PHYS307 - Applied Modern Physics

Spring 2021

Experiment 5 - Spectra of Alpha Particles

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Introduction

In this experiment, our aim is to study the properties of α-particles and observe the energy spectrum of radiation emitted by ^{226}Ra, then identify an unknown α-particle source and quantify its activity.[1]

Radioactivity is defined as the process of atomic nuclei that is characterised as unstable, losing energy by the means of radiation. As there are different mechanisms for this process to occur depending on the radiating nuclei, there are different types of radiation. These types are α radiation, β radiation and γ radiation named after the particle created as a result of the process.[2] In this experiment, we will be working with the *alpha* particles.

As radioactivity is the result of unstable nuclei decaying into other particles, there are certain quantitative measurements which specifies the properties of this decay. First of these measures is the decay rate. Decay rate is the number of decay events occuring in a small time interval and it is related with the number of nuclei in the sample.[1]

$$\underbrace{-\frac{dN}{dt}}_{\text{Decay Rate}} = N\lambda \tag{1}$$

This quantity is also named activity and denoted as R and has the units Becquerel(Bq). 1 Becquerel is equivalent to one decay event per second.

$$R = \underbrace{-\frac{dN}{dt}}_{\text{Decay Rate}} = N\lambda \tag{2}$$

Another quantitative measure is the half-life. Half-life quantifies the amount of time required for the number of particles in the sample to halve due to decay. As the decay is modelled with a first order differential equation, its solution is of the exponential form.

$$N(t) = N_0 \exp(-\lambda t) \tag{3}$$

where N_0 denotes the amount of nuclei in the beginning. This equation can solved for t such that the initial amount of nuclei is double the amount of current. This leads to

$$t_{1/2} = \frac{ln(2)}{\lambda} \tag{4}$$

Alpha decay is the process in which the decaying nuclei radiates an alpha particle which is itself a helium nucleus. This process can be shown with the following equation

$$ {}^{A}_{Z}\mathrm{X} \rightarrow {}^{A-4}_{Z-2}\mathrm{Y} + {}^{4}_{2}\mathrm{He} \tag{5} $$

In this equation, X is the mother nucleus and Y is the daughter nucleus. As it can be seen from the equation, mother nuclei has greater atomic (A) and mass (Z) number than daughter nuclei. This difference is what creates the Helium nucleus. Since α particle has atomic number 4 and mass number 2, it can be said that daughter nucleus is 4 atomic, 2 mass number lesser than the mother nucleus, therefore it is lighter than it.

Having said that daughter nucleus is lighter than the mother nucleus and there is a new particle created, this process should be consistent with the principles of conservation of energy and conservation of momentum. After writing the equations for these principles and taking mass-energy equivalence into consideration, we obtain the following equation

$$ K_{\alpha} = \frac{A-4}{A} Q \tag{6} $$

α decay occurs in nucleus with high mass[13] therefore A is considerably greater than four. This implies that the quotient part of the equation is lesser than but significantly close to unity. Since Q denotes the kinetic energy (following from mass-energy equivalence) which results from the fact that the sum of resulting masses are being less than the initial mass (that is mother nucleus) we can reach the conclusion that the majority of disintegration energy will be taken by the α particle.[1] Therefore, during the experiment we can expect the kinetic energy of α particles to be roughly equal to the Q value of the decay. This is an important fact for our experiment since we can use their kinetic energies to specify their source using Q number.

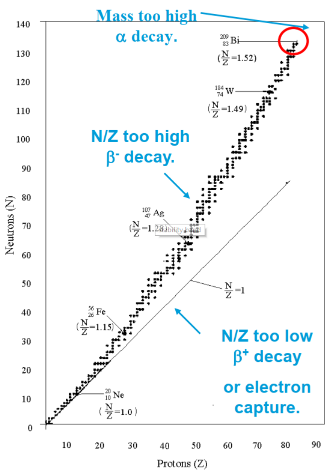

Figure 1: In this figure, neutron and proton numbers are tabulated and the resulting process is shown.

