Measuring Half Life and Stopping Power Through the Alpha Decay of ^{212}Pb

Audréanne Bernier (261100643), Olivia Pereira (260985600)

McGill University Department of Physics

Supervisor: Professor David Cooke

December 2, 2024

Abstract

This experiment aims to measure the stopping power of air and the half-life of alpha particles released during the various steps of the decay of ^{212}Pb into ^{208}Pb. This is done by placing a ^{212}Pb sample in a vacuum chamber and using the known decay energy of ^{241}Am to calibrate an energy scale. The disc was charged for over four days before being placed in the detector chamber for 165.5 hours, resulting in a histogram with distinct energy peaks at 5.65, 5.81, 6.09, 6.12, and 8.75 ($\pm$0.4) MeV, corresponding to known decay channels of ^{212}Bi and ^{212}Po. These measured energies agree with theoretical values within uncertainties, with errors of 0.73%, 0.73%, 0.02%, 1.19%, and 0.36%, respectively, but consistent underestimation suggests potential systematic issues. The stopping power of air increased with pressure, as expected from literature. The reduced χ^2 for the fits of $^{212}\text{Bi} \rightarrow ^{208}\text{Tl}$ and $^{212}\text{Po} \rightarrow ^{208}\text{Pb}$ were calculated to be 0.123 and 0.094 respectively. However, it was observed that the data did not match the linear relationship described by the Bethe formula.

Contents

1 Introduction

Alpha decays are observed when the nucleus of an element decays to another element, emitting alpha particles in the process. Similarly to photons, these particles are emitted in discrete amounts of allowed energies and are essentially ^{4}He nuclei without any electrons (i.e. two protons and two neutrons). As alpha particles are emitted, they can be detected as they pass through a material, interacting with the electrons and transferring energy, causing excitation and ionization. The Bethe Formula can describe the energy loss [1, 2]

$$\left\langle \frac{dE}{dx} \right\rangle = -\left(\frac{4\pi}{m_e c^2}\right)\left(\frac{nz^2}{\beta^2}\right)\left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \left[\ln\left(\frac{2m_e c^2\beta^2}{(1-\beta^2)I}\right) - \beta^2\right], \tag{1}$$

where I is the mean excitation potential (the average energy required to excite an electron), β is the velocity of the alpha particle scaled by c, n is the electron density in the material, z is the charge number of the incident alpha particle, m_e is the electron mass, e is the fundamental charge, c is the speed of light, and ϵ_0 is the permittivity of free space.

The energy loss per distance travelled given by Equation 1 (also known as the stopping power) is dependent on the density of the material and, therefore, on temperature, pressure, structure, etc. From the ideal gas law, the electron density of the material for a given pressure can be calculated using

$$n = \frac{P}{k_B T}, \tag{2}$$

where T is the temperature, P is the pressure, and k_B is the Boltzmann constant. This means that the stopping power is proportional to the pressure for a given setup. The velocity of the particle can also be calculated as

$$\beta = \sqrt{1 - \left(\frac{E_0}{E_k + E_0}\right)^2}, \tag{3}$$

where E_0 is the particle's rest energy and E_k is the kinetic energy. Experimentally, the energy of the alpha particles can be measured at different pressures, and from this, the stopping power can be calculated according to

$$\left\langle \frac{dE}{dx} \right\rangle = \frac{-\Delta E}{dx} \propto -P, \tag{4}$$

where ΔE is the energy difference with respect to reference energy, and dx is the distance travelled by the particle in the air. The resulting relationship with pressure can then be compared with the stopping power given by Equation 1.

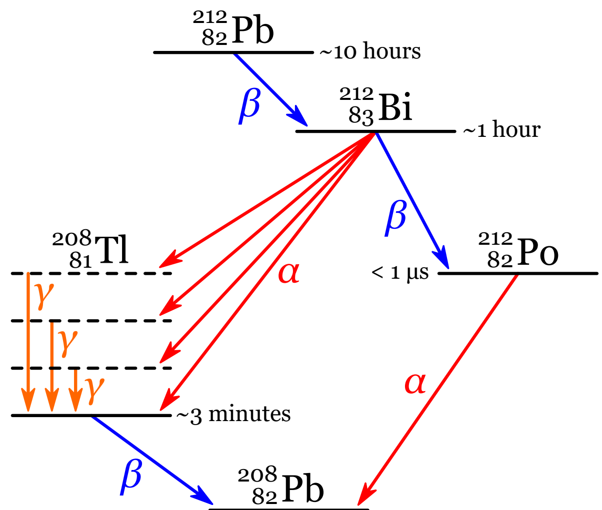

Figure 1: Schematic of the decay chains that occur for ^{212}Pb. In this experiment, the particles detected are the alpha particles emitted in the four possible transitions from $^{212}\mathrm{Bi} \rightarrow^{208}$ Tl, and the alpha particle emitted in the $^{212}\mathrm{Po} \rightarrow^{208}$ Pb [3].

