Linear Attenuation Coefficient for Cosmic-Ray Muons in Lead

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Abstract. The linear attenuation coefficient (μ) for cosmic-ray muons in lead was experimentally determined using two vertically stacked scintillation detectors. By measuring the coincidence count rate across varying thicknesses of lead shielding (0.0 to 25.0 cm), the attenuation was modeled using the linearized relationship $\ln(I_0/I) = \mu x$. A standard Ordinary Least Squares regression yielded an experimental coefficient of $\mu = 0.007646\ \mathrm{cm}^{-1}$, representing a 1.67% deviation from the theoretical value of $0.00752\ \mathrm{cm}^{-1}$. The analysis identified a detection noise floor at higher shielding thicknesses caused by secondary particle showers and ambient background radiation, validating the use of the standard linear regression model over a Regression Through the Origin (RTO).

INTRODUCTION

Muographic imaging is a specialized non-invasive technique utilizing high-energy cosmic rays to visualize the internal density and structure of massive geological and archaeological structures [1, 2]. Because cosmic-ray muons are absorbed by matter as a function of material density, detectors can measure reduced count rates after particles traverse an object to generate precise density maps [1].

This experiment focuses on determining the linear attenuation coefficient (μ) for cosmic-ray muons in lead, a high-density metal often used for radiation shielding. Characterizing this coefficient is vital for muographic imaging, as it allows for the accurate conversion of measured particle flux into reliable physical data regarding a target's interior structure [2].

BACKGROUND

Cosmic rays are high-energy particles, predominantly hydrogen nuclei, that permeate the solar system at relativistic speeds [3]. When these particles collide with nuclei in the atmosphere, they generate secondary particle showers, which include muons [3, 4]. Muons are subatomic leptons with a mass approximately 200 times that of an electron and a decay time of 2.2 μs [3, 5]. Despite this short decay rate, muons produced by cosmic rays with energies exceeding 4 GeV reach the Earth's surface with an average flux of approximately 70 $m^{-2}s^{-1}sr^{-1}$ [3].

The energy loss for a muon as it passes through matter is defined by the Bethe-Bloch equation [5]:

$$-\frac{dE}{dx} = \left(\frac{ze^2}{4\pi\varepsilon_0}\right)^2 \frac{4\pi Z\rho N_A}{4mv^2} \tag{1}$$

Due to their weak interaction with matter, muons can penetrate several kilometers into the Earth's crust [2, 6], making them ideal for sub-surface structural analysis.

METHODOLOGY

The attenuation of cosmic-ray muons through lead was measured using two scintillation detectors in a coincidence setup (Fig. 1). The two detectors were vertically aligned so that a muon passing through both produced a coincidence count. Lead bricks were placed above the top detector to ensure scattered muons remained within the detection path [2].

FIGURE 1. Experimental setup consisting of five layers of lead bricks placed above two scintillation detectors.

Baseline unshielded count rates (I_0) were recorded for 1.5 days to establish stability (Fig. 2). The drop in the middle of Fig. 2 is a documented artifact caused by an asynchronous data collection restart, rather than a physical rate decrease.

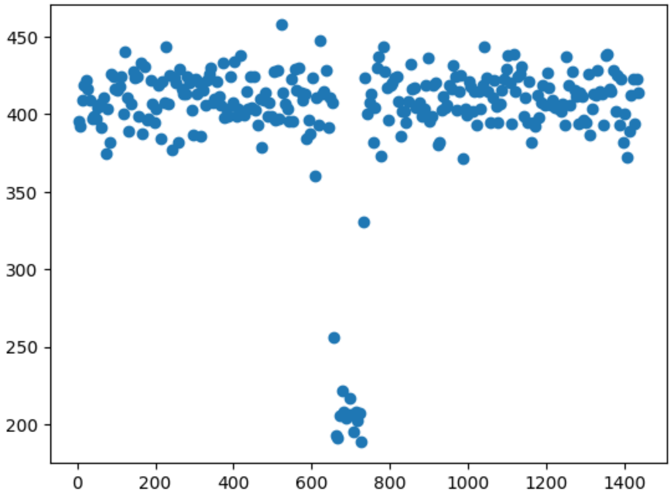

FIGURE 2. Background muon count rate measured over approximately 1.5 days, demonstrating rate stability.