As discussed previously, there are other types of decays called β and γ decay. β decay is a result of too high or low N/Z ratios which is the ratio of number of neutrons to the number of protons, unlike α decay which is determined by the mass. Too high or too low N/Z ratio causes imbalance between strong nuclear force and electrostatic force, this causes the nuclei to be unstable. While undergoing this process, the nuclei emits a β particle which can be either a β^- (when N/Z is too high) or β^+ (when N/Z is too low), the β particle itself is an electron (or positron depending on the sign shown previously).

On the other hand, in γ decay, γ particles which are photons with very high energy are released. γ decay usually accompanies other types of decay and happens after them if some conditions are met. For example, if the daughter nucleus of a decay is left in an excited state, it can further undergo γ decay in order to return to a lower energy state[4]

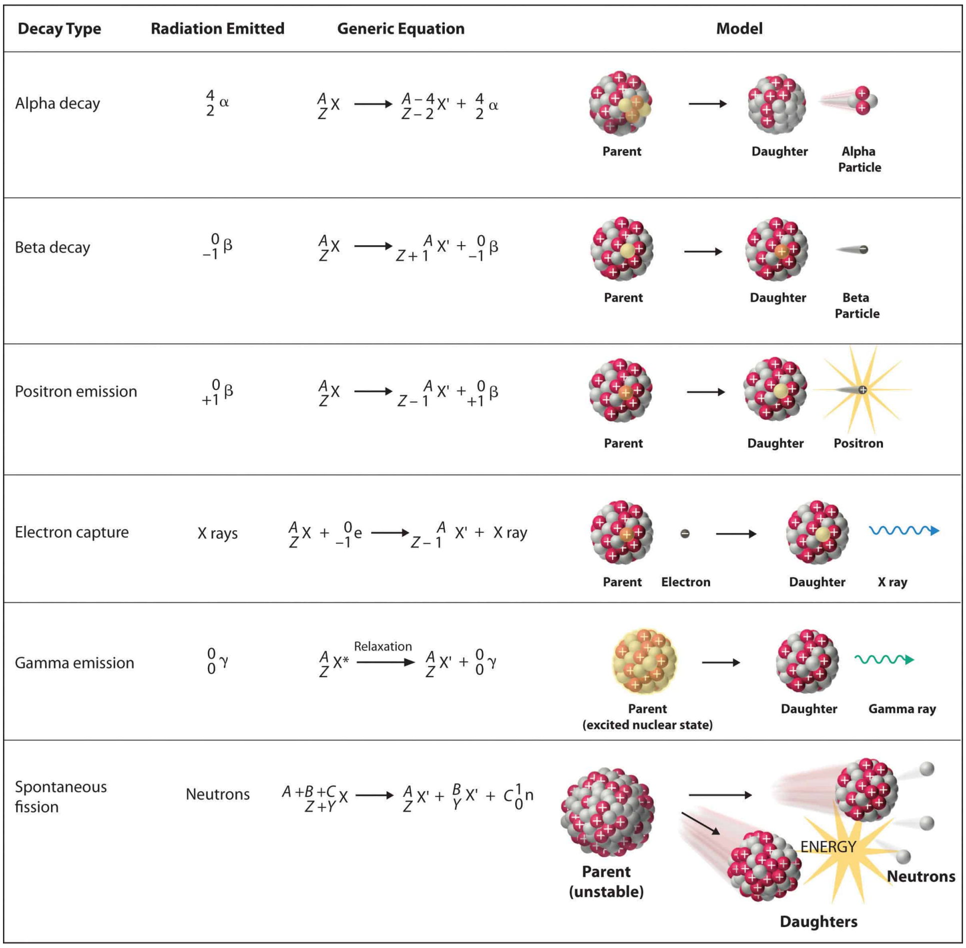

Figure 2: This figure shows different types of radioactive decay processes along with their emitted particles

Each of these three different particles have different properties in terms of their energies and penetration power. The α particles consist of 2 neutrons and 2 protons, therefore they are considerably heavy particles with high energy, thus their ionization power is very high.[1] However, they are positively charged particles which can cause them to interact with other atoms and they are massive so they lose a great deal of energy while traveling in matter.[1] This causes their penetration power to be relatively low, as in they can even be blocked by a piece of paper.