Additionally, the energies of the decayed alphas depend on the decay process of ^{212}Pb itself, which can be seen in Figure 1. The specific energy of decay for each channel can be estimated, as well as the branching ratios for the different decay channels of ^{212}Bi into ^{208}Tl [4], which are predicted to occur most notably at energies (relative intensities) of 6.08988 MeV (27.712%), 6.05078 MeV (69.91%), 5.768 MeV (1.70%) and 5.607 MeV (1.13%) with other rarer transitions being possible [4]. The counts observed from a decaying sample at different energies can thus serve to make a population study of the alpha particles detected.

2 Setup

2.1 Charging the lead sample

In this experiment, ^{212}Pb samples are created by charging a disc in a chamber filled with radon gas. By subjecting them to a 1000 V potential difference, the radon gas in the chamber will 'stick' to the polarized sample and decay into lead, which can be used for the remainder of the experiment.

2.2 Detection apparatus

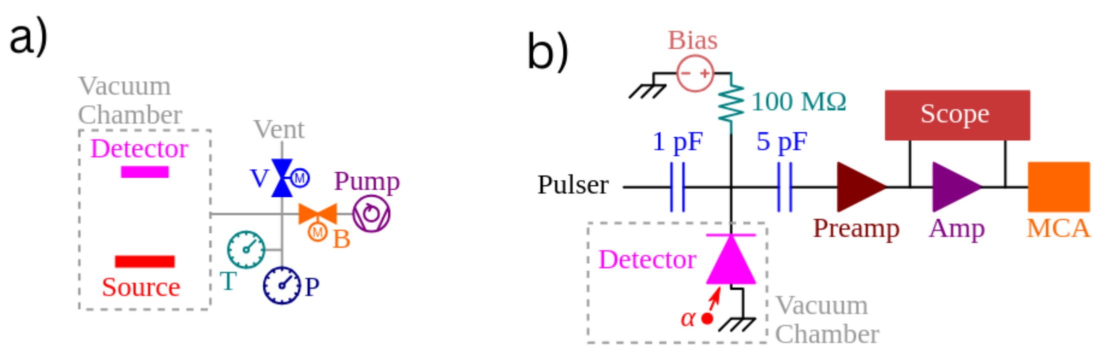

Figure 2: Apparatus setup for the experiment. a) The source is placed inside a vacuum chamber that is pressure (P) and temperature (T) controlled, with an adjustable vent (V) and pump control valve (B) to control the pressure within the chamber. A gauge showed the pressure in the chamber in the millibar and millitorr range. b) Signals from the pulser and detector have a negative voltage bias applied to them before passing through both a preamplifier and amplifier, with an oscilloscope monitoring the output of the amplifier. The signals are then delivered to the MCA to be binned and collected digitally.

Charged samples are placed in a vacuum chamber containing a silicon P-N junction used as a detector. When an alpha particle goes through the depletion region of the detector, bound charges are released in an amount proportional to the particle's energy, allowing the current to flow from the capacitor in the circuit. A voltage supply recharges the capacitor, and the current pulse is converted to a voltage pulse. The peak voltages are measured as counts and binned into a histogram, where the axis can be converted from voltage to particle energy due to the linear relationship between the two. The decay of the ^{212} Pb nucleus to ^{208}

Pb occurs on the hour scale and can therefore be easily measured.

