Lab Report

EXPERIMENT 6: Radioactivity

Group 10
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We hereby declare that we are the sole authors of this Lab Report and that we have not used any sources other than those listed in the bibliography and identified as references. We further declare that We have not submitted this thesis at any other institution in order to obtain a degree.

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Contents

1 Abstract

The investigation is mainly concerned with measuring radioactive decay of samples Barium-137m Americium-241, and their activity to compare with theoretical predictions for half-life, by capturing the decay rate and the effect of different shielding materials to observe the range and energy levels of α and γ radiation.

The background radiation was measured to be $(14.60\pm 0.40)\ min^{-1}$. Using the Poisson distribution, we found the value of mean count rate per second (CPS) of the AM-241 sample to be$A_{Am} = (2.6 \pm 1.7)s^{-1}$, Additionally, the range of alpha particles through was found to be $d_\alpha = (22 \pm 1)mm$.

Finally, the halflife of Ba-137 was found to be $t_{1/2} = (169.06 \pm 0.62)s$.

Introduction

In this experiment, we will focus on determining the half-life of various radioactive samples by conducting precise measurements and calculations. Additionally, we will investigate how different materials interact with and absorb radiation, examining the attenuation effects based on material type and thickness. To achieve these objectives, we will employ a range of experimental techniques. A detailed discussion of these methods, along with the underlying principles governing radioactive decay and radiation absorption, will be provided.

Radioactive decay is a random and spontaneous process in which an unstable atomic nucleus transforms into a more stable configuration by emitting radiation, which comes in the form of alpha particles (helium nuclei), beta particles (electrons/positrons), or gamma rays (photons). The happens because the nucleus has excess energy or an imbalance in nuclear forces, making it unstable, for example, α emission:

$$^{226}_{88}Ra \to {}^{222}_{86}Rn + {}^{4}_{2}He$$

Radioactivity is a process which in nature occurs in a highly random and unpredictable way, but in a general sense, the rate of decay follows a trend of exponential decrease in rate. One can measure the number of particles N that have yet to decay from a sample with starting number of nuclei N_0 at a time t using the following equation [2]:

$$N(t) = N_0\ e^{-\lambda t} \tag{1.1}$$

Where λ represents the decay constant of the radioactive sample. To find the decay constant, we use Equation (1.1), which can be linearized by taking the natural log on both sides

$$\ln\ N(t) = -\lambda t + \ln\ N_0 \tag{1.2}$$

Using $\ln\ N$ against t for Ba-137m. Due to the random decay of particles, another quantity which is relevant is the time taken for half of the particles of a sample to decay. This is known as half life and can be derived from Equation (1.1) by finding the appropriate $t_{1/2}$ such that $N(t_{1/2}) = \frac{N_0}{2}$:

$$N(t) = \frac{N_0}{2} = N_0\ e^{-\lambda t}$$

$$\frac{1}{2} = e^{-\lambda t} \iff \ln\ 2 = \lambda t$$

$$t_{1/2} = \frac{\ln 2}{\lambda} \tag{1.3}$$

Moreover, one can take the derivative of $N(t)$ with respect to t to find the rate of decay of nuclei - known as the "*Activity*" or Count Rate of the radioactive sample and measured in Becquerels (Bq) - because it concerns the number of samples that decay per unit of time [2]:

$$A(t) = \frac{dN}{dt} = -\lambda N_0 e^{-\lambda t}$$
$$A(t) = A_0 \; e^{-\lambda t} \tag{1.4}$$

Attenuation of different materials

Attenuation refers to the gradual reduction in the intensity of radiation as it passes through a specific material. This occurs due to absorption and scattering of radiation by atoms in the material. The effectiveness of attenuation depends on the type of radiation, the material's properties such as density and atomic number, and the energy of the radiation itself. The general behavior of attenuation follows an exponential decay law, where the intensity of radiation decreases as it penetrates further into a material.