Experimental Details

Our experimental setup consists of the following equipment

- Alpha Source

- Detector
- Vacuum Gauge
- Vacuum Pump
- Vacuum Tube
- Pre-Amplifier
- Multi Channel Analyser
- Computer
- Power Supply

The main part of the experiment is the vacuum tube which houses both the radiation source and the detector. Inside the vacuum tube, the source is positioned with the knobs on one end of the tube so that it is close to the detector as much as possible. The reason of this positioning is the same with the reason of using a vacuum tube in the first place. As stated previously, α particles can easily blocked by matter on the contrary to say, γ particles. Therefore if we are to perform an experiment with α particles, we should take this effect into consideration, however it wouldn't be a problem with γ particles. Hence, the air is evacuated from the environment to prevent interaction between matter and α particles. The vacuum is provided by the vacuum pump and it can be measured with the vacuum gauge. The positioning of the source also aids this purpose, since it is impossible to create perfect vacuum it is desirable to position the detector and source as close as possible to minimise any contact with air.

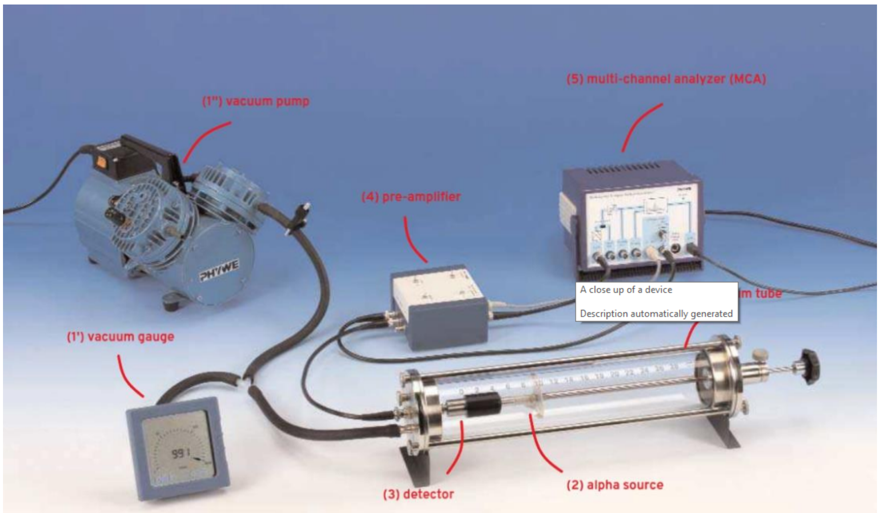

Figure 3: Experiment Setup

The detector that detects α particles is a surface barrier (a type of diode) type detector and it is made of silicon.[1] The p-n junction that makes up the diode consists of holes (lack of negative charges so positively charged) on the p side and electrons (excess of electrons so negatively charged) on the n side. When a voltage is applied on the inverse direction, p-type connected to negative terminal and n-type connected to positive terminal, (reverse-bias voltage, otherwise current will flow freely) the electric field causes charges to move away from center thus leaving a region called depletion region in the center of the junction, whose size can be adjusted with the reverse-bias voltage, this reverse-bias voltage is provided by the power supply. Since the charges are separated, there should be an electric field in the depletion region, this acts as a barrier and makes the diode act as insulator. Since α particles are charged, they are also blocked by the electric field of this depletion region, so this junction acts as a potential barrier to the α particles. When α particles deposits their energy in the depletion region they create free electron-hole pairs in this region[3] and due to the electric field present, these pair move towards their respective sides (electrons to n-type, holes to p-type) and this creates an electric current which can be measured. Essentially, we can utilize this type of detectors since α particles carry electric charge.

The pre-amplifier has two roles in this experiment, it amplifies the charge pulses created by the detector and converts them into voltage pulses.[5] In general, transistors are utilized for the signal amplification and capacitors are used to convert charge build up into voltage as charges on the capacitor plates create potential difference.