Data was collected for approximately two days per lead thickness. Following counting statistics, the relative uncertainty is $1/\sqrt{N}$, where N is the total count [7]:

$$\sigma_N = \sqrt{N} \tag{2}$$

Collecting data for a longer time increased the number of counts and reduced the relative uncertainty:

$$\frac{\sigma_N}{N} = \frac{1}{\sqrt{N}} \tag{3}$$

Longer collection times made the differences between count rates more statistically meaningful. For each lead thickness, the count rate was calculated using:

$$R = \frac{N}{t} \tag{4}$$

where R is the count rate, N is the total number of counts, and t is the measurement time. The measured rate for each thickness of lead was then compared to the rate without lead shielding.

The attenuation was modeled using the exponential attenuation equation [2, 5]:

$$I = I_0 e^{-\mu x} \tag{5}$$

where I is the measured muon intensity after passing through lead, I_0 is the unshielded intensity, μ is the attenuation coefficient, and x is the lead thickness. Since the measured count rate is proportional to the muon intensity, the count rate was used in place of intensity. The equation was linearized by taking the natural logarithm:

$$\ln\left(\frac{I_0}{I}\right) = \mu x \tag{6}$$

The slope of the linear fit of $\ln(I_0/I)$ versus lead thickness gave μ, allowing the muon attenuation coefficient in lead to be determined.

RESULTS

Count rates were normalized to counts per day to maintain statistical rigor (Table I). The baseline rate was $115,185.57$ counts/day. Standard Ordinary Least Squares (OLS) regression yielded an experimental coefficient of $\mu = 0.007646$ cm^{-1} ($R^2 = 0.7896$).

TABLE I. Experimental muon count rates normalized to counts per day.

Lead Thickness (cm)	Count Rate (counts/day)
0.0	115,185.57
10.0	97,982.42
15.0	96,138.86
20.0	94,795.47
25.0	94,940.43

The results demonstrate a 1.67% percent error relative to the theoretical value of 0.00752 cm^{-1} [8]. To evaluate the impact of the noise floor, a Regression Through the Origin (RTO) was performed (Fig. 4), resulting in a higher $\mu = 0.009672$ cm^{-1} and lower $R^2 = 0.7132$.

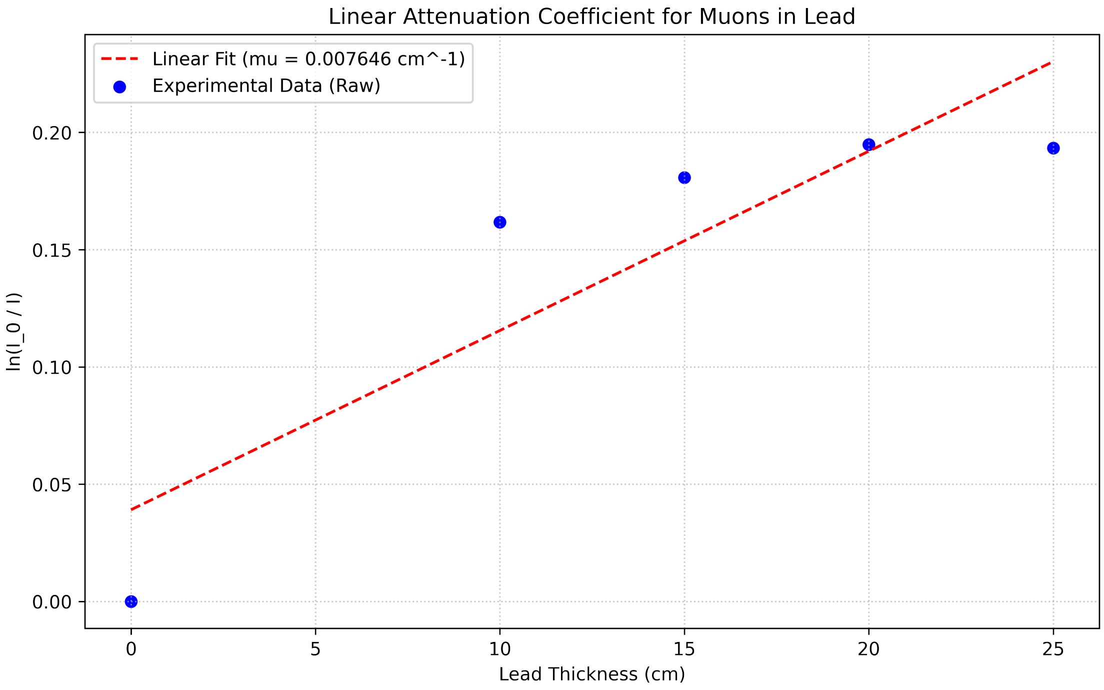

FIGURE 3. Standard OLS linear regression of the natural log ratio versus lead thickness.