Different types of radiation interact with materials in different ways. Alpha particles, due to their high mass and charge, are easily absorbed and can be stopped by a few centimeters of air or even a sheet of paper. Beta particles require slightly denser materials such as plastic, glass, or a few millimeters of aluminum to reduce their intensity, as they lose energy through ionization. Gamma rays, however, being highly penetrating, require materials with high atomic numbers such as lead or thick layers of concrete to be effectively attenuated. These materials absorb gamma radiation through processes such as the photoelectric effect.

The effectiveness of a material in shielding radiation is often quantified by its attenuation coefficient μ. This represents the degree of which a material can shield away radiation

2 Experimental Setup and Procedure

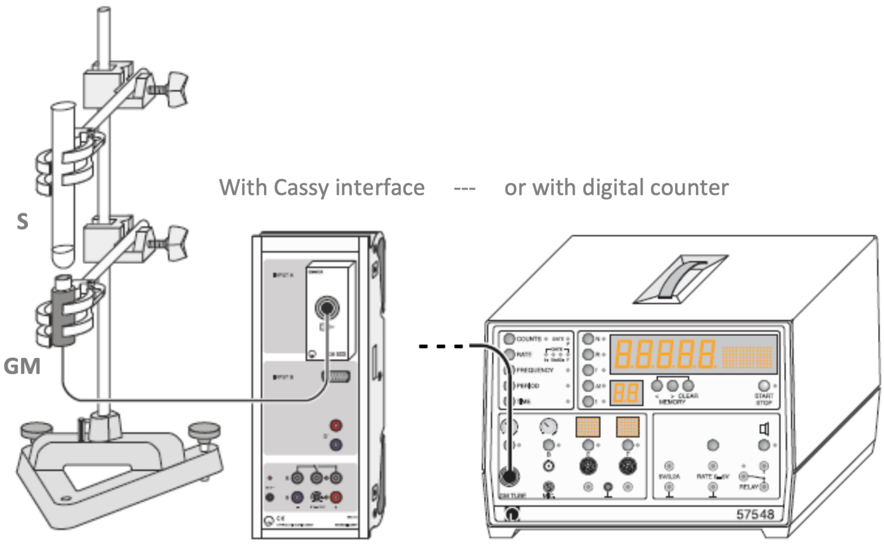
Equipment List

- Am 241 sample with protection housing
- Geiger Muller tube with digital counter
- Cassy interface
- Plates of different material and holder
- Cs-137 isotope generator
- Laptop

The setup was done using a Geiger-Müller tube to capture the Count Rate by positioning the sample directed towards the opening of the tube at specific distances. The digital counter was connected directly to the tube and into the laptop. The substance and tube were both held by a stand with a small clamp facing away from the room.

The following **(Figure 2.1)** is a picture of the setup utilized for the measurements of Ba-137m.

Figure 2.1: Setup for GM - Tube using Digital Counter



Possible sources of error include the positioning of the source being at an angle, the measurement of the distance, the effect of background radiation, and the setup within the Geiger-Müller tube. To minimize this, some measurements were taken to record the effect of background radiation to adapt all further measurements and a test on the optimum voltage for the GM-Tube.

Safety with Radioactivity

Working with radioactive substances in our experiment was conducted under strict safety regulations to ensure the well-being of all participants. At Constructor University, the handling of radioactive materials follows federal and state laws, specifically the Radiation Protection Regulation (Strahlenschutzverordnung, StrlSchV)

The radioactive substances used in this experiment were carefully selected and tested according to the StrlSchV guidelines, ensuring their suitability for educational purposes. The experiment was conducted in a controlled and safe environment, by minimizing exposure, maximizing distance and using appropriate shielding against the Radioactive Samples as well as adhering to other practices for radiation safety. In case of any concerns, designated radiation protection officers were available to provide assistance. These precautions ensured that all activities were performed in a safe, regulated, and compliant manner, protecting both participants and the surrounding environment.

Setting Up the GM Tube

The Tube measures radioactivity by detecting particles from a noble gas ionized by the Am-241 inside the tube that are then recieved by a cathode to detect a count. The anode is a wire connected to the tube with a given voltage to allow the acceleration and collision of ionized particles.