Then, the voltage pulses created by the pre-amplifier arrives to the multi-channel analyser. This device has multiple important roles in the experiment. First, the signals are further amplified so that they can be measured. Then the voltage pulses are sorted according to their pulse heights and they are grouped together within a certain interval and assigned a channel, this channel contains information about number of signals within the given range of the interval.[6] By looking at **Equation-11** in the lab manual and recalling the previous discussion (energy deposition causing current) about the detector, we can say that our detector provides us signals with increasing pulse height with respect to energy of the particles, the multi-channel analyser allows us to transform our observations to a some kind of spectra by grouping signals from particles with similar energies into groups and assigning them a channel. If we are to make an analogy, the channels corresponds to the different colors and the number of pulses in the channels corresponds to brightness in the spectra of light when diffracted by a prism or grating. The data created by the multi-channel analyser can be observed by the software that can be found in the computers used in the experiment.

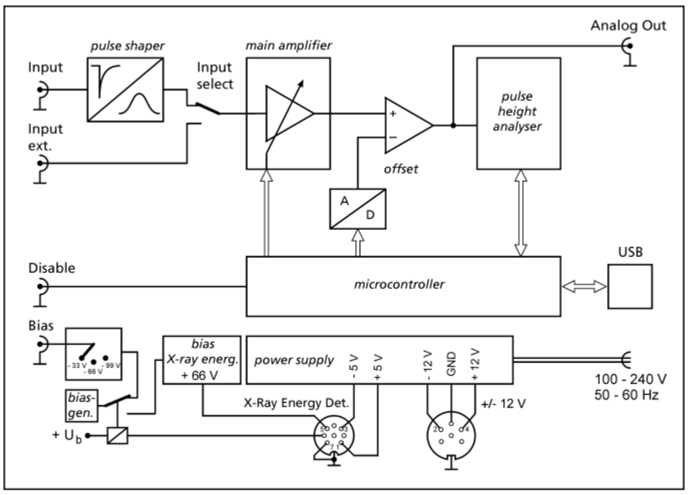

Figure 4: Functional Diagram of the MCA

Data & Measurement

First Part

From the first part of the experiment, we've obtained the following data As the multi-channel analyser

Channel Number (Peak)	Sources of Alpha Particles	Energy (keV)
1183	Ra-226	4780
1538	Rn-222	
1801	Po-218	
2653	Po-214	7680

Table 1: Data Obtained from the Experiment

groups the voltage values of the signals into bins in a linear fashion, therefore expected energy values of the channels and their channel numbers should be linearly related. Using this knowledge, we can obtain the energies for second and third channels using linear interpolation

$$\text{slope} = \frac{E_{\text{last row}} - E_{\text{first row}}}{Ch\#_{\text{last row}} - Ch\#_{\text{first row}}} = \frac{7680 - 4780}{2653 - 1183} = 1.972 \tag{7}$$

This slope can be used in the general line equation

$$y - y_1 = m * (x - x_1) \tag{8}$$

In this case, x axis denotes the channel number and y axis denotes the energy levels by the specifications of the plotting specifications of the multi-channel analyser. By choosing our reference as the channel in the first row of **Table-1** we obtain the following expression to interpolate energy levels between first and last row.

$$E = 1.972 * (Ch\# - 1183) + 4780 \tag{9}$$

So for the second row of **Table-1**

$$E_{\text{Ch 1538}} = 1.972 * (1538 - 1183) + 4780 = 5480.06\ keV \tag{10}$$

We repeat the same procedure for the remaining data

$$E_{\text{Ch 1801}} = 1.972 * (1801 - 1183) + 4780 = 5998.696\ keV \tag{11}$$

So the **Table-1** can be completed as

Channel Number (Peak)	Sources of Alpha Particles	Energy (keV)
1183	Ra-226	4780
1538	Rn-222	5480.06
1801	Po-218	5998.69
2653	Po-214	7680

Table 2: Data Obtained from the Experiment with Interpolated Values for Second and Third Row

In the experiment manual, the theoretical energy values for Rn-222 and Po-218 are given as 5480 keV and 6000 keV respectively. Now we can calculate the true percentage error using

$$\epsilon_t = \left| \frac{\text{true value} - \text{experimental value}}{\text{true value}} \right| * 100\%$$

For Rn-222, the error can be calculated as

$$\epsilon_t = \left| \frac{5480 - 5480.06}{5480} \right| * 100\% = 0.001\% \tag{12}$$

and for Po-218

$$\epsilon_t = \left| \frac{6000 - 5998.69}{6000} \right| * 100\% = 0.02\% \tag{13}$$

