PHYS 7398
Muon Lifetime

Amanda Nowicki
Department of Physics and Astronomy, Louisiana State University

(Dated: March 23, 2025)

This experiment measured the mean lifetime of cosmic muons using a plastic scintillator coupled with a photomultiplier tube (PMT). Muons, produced in the upper atmosphere by cosmic ray interactions, are capable of reaching Earth's surface due to relativistic time dilation. When a muon stops in the scintillator and decays, the resulting signals were used to determine the time between arrival and decay. A time calibration curve was generated using a pulse generator