Below the threshold Voltage V_T, The particles that are ionized by the radiation do not experience sufficient attraction force to electrode. At some point they will begin to do so and the GM Tube will detect until all charged particles are attracted to the electrode. There will be a range of values of the voltage which will produce a similar count rate for which the GM Tube displays. This is the operating range $\mathbb{V}_P$ of the Tube and is known as the Plateau in the curve. If the voltage is then increased beyond this range, it will begin capturing random spikes and allow continuous discharge from the apparatus.

For the procedure, we measured the count rate starting from a Voltage of 100V and increased by 20V after each measurement, until reaching a voltage of 500V. The Digital counter was set to: Imp, Gate Time: 10 seconds.

Background Radiation

Background radiation is the constant presence of radiation in the environment, originating from sources such as cosmic rays and naturally occurring radioactive materials in the Earth. As a result, all measurements taken with a GM tube are systematically influenced by background radiation. Therefore, the count rate from the environment must be accounted for when analyzing the activity of Am-241. The objective is to determine the background radiation activity in counts per minute, the digital counter was set to measure the rate with a gate time of 1 minute, and data was collected over a total of 5 minutes, resulting in $n = 5$ separate readings for background activity. Then utilizing the equations for Mean and Standard Error, one can compute the me fan count $\overline{N} \pm \Delta\overline{N}$ of background radiation with equations 2.1 [1]:

$$\overline{N} = \frac{\sum_{i=1}^{n} N_i}{n} \qquad \Delta\overline{N} = \frac{\sigma_N}{\sqrt{n}} \tag{2.1}$$

Where N is the number of nuclei decayed, n is the number of measurements done, and σ_N is the standard deviation for N. The formula for standard deviation for any set of averaged values of a variable x_i is given as [1]:

$$\sigma_x = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{2.2}$$

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Poisson Distribution for Activity of Am-241

Due to the random nature of the radioactive decay rate of a substance, we decided to measure the frequency of different count rates R (measured in s^{-1}) and compare them using a Poisson distribution. Since random decay normally follows Poisson statistics we expect the data to resemble a normal distribution but with a noticeable bias toward lower count rate. This skew arises because, in a Poisson process, there is a higher probability of measuring lower count rates. To calculate the error of the mean, for all Poisson distributions the equation in 2.3 is used [1]:

$$\Delta\lambda = \pm\sqrt{\lambda} \tag{2.3}$$

Where λ is the expected mean number of events occurring in a fixed time interval during any process that follows Poisson statistics.

Measuring Distance of Alpha radiation

Due to the high mass of α radiation, it is known to travel only about 2-3 cm in air before becoming undetectable. To verify this range, the procedure involves recording the count rate R of the Am-241 sample at varying distances to observe its effect on activity. A second trial is then conducted using the same sample and distance measurements, but with an A4 sheet of paper that acts as an absorber which completely blocks α radiation, allowing only γ radiation to be detected. When plotting distance against the natural logarithm of the count rate, a sharp drop in the first plot clearly indicates the distance at which α particles are fully absorbed by air. The gate time utilized in the digital counter is 10 seconds and we stopped the recordings after every measurement to ensure that the displacement of the sample was done accurately and safely.

Gamma Radiation Absorption of different materials

When measuring how different materials absorb gamma radiation, we fixed the detector 2.5cm away from the source to be able to compare the counts detected by the GM tube and to see the relative effect that Pb, Fe, Al, hard paper and plexi-glass has on the number of decayed photons received N_{mat} in proportion to the original counts detected by measuring without a material shielding N_0. For each material we measured 3 different results using a gate time of 10 seconds for 30 seconds total and then we replicated the readings to ensure reproducibility and minimize error. This lead to a total of 6 measurements for each material, including No material. Then for each material the value $\frac{N_0 - N_{mat}}{N_0}$ is computed to compare the materials.