Part Two

For an unknown α particle emitter, following data was obtained from the multi-channel analyser

$$\text{Channel Number} = 1355 \tag{14}$$

The previously obtained slope and reference point for linear interpolation can be used to estimate the energy level for this source

$$E_{\text{Ch } 1355} = 1.972 * (1355 - 1183) + 4780 = 5119.184\ keV \tag{15}$$

Therefore **Equation - 14** and **Equation - 15** can be tabulated as

Channel Number (Peak)	Energy (keV)	Sources of Alpha Particles
1355	5119.184	

Table 3: Assigned Channel of the Pulses from Unknown Source and Estimated Energy

Using a lookup table[7] and a pre-determined error margin of ± 5 we can find the possible candidates for the unknown α source.

Energy (keV)	Intensity (α per 100 decay)	Parent
5114.9	100	^{208}Po (2.898 y)
5115.4	100	^{207}Po (5.80 h)
5516	0.10	^{209}At (5.41 h)
5117.20	0.0004	^{241}Am (432.2 y)
5118	100	^{176}Ir (8 s)
5119	0.6	^{230}Pa (17.4 d)
5123.68	27.1	^{240}Pu (6563 y)
5128.7	0.00062	^{227}Th (18.72 d)
5131	0.38	^{210}At (8.1 h)
5131	0.0020	^{224}Ac (10.0 d)
5133	N/A	^{241}Am (432.2 y)

Table 4: Candidates for the Unknown Source with ^{230}Pa Being the Closest in Terms of Energy Value

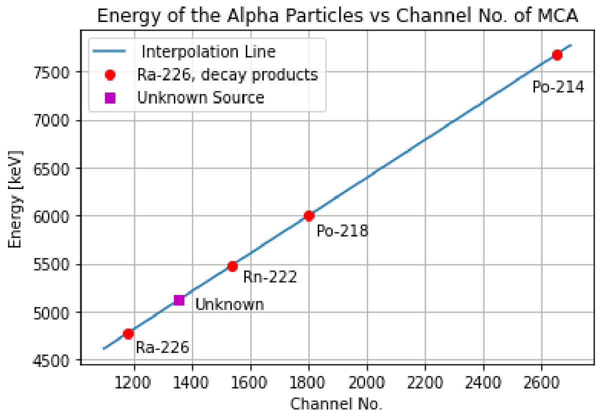

Figure 5: This figure shows the energy and channel number of Ra-226 and its decay products along with a linear interpolation line and data from an unknown source

Discussion & Conclusion

Previously, we have narrowed down our search to eleven candidates but there are still some assumptions that we can make in order to narrow down the list further.

- As it is used in a student experiment and we are aware that the source is held bare handed during experiment, its activity must not be too high.
- On the other hand, data acquisition happened significantly fast. Therefore its half-life can't be too long.

We know the relation between the half-life and activity to be inversely proportional. Shorter half-life implies higher activity and vice versa. By the first given above, the half-life can't be too short, and by the second reason, its half-life can't be too too long either.

Using this assumption, we eliminate the sources with half-life shorter than 100 years and longer than 700 years. The only parent nuclei that satisfy this criteria is ^{241}Am. In **Table-4**, there are two entries for ^{241}Am with different energy levels. In the original table provided, energy values for some entries had subscripts but a legend was not provided so they were omitted from **Table-4**. The two entries of ^{241}Am differ by energy levels (5117.20 and 5133) and the subscripts, also intensity data for the second entry is missing. Since the energy value for second entry of ^{241}Am is relatively high and its intensity is missing, that entry is disregarded. Therefore, our only candidate left is ^{241}Am with energy level of 5117.20 keV. Since we have determined our unknown source, we can proceed with error calculations.

We define our error as the error of experimental energy value and theoretical energy value. Therefore

$$\epsilon_t = \left| \frac{^{241}\mathrm{Am}_{\mathrm{theoretical}} - {}^{241}\mathrm{Am}_{\mathrm{experimental}}}{^{241}\mathrm{Am}_{\mathrm{theoretical}}} \right| * 100\% = \left| \frac{5117.20 - 5119.184}{5117.20} \right| * 100\% = 0.038\% \tag{16}$$

is our experimental error. Even though it is still relatively low, the error on this part is greater than the errors we've calculated in Part-I, that is for the Ra-226 decay.