2.3 Calibration

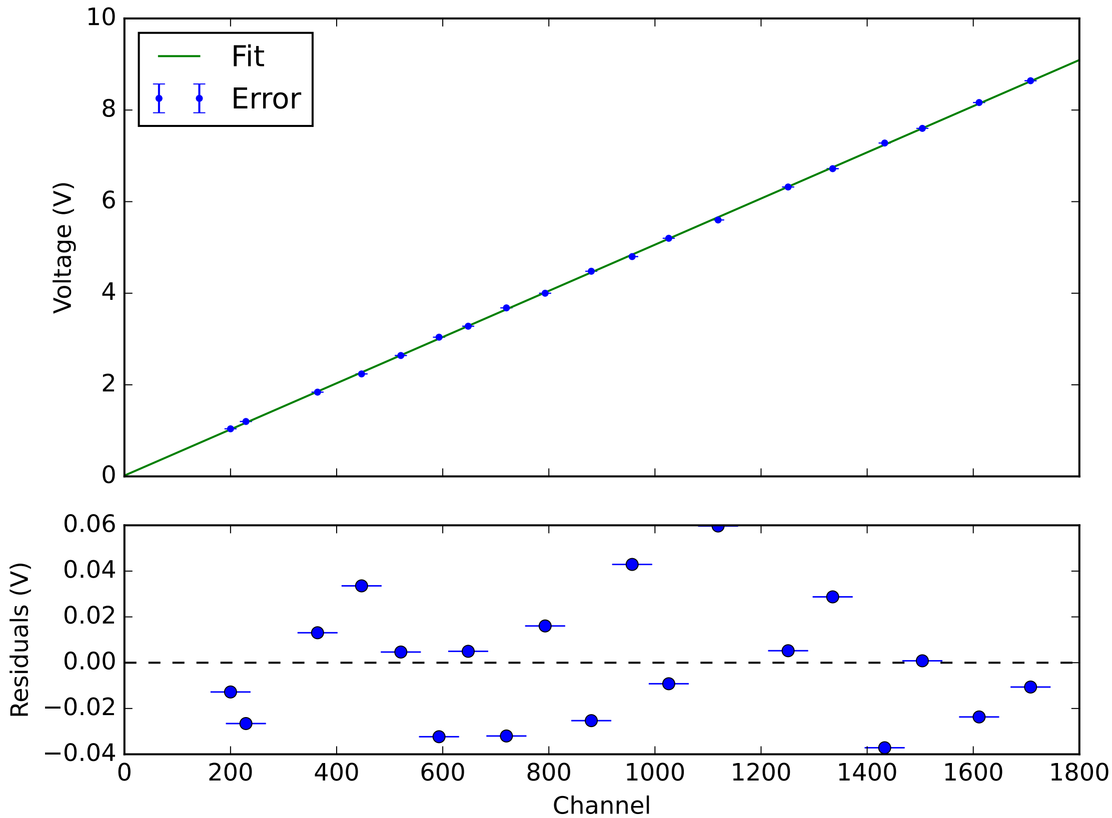

Figure 3: Calibration process for assigning energy levels to each MCA channel. The voltage height of the pulser was adjusted, and the corresponding bin location of the peak was recorded 8 times, allowing for a relationship between voltage and channel to be established. The relationship was taken to be linear, with residuals shown in the bottom panel. This voltage-channel relationship was later used to convert the channels to energy using the Americium source. The fit was extended to pass through the 0-voltage point to show that the fit passes through the origin.

The energy scale was calibrated by varying the pulser voltage and using an Americium source (see Figure 3). For this calibration, the energy location of the prominent Americium peak was taken to be known at 5.4612 MeV [5], and a clear peak for this was obtained (see Figure 3). The voltage applied to the pulser (see Figure 2) was varied to obtain 19 peaks, with the peak voltages measured digitally using the *mcphysics sillyscope* interface for the Rigol oscilloscope at a precision of 0.0001 V. This data was used to establish a voltage-channel (linear) relationship and get a corresponding voltage for all channels, with uncertainties resulting from the uncertainty in the fit parameters (reduced $\chi^2 = 2.02$). An energy scale was thus established using the known channel and voltage of the Americium peak, with uncertainties on the energies at each channel established by propagating the errors in the measured and fitted voltages used in their calculation.

3 Results

3.1 Alpha particle population analysis

<table>
<tr><th>Decay Process</th><th>Measured Energy (MeV)</th><th>Reference Energy (MeV)</th><th colspan="2">Measured Abundance (%)</th><th colspan="2">Reference Abundance (%)</th></tr>
<tr><td rowspan="4">^{212}Bi $\rightarrow^{208}$ Tl</td><td>5.65 ± 0.04</td><td>5.607</td><td>1.11 ± 0.05</td><td rowspan="4">39.2 ± 0.2</td><td>1.13</td><td rowspan="4">35.94</td></tr>
<tr><td>5.81 ± 0.04</td><td>5.786</td><td>1.99 ± 0.07</td><td>1.70</td></tr>
<tr><td>6.09 ± 0.04</td><td>6.05078</td><td>71.0 ± 0.4</td><td>69.91</td></tr>
<tr><td>6.12 ± 0.04</td><td>6.08988</td><td>25.9 ± 0.3</td><td>27.12</td></tr>
<tr><td>^{212}Po $\rightarrow^{208}$ Pb</td><td>8.75 ± 0.04</td><td>8.78486</td><td colspan="2">60.8 ± 0.3</td><td colspan="2">64.06</td></tr>
</table>