Half-life of Ba-137m

The measurements for half-life can be done easily but with high levels of uncertainty by measuring the decay of a substance for a given time interval and calculate the time for half of the sample to decay. To minimize the error, our method rather involved plotting the curve for the activity of a sample of Barium-137 which is undergoing rapid decay. Due to this, the sample was only handled by instructors to ensure that the activation of the Ba-137m is done within the strict requirements of the setup

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A gate time of 10 seconds was used in the Digital Counter and the measurements were recorded for longer than 5 minutes to ensure our data is representative of the whole sample. Once plotted, one can linearize the plot by taking the natural log of the equation as shown in Equation (1.2). Using a linear regression, one can extract the gradient to find the decay constant by simply observing from equation 1.2 that $\lambda = -m$ and from Equation (1.3) find a value for $t_{1/2}$ For finding the error in the gradient of the linearized plot, the following equation 2.4 is used:

$$|\frac{\Delta m}{m}| = \sqrt{\frac{1}{n-2} \cdot \frac{(1-R^2)}{R^2}} \tag{2.4}$$

Finally, the formula for the propagated error of a calculated variable is given in equation as follows:

$$\Delta y = \sqrt{\left[\left(\frac{\partial y}{\partial x_1}\right)_{x_j \neq x_1} \Delta x_1\right]^2 + \left[\left(\frac{\partial y}{\partial x_2}\right)_{x_j \neq x_2} \Delta x_2\right]^2 + \cdots + \left[\left(\frac{\partial y}{\partial x_p}\right)_{x_j \neq x_p} \Delta x_p\right]^2}$$

$$\Delta y = \sqrt{\sum_{q=1}^{p} \left[\left(\frac{\partial y}{\partial x_q}\right)_{x_j \neq x_q} \Delta x_q\right]^2} \tag{2.5}$$

3 Results and Error Analysis

Theoretical Activity

To first work with Am-241, we had to calculate the current theoretical/expected activity of the sample, since the initial activity of Am-241 was measured $370kBq$ in February 2002. For Am-241, it is known that the half-life $t_{1/2}$ is 432 years.[2] Use Equation (1.3) and Equation (1.4) to derive the corresponding activity:

$$\lambda = \frac{\ln 2}{t_{1/2}}$$

$$\tilde{A}(t) = A_0 \ e^{-\ln 2 \frac{t}{t_{1/2}}} = A_0 \ 2^{-\frac{t}{t_{1/2}}}$$

With input values $t = 23y$ and $t_{1/2} = 432y$ the activity on February 2025 is estimated to be:

$$\tilde{A}(23y) = 2^{-\frac{23y}{432y}} = 357kBq$$

The error is not considered within this calculation due to the theoretical nature of the values.

Testing Operating Voltage for GM-tube

(Figure 3.1) shows the voltage V against counts N every 10 seconds. The first 10 values are not shown for simplicity since they all measured 0:

The threshold voltage V_T can be found as well as the Plateau range $\mathbb{V}_P$ between $400V$ and $500V$ by plotting the results in a scatter-graph:

From (Figure 3.2), a voltage of 420V was found to be appropriate for the upcoming measurements.

Figure 3.1: Counts for Am-241 vs Voltage [V]

Voltage V	**Counts of Decayed Am-241** N
300	0
320	0
340	0
360	18730
380	21686
400	22618
420	23131
440	23361
460	23204
480	23117
500	22712

Background Radiation

The measurements of the background radiation are presented in (Figure 3.3) as follows:

Using Equation (2.1) and 2.2 we find the mean count to be $\overline{N} = \frac{15+14+14+16+14}{5} = 14.6$ and Error of the mean $\Delta\overline{N} = \frac{\sqrt{\frac{(15-14.6)^2+...+(14-14.6)^2}{4}}}{\sqrt{5}} = 0.4$

Therefore, the value of the Background Activity (Counts per minute) found was

$$\overline{R}_{Background} = (14.6 \pm 0.4) min^{-1}.$$

$$\overline{R}_{Background} = (2.433 \pm 0.067) \cdot 10^{-1} s^{-1}$$

Distribution of random decay

We measured the decay statistics and analyzed our results against a Poisson Distribution to find the mean count per second and to verify the reproducibility of our further results by corroborating that the distribution approximates a normal shape.

The following table in (Figure 3.4) shows the data recorded:

We can plot the data from Figure 3.4) into a histogram to get (Figure 3.5):

Which helps picture the distribution, the results show how as the number of trials done will increase, it is expected that the distribution will resemble a normal distribution.