There are a number of possible sources for this error, one of the most apparent ones is the imperfect vacuum which causes absorption of α particles by matter (especially air). Even though the calculated errors are relatively small, we have observed only nine peaks instead of four. This is caused by the aforementioned imperfections as the energies of the remaining peaks are small, and they are further attenuated by air. We should also note that there is a thin metallic window on the source which prevents contamination, however it also absorbs some of the α particles just like air. We can also discuss the errors related with electronic equipments such as noise etc. In order to improve our measurements and calculations, we can use a source with no metallic window (making sure it is not contaminated) and increasing the power of the vacuum pump. By doing such improvements we may be able to observe all nine peaks. Moreover, we can also repeat the experiment multiple times and average its results before calculating a slope for linear interpolation so that we can increase the resolution of our measurements and reduce experimental errors.

As described above, less than perfect vacuum is one of the reasons that makes some of the peaks. Therefore, reducing the quality of vacuum, even completely removing it will effect the experiment negatively. Some of the peaks might disappear, even all of them might disappear if the air is particularly dirty (dust etc). If this were the case, the arriving α particles would have less energy, since the channels assigned by MCA are related to their energy, lower energy will correspond to lower channel numbers which implies a shift of the peaks towards left.

While discussing the outcomes of a hypothetical absence of a vacuum tube in the experiment, we said that the effects will be even more intense if the air is not clean. Even though there are differences, the operating principle of an ionization type smoke detector works on similar grounds. Emitted α particles ionize air in two chambers one of which is isolated from outside environment. Due to the potential difference between the electrodes in these two chambers, electric current is carried across electrodes by these ions. When smoke enters the non-isolated chamber, it interferes with the current flow as ions are attached to smoke particles.[8] An electric circuit compares the current flows in both chambers and sounds an alarm if it detects a difference. Such devices can be built with α particle emitters due to the fact that α particles are highly ionizing so that they can ionize air molecules.

Appendix

```
import numpy as np
import matplotlib.pyplot as plt

channelValues = np.arange(1100,2800,100)
lineEqn = lambda x: 1.972*(x - 1183) + 4780

channelNumbers = np.array([1183, 1538, 1801, 2653])
energies = np.array([4780, 5480.06, 5998.69, 7680])

unknownSource = np.array([1355, 5119.184])

fig, ax = plt.subplots()
ax.plot(channelValues, lineEqn(channelValues),label = ' Interpolation Line')
ax.plot(channelNumbers, energies,'ro', label = 'Ra-226, decay products' )
ax.plot(unknownSource[0],unknownSource[1],'ms', label = 'Unknown Source')
ax.set_ylabel('Energy [keV]')
```

```
ax.set_xlabel('Channel No.')
ax.legend()
ax.grid()
ax.set_title('Energy of the Alpha Particles vs Channel No. of MCA')
ax.text(0.16, 0.05, 'Ra-226', horizontalalignment='center', verticalalignment='center',
    transform=ax.transAxes, color = 'black')
ax.text(0.37, 0.26, 'Rn-222', horizontalalignment='center', verticalalignment='center',
    transform=ax.transAxes, color = 'black')
ax.text(0.51, 0.4, 'Po-218', horizontalalignment='center', verticalalignment='center',
    transform=ax.transAxes, color = 'black')
ax.text(0.93, 0.83, 'Po-214', horizontalalignment='center', verticalalignment='center',
    transform=ax.transAxes, color = 'black')
ax.text(0.29, 0.18, 'Unknown', horizontalalignment='center', verticalalignment='center',
    transform=ax.transAxes, color = 'black')
fig.savefig('plot.png',facecolor = 'w', bbox_inches = 'tight')
```

References

[1] The energy spectra of alpha particles - lab manual.

[2] Radioactive decay. https://en.wikipedia.org/wiki/Radioactive_decay. Access Date: June 21, 2021.

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[6] Multichannel analyser - owner's manual. https://www.phywe.com/physics/modern-physics/quantum-physics/phywe-multichannel-analyser-mca_2196_3127/. Access Date: June 21, 2021.

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