Table 1: Population statistics of alpha particles detected in this experiment. The locations of the measured energies for each peak are in agreement (within error) with the literature values [4]. The measured abundances are shown for the overall abundance of alpha particles released from polonium ($60.8 \pm 0.3\%$) and bismuth ($39.2 \pm 0.2\%$) also agree with literature values, along with the specific branching ratios within the bismuth decay to different energy levels of tellurium.

A disc was charged for 4 days and 37 minutes before being left in the chamber with the detector for approximately 165.5 hours (a little over 6 days). The resulting histogram is shown in Figure 4, with four distinct peaks in counts. Using the calibration in energy space, these peaks correspond to energies of 5.65, 5.81, 6.09, 6.12, and 8.75 (± 0.4) MeV. The first four energy peaks correspond to four different possible decay channels of ^{212}Bi to ^{208}Tl, as seen in Figure 1, presenting errors of 0.73%, 0.73%, 0.02% and 1.19%, respectively with the theory values of 5.607, 5.768, 6.08988, and 6.05078 MeV [4]. The final peak is from the decay of ^{212}Po to ^{208}Pb, which has an error of 0.36% when compared to the known theory value of 8.78486 MeV. The location of all energy peaks, summarized in table 1, agrees with the theory within uncertainties, affirming the precision of this experiment. However, the values seem consistently lower than the theoretical value, indicating a potential issue with systematics.