Figure 3.3: Count Rate for Background radiation

N_i	**Counts per minute (min^{-1})**
N_1	15
N_2	14
N_3	14
N_4	16
N_5	14

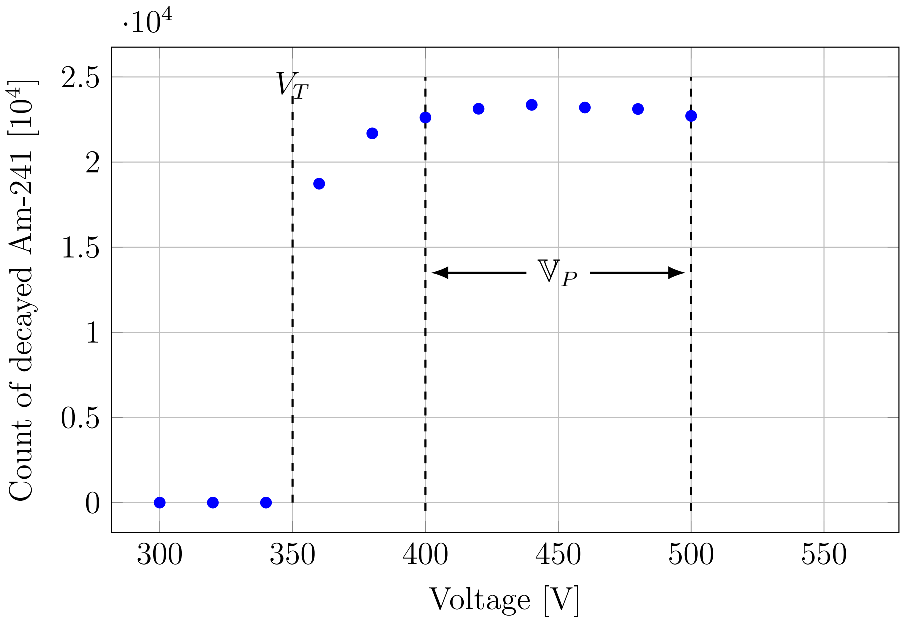


Figure 3.2: Voltage [V] vs Count N of decayed Am-241

Figure 3.4: Frequency distribution of counts per second

Count Rate R **(s^{-1})**	**Frequency** f	$R \cdot f$
0	30	0
1	107	107
2	149	298
3	138	414
4	92	368
5	45	225
6	26	156
7	10	70
8	7	56

Given the data, one can calculate the mean count per second $\overline{R}$ and standard error $\Delta\overline{R}$ using Equation (2.3) to derive the mean Count rate of the americium sample

$$\overline{R}_{Am} = \frac{(30 \cdot 0 + 107 \cdot 1 + ... + 7 \cdot 8)}{(30 + 107 + 149 + ... + 7)} = 2.8046358$$

$$\Delta\overline{R}_{Am} = \sqrt{2.8046358} = 1.6747047$$

$$\overline{R}_{Am} = (2.80 \ \pm \ 1.67)s^{-1}$$

To find the Activity of the americium sample, we need to subtract the average background count rate from the average measured count rate of the americium sample.

