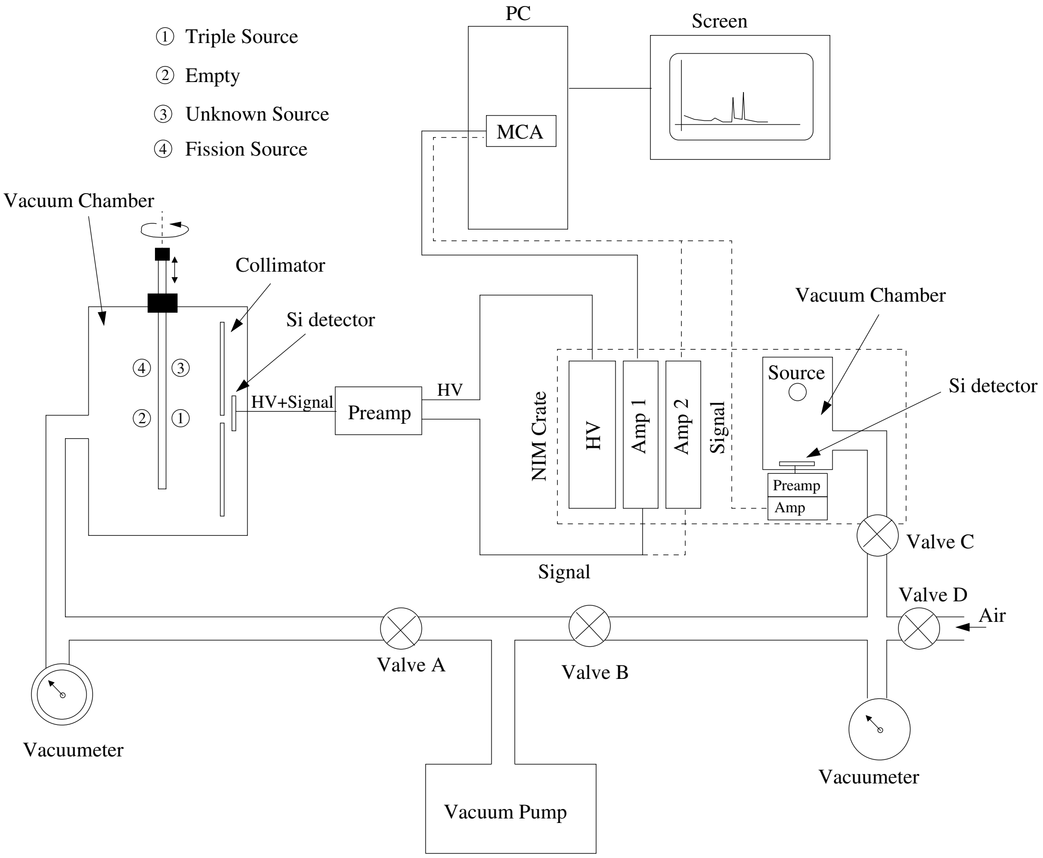

Figure 2: A schematic view of the two vacuum chambers and the electronics for energy measurements of alpha particles and fission fragments. A surface barrier silicon detector (one in each chamber) is used to detect the energy of the incoming particles. Three different radioactive sources are mounted on a manipulator rod in the large vacuum chamber. A fourth position is used when not measuring. By pulling/pushing or rotating the rod 180°, the source of interest is put in front of the collimator and the detector is then shielded from the other two sources. The rod should be placed in position #2 when the measurements are finished, so that the detector is not irradiated unnecessarily. The venting valve (D) in the picture is used to control the pressure in the small vacuum chamber by letting in small amounts of air at a time. A multi-channel analyser (MCA) card in the PC is used to collect the data. The energy spectrum is displayed on the computer screen. The two main amplifiers #1 and #2 can be set at a high and a low gain in order to accomodate the different energy ranges for α particles and fission fragments, respectively.

The Measurements

Before starting the measurements, let the laboratory assistant explain the proper handling of the vacuum system. In case of incorrect use, oil from the vacuum pump can pass into the vacuum chamber and damage the Si detector. Follow the lists of points below to perform the measurements.

Calibration

The triple alpha source (^{244}Cm, ^{241}Am and ^{239}Pu) with known alpha energies is used to obtain a good energy calibration.

- Place source #1 facing the Si detector using the rod manipulator.
- Start the data acquisition with the MCA software. Record an energy spectrum of the triple alpha source using the surface barrier Si detector in the large vacuum chamber.
- Explain the details of the spectrum. Can one alpha decay give rise to more than one peak? Look in the *Table of Isotopes* and discuss with the assistant.
- Use the deduced energies of the main alpha peaks to calibrate the MCA with the Maestro software.

Unknown Source

The source in position #3 in the large vacuum chamber is an unknown source that contains naturally occurring radioactive isotopes.

- Measure the energies from the unknown alpha source.
- Compare with the decays of the radioactive series, see figure 1. Use the *Table of Isotopes*. What element/elements is/are involved? What material is the unknown source made of?
- Can we say anything about the age of the source?

Spontaneous Fission

The radioactive source placed in position #4 in the large vacuum chamber is ^{252}Cf. This nuclide is unstable against alpha decay as well as spontaneous fission.

- Collect data to obtain a new energy spectrum. Adjust the amplifier to see details in different energy regions. Identify both fission fragment bumps and the alpha peaks. Determine the alpha energies.
- What are the approximate energies for the fission fragment distributions? Can we rely on these energies with the current calibration? Discuss with the assistant.
- What can we say about the mass distribution of the two fission fragments? Which fission fragment bump belongs to which fission fragment mass distribution (large/small masses)?
- Finally determine the branching ratio between alpha decay and spontaneous fission in ^{252}Cf.

Determination of the Range of Alpha Particles in Air

The last measurement is made using the small vacuum chamber in the NIM electronics crate. It contains a triple alpha source (^{244}Cm, ^{241}Am ,^{239}Pu) and a silicon surface barrier detector.

- Think of how you can determine the range of the alpha particles in air at atmospheric pressure using the equipment at hand.
- Meausure the alpha particle energies as a function of pressure. Use the vacuum valve to control the air pressure in the chamber. Measure at about ten different pressure values. Plot the results.
- Record also the energy resolution as a function of pressure. Can you explain the observed effect?
- Deduce the range of the alpha particles in air at 1 atm.
- Produce a $\frac{dE}{dx}$ curve for alpha particles in air.

Questions to answer before the laboratory exercise

Find the answer to the following questions and discuss them with the assistant before starting the measurements.

- How can the physical mechanism behind alpha decay be described in simple terms?
- What can we say in general about the efficiency of a typical alpha particle detector?
- Explain why alpha decay is sometimes accompanied by gamma emission.
- Will the range (in for example silicon) of a typical fission fragment be larger or smaller than the range of an alpha particle at a typical decay energy?

Report

The students should write a report after the laboratory exercise to be handed in to the laboratory assistant at a later date.