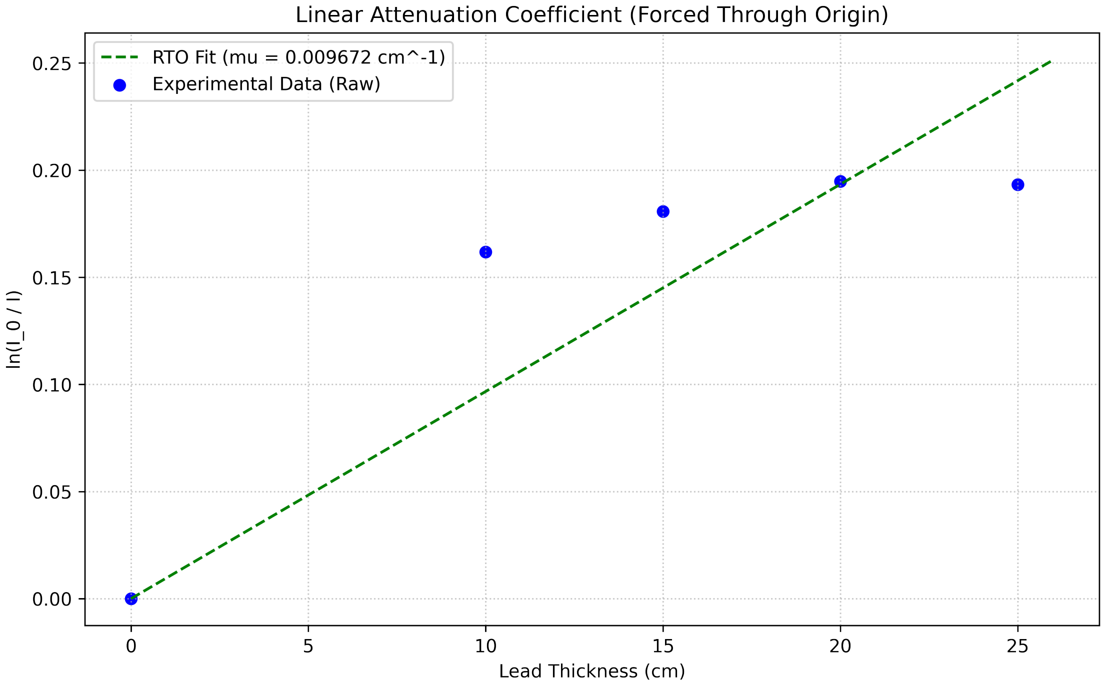

FIGURE 4. RTO fit illustrating the influence of the detection noise floor.

The visual data in Fig. 3 and Fig. 4 indicate a plateauing effect at thicknesses of 20 cm and 25 cm, where the count rate reduction slows. This suggests that the experimental setup reached a detection noise floor, which will be analyzed in the subsequent discussion.

DISCUSSION

The strong agreement with theoretical models (1.67% error) is supported by high sample sizes that kept statistical uncertainty below 1% [7, 8]. The non-zero y-intercept in the OLS model effectively isolates systematic background noise and secondary particle showers produced by high-energy muon interactions with lead nuclei [3, 4]. This ”noise floor” explains the plateauing effect at thicknesses of 20–25 cm. The OLS model is a superior physical representation compared to the RTO model, as it accounts for these background interactions in the intercept rather than the slope, avoiding the 28.6% error seen in the RTO fit.

CONCLUSION

The attenuation coefficient for cosmic-ray muons in lead was successfully measured as $\mu = 0.007646\ \text{cm}^{-1}$. The OLS regression effectively managed the noise floor created by secondary particle showers at high shielding thicknesses. These results confirm that characterizing the linear attenuation coefficient is a reliable precursor for generating accurate density models in muographic imaging.

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