$$\overline{A}_{Am} = 2.8 - 0.2433 = 2.5567s^{-1}$$

$$\Delta\overline{A}_{Am} = \sqrt{1.67^2 + 0.0067^2} = 1.6747$$

Therefore, the activity of americium was measured to be

$$\overline{A}_{Am} = (2.6 \pm 1.7)s^{-1}$$

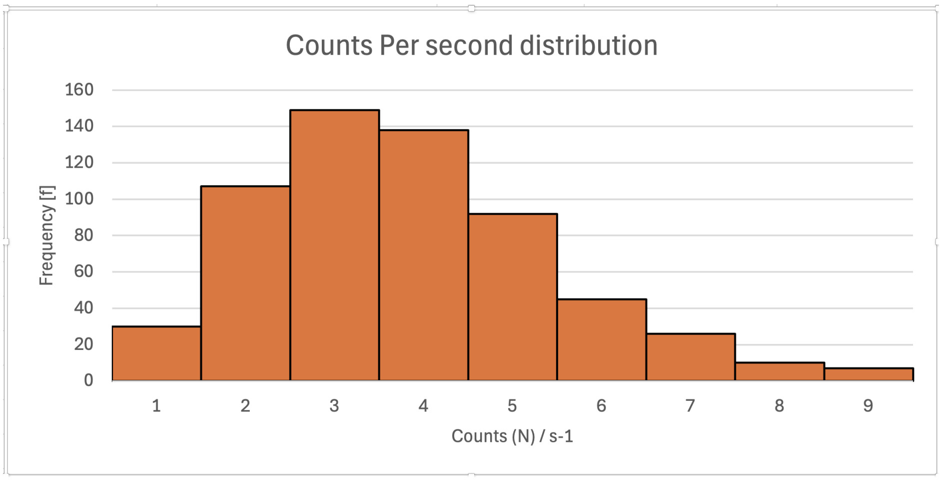


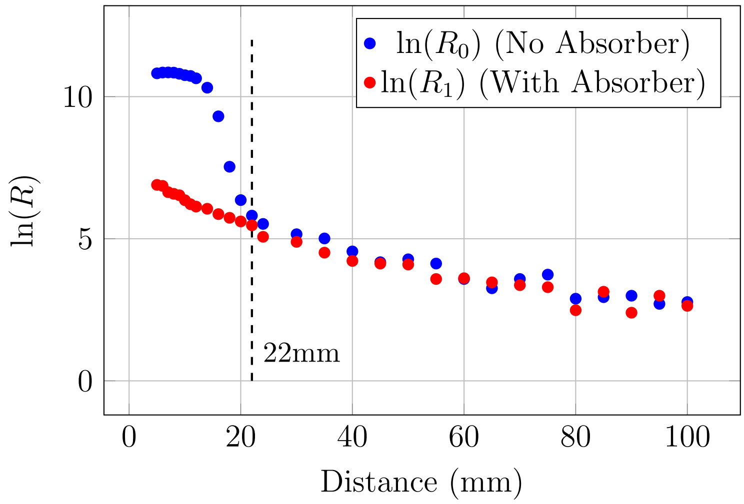
Figure 3.5: Setup for GM - Tube using Digital Counter

The theoretical uncertainty using Poisson statistics should be $\Delta \overline{A}_{Am} = \sqrt{2.6} = 1.61.. \approx 1.7$, verifying our initial assumption that radioactive decay follows a random pattern.

Distance of α Radiation

For the results from the method explained in the procedure see (Figure A.1) in Appendix A for the full dataset.

Figure 3.6: Comparison of $\ln(R_0)$ and $\ln(R_1)$ vs Distance (mm)



The graph for $\ln(R_0)$ shows the depletion of alpha particles detected by the GM Tube due to the energy loss of alpha particles as they travel air. The Second plot shows the effect of using a piece of A4 paper to only allow the passing of gamma particles.The following are reasons the range of alpha particles may deviate from theoretical results: The effect of a thicker or denser source of radioactivity may cause self-absorption, reducing the number of emitted alpha particles that reach the detector; the GM tube's window material (mica) can absorb some alpha particles before detection, leading to an underestimated range; misalignment between the source and detector can cause a reduction in the detected count rate, affecting the measured range.

After finding the first value for distance for which the difference between $\ln(R_0)$ and $\ln(R_1)$ is minimized, we calculated the range of alpha particles to be:

$$d_\alpha = 22 \pm 1mm \tag{3.1}$$

For the measurement of d_α we used an analog instrument, for which the uncertainty is the smallest division divided by 2, however since 2 separate measurements were done with the same instrument, the total absolute uncertainty will be doubled and hence equal to the smallest division of the ruler: $\Delta d_\alpha = 1mm$.