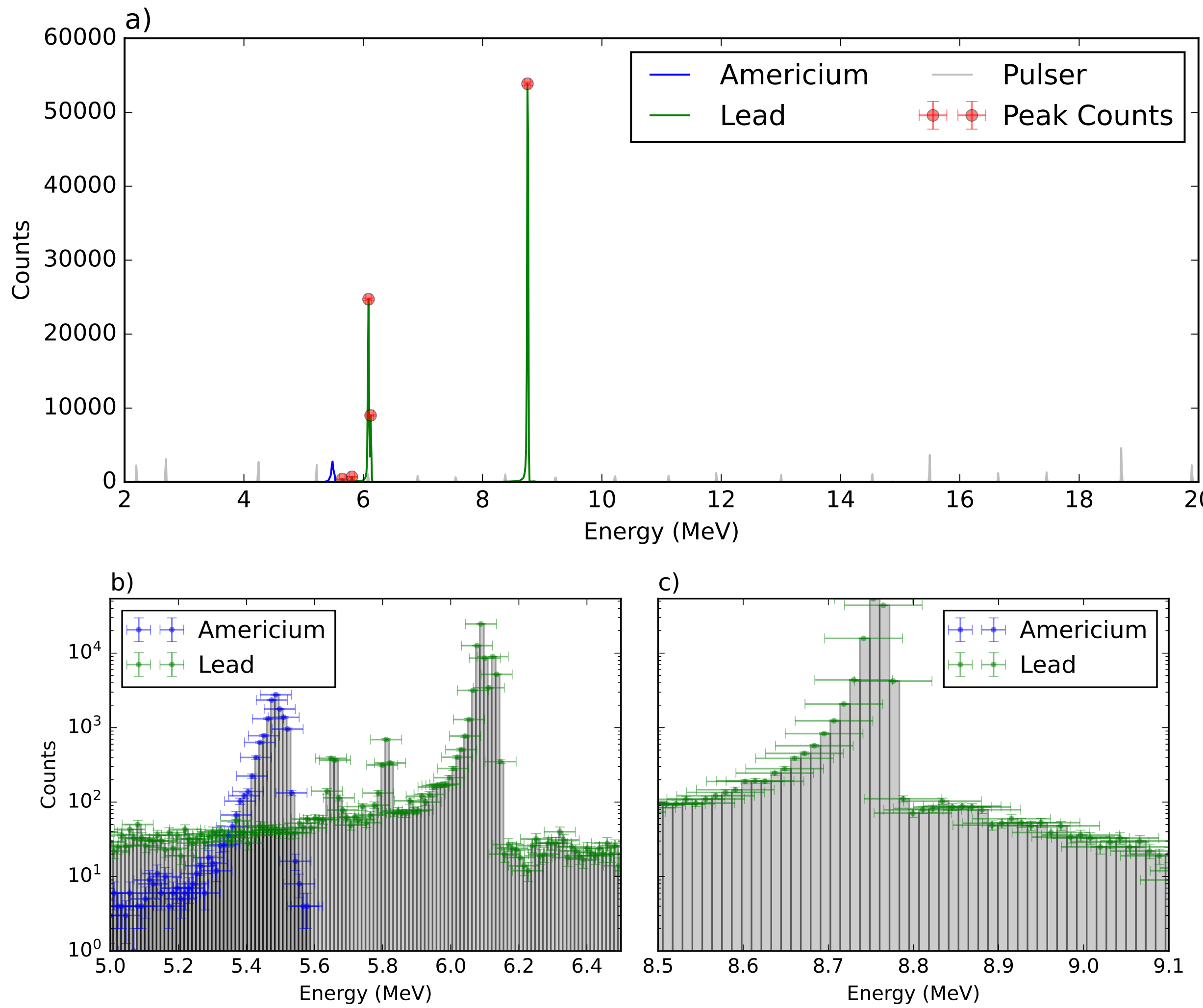

Figure 4: Histograms of counts detected for different runs of the experiment. a) shows the full energy scale probed with the pulser (grey), the americium source (blue) and the lead source (green) with peaks identified in red with errors. Panels b) and c) show the counts with error bars, where errors in the counts themselves come from Poissonian statistics of $\sqrt{\text{counts}}$ and the energy errors come from the calibrations. Panel b) specifically shows the americium transition and the four distinct ^{212}Bi $\rightarrow^{208}$ Tl transitions, while panel c) shows the single ^{208}Po $\rightarrow^{208}$ Pb transition.

Based on Poissonian statistical principles, the uncertainty in each bin's counts is considered $\sqrt{\text{counts}}$. The relative abundance of alphas of different energies can be analyzed to study the branching ratios of the different decay channels. The results summarized in Table 1 show close agreement with the overall branching ratio of ^{212}Pb between bismuth and polonium; however, the values of this experiment overestimate the ratios, which could be due in part to the absence of other rarer decay paths analyzed. The measured abundances of each of the four most common decay processes (shown in Figure 4 from bismuth to tellurium show close agreement with literature values [4].

3.2 Pressure dependence and stopping power

To characterize the pressure dependence of the stopping power of air, a lead disc was charged for approximately four hours and then left in the vacuum chamber for pressure runs of around 20 minutes. Because of these short time intervals, the measurements only show the two prominent lead peaks corresponding to the $^{212}\mathrm{Bi} \rightarrow^{208}$ Tl and $^{212}\mathrm{Po} \rightarrow^{208}$ Pb decays, with no observations of transitions to different energy levels. The energy of the peaks was recorded at various pressures, and from these, the stopping power was calculated according to Equation 4. The energy difference was taken to be $\Delta E = E_{\mathrm{ref}} - E$ where the reference energy was chosen to be the energy of the peak at the lowest recorded pressure (around 80 millitorr). Linear fits were performed on the data as a function of pressure, as shown in Figure 5. The theoretical curves were obtained from Equation 1 where the velocity of the alpha particle β was calculated using the measured energy of the particles.

The reduced χ^2 for the fits were calculated to be 0.123 and 0.094 for panels a) and b), respectively, indicating that the uncertainties on the energy measurements are likely overestimated. The expected linear relationship between stopping power and pressure is recovered, with higher pressures resulting in more significant decreases in energy as the particle travels through air. This is because at higher pressures, air density increases, which leads to a greater frequency of collisions between the alpha particle and air molecules. This results in the alpha particle seeing a higher rate of energy loss per unit distance. However, the discrepancy between the data and theoretical curves could be caused by systematic errors in taking the measurements or improper calculations or assumptions when using the Bethe formula. Corrections to the Bethe formula exist to account for nonrelativistic and relativistic effects, as well as differences due to particle masses and charges, among other factors [2]. These