Gamma Radiation Procedure

The (Figure 3.7) shows the values for the materials and the counts detected for each material:

Figure 3.7: Radiation Count Measurements for Different Materials

Materials	C_1	C_2	C_3	C_4	C_5	C_6	**Mean Counts**	**EOM**
Lead	4	3	4	7	4	2	4	4.0988
Iron	30	26	20	33	32	30	28.5	11.7729
Aluminum	139	157	124	149	148	144	143.5	27.5717
Hard Paper	174	192	192	200	188	195	190.17	21.7117
Plexiglass	176	177	193	165	201	194	184.33	33.6452
Air	224	244	236	251	237	245	239.5	23.0174

Figure 3.8: Absorption Ratio vs Density

Density	$\frac{N_0 - N_{\mathbf{MAT}}}{N_0}$
11.41	0.9833
8.1	0.8810
2.68	0.4008
1.39	0.2059
1.12	0.2303
0	0

Half-Life Calculation for Ba-137m

After performing the procedure the results for the Count Rate for Ba-137 is seen in (Figure 3.10) :

The plot strongly shows the exponential decay from the Count rate as time passes. That is why by using Equation (1.2), and finding the linear regression for the data points in (Figure 3.10), one can then equate the gradient $m = -0.0041$ to $-\lambda$. Finally, from Equation (1.3):

$$t_{1/2} = \frac{\ln 2}{\lambda} = \frac{\ln 2}{0.0041} = 162.06s$$

Figure 3.9: Absorption Ratio vs Density (gcm^{-3})

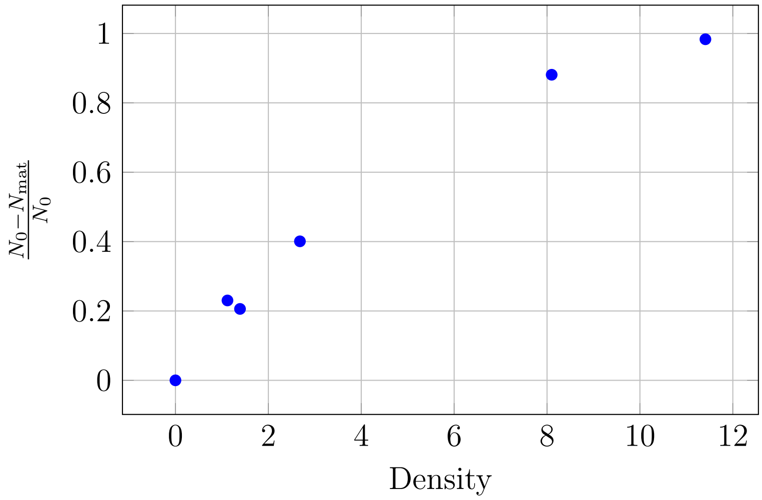
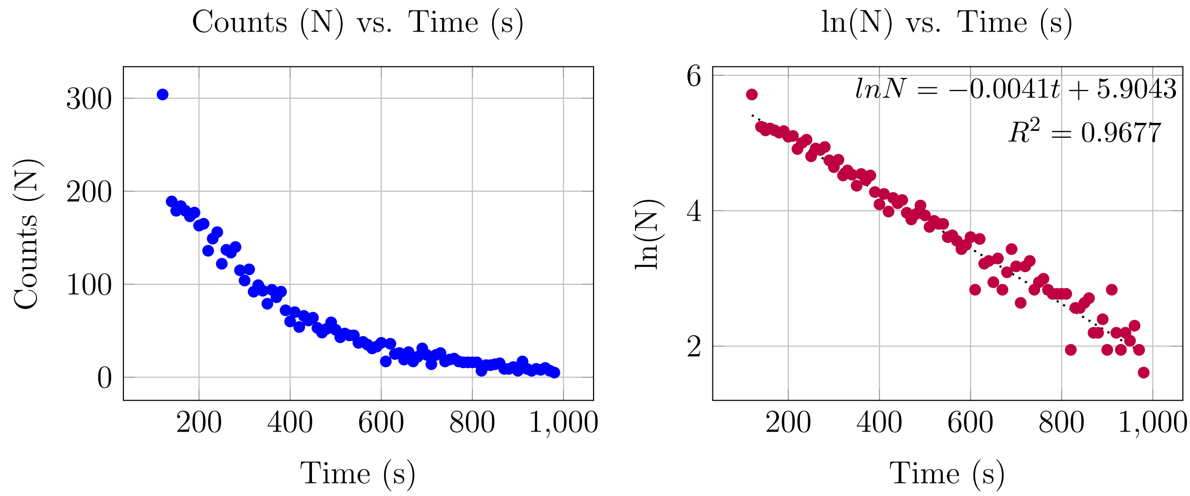


Figure 3.10: Comparison of Counts vs. Time and ln(N) vs. Time with best fit line



To calculate the error, use Equation 2.4 and input the value for $R^2 = 0.9677$ and $n = 86$ different measures to get:

$$|\frac{\Delta m}{m}| = \sqrt{\frac{1}{86-2} \cdot \frac{(1-0.9677^2)}{0.9677^2}} = 1.49316 \times 10^{-5}$$

The error for the half life can be found then from by computing the following expression:

$$|\frac{\Delta m}{m}| \cdot t_{1/2} = 1.49316 \times 10^{-5} \cdot 169.06s = 0.6157s$$

The final result for the half life is:

$$t_{1/2} = 169.06 \pm 0.62s \qquad (3.2)$$

4 Discussion and Conclusion

The range of alpha particles was found to be $d_\alpha = (22 \pm 1)mm$, consistent with expected values for alpha radiation in air (2-3 cm) within the uncertainty range

However, the measurement of the half-life of Ba-137, found to be $t_{1/2}$=(169.06±0.62), was way off the theoretcal value of 153s, this was affected by procedural errors, leading to a degree of inaccuracy. A key issue was an improperly connected cable, which resulted in the loss of crucial data at the beginning of the decay measurement. Since Ba-137 undergoes rapid decay, the missing data from the initial phase significantly impacted the accuracy of the half-life determination. Without these early high-count readings, the dataset primarily consisted of lower count rates, which are more susceptible to background radiation interference. Additionally, potential inconsistencies in cable connections throughout the experiment likely introduced further errors. These factors collectively reduced the reliability of the half-life measurement, highlighting the importance of proper equipment setup and calibration in ensuring precise experimental results.

References

[1] Jürgen Fritz Dr. Donfack Patrice. *Modern Physics Lab Manual*. Constructor University, Spring 2023.

[2] Tim Jesko Söcker Dr. Donfack Patrice. *Modern Physics Lab Manual*. Constructor University, Spring 2025.

A Appendix: Experimental Data

Figure A.1: Radioactive Counts with and without Absorber

Without Absorber			With Absorber (A4 Paper)		
Distance (mm)	**Counts (R_0)**	**Ln(R_0)**	**Distance (mm)**	**Counts (R_1)**	**Ln(R_1)**
5	50010	10.8199	5	988	6.8956
6	51455	10.8484	6	954	6.8607
7	51625	10.8518	7	764	6.6386
8	51279	10.8450	8	721	6.5806
9	49258	10.8048	9	686	6.5309
10	46829	10.7543	10	576	6.3561
11	45614	10.7279	11	500	6.2146
12	41976	10.6449	12	460	6.1312
14	30186	10.3151	14	426	6.0544
16	11020	9.3075	16	353	5.8665
18	1869	7.5332	18	310	5.7368
20	578	6.3596	20	273	5.6095
22	335	5.8141	22	285	5.4723
24	250	5.5215	24	159	5.0689
30	174	5.1591	30	133	4.8903
35	150	5.0106	35	91	4.5109
40	95	4.5539	40	68	4.2195
45	65	4.1744	45	62	4.1271
50	72	4.2767	50	60	4.0934
55	62	4.1271	55	36	3.5835
60	36	3.5835	60	37	3.6109
65	26	3.2581	65	32	3.4657
70	36	3.5835	70	29	3.3673
75	42	3.7377	75	27	3.2958
80	18	2.8904	80	12	2.4849
85	19	2.9444	85	23	3.1354
90	20	2.9957	90	11	2.3979
95	15	2.7081	95	20	2.9957
100	16	2.7726	100	14	2.6391