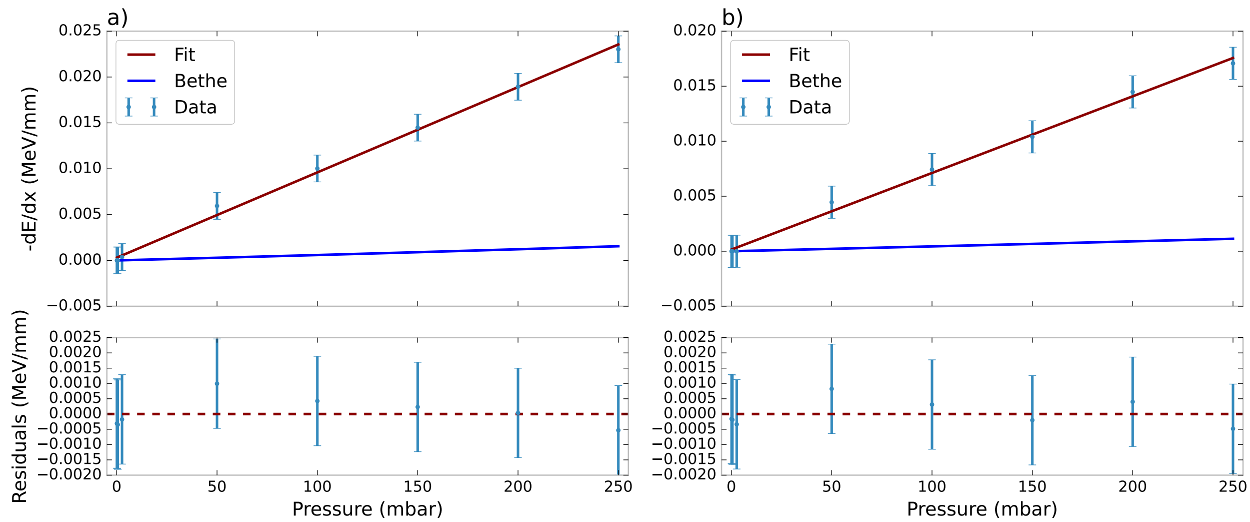

Figure 5: Stopping power of the two lead decay peaks where panel a) correspond to ^{212}Bi $\rightarrow^{208}$ Tl and panel b) to ^{212}Po $\rightarrow^{208}$ Pb. The theoretical curves were calculated using the Bethe formula as shown in Equation 1.

could refine the theoretical predictions and better align them with experimental observations. However, given the significant deviation observed between our results and Equation 1, it seems unlikely that these corrections are the primary source of error, as they are not anticipated to dominate the discrepancies observed.

4 Conclusion

This report investigates the stopping power of air and the half-life of alpha particles produced during the decay of ^{212}Pb into ^{208}Pb. Using a ^{212}Pb source in a vacuum chamber, the energy scale was calibrated via ^{241}Am decays, identifying energy peaks at 5.65, 5.81, 6.09, 6.12, and 8.75 MeV with associated uncertainties. These peaks correspond to theoretical decay channels of ^{212}Bi and ^{212}Po, with deviations from theory ranging between 0.02% and 1.19%, indicating systematic underestimation. The stopping power of air was measured by varying chamber pressure, and an expected increase in pressure was observed. However, the data deviated from the linearity predicted by the Bethe formula. The reduced χ^2 values of 0.123 and 0.094 for the ^{212}Bi and ^{212}Po decays suggest that the energy data aligns closely with the fitted models but highlight the need for further refinement to resolve systematic discrepancies. The results demonstrate consistency with theoretical predictions and validate the experimental approach, though systematic effects warrant additional investigation. The study contributes to understanding alpha particle interactions and nuclear decay dynamics.

References

[1] H. Bethe, "Zur theorie des durchgangs schneller korpuskularstrahlen durch materiel," vol. 397, no. 3, pp. 325–400, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/andp.19303970303. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/andp.19303970303 1

[2] F. Salvat, "Bethe stopping-power formula and its corrections," vol. 106, no. 3, p. 032809. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevA.106.032809 1, 7

[3] *Alpha Decay Lab Manual*. McGill Department of Physics. 2

[4] M. Martin, "Nuclear Data Sheets for A=208," *Nuclear Data Sheets*, vol. 108, pp. 1583–1806, Aug. 2007. [Online]. Available: https://ui.adsabs.harvard.edu/link_gateway/2007NDS...108.1583M/doi:10.1016/j.nds.2007.07.001 2, 5, 7

[5] M. Basunia, "Nuclear Data Sheets for A = 237," *Nuclear Data Sheets*, vol. 107, no. 8, pp. 2323–2422, Aug. 2006. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0090375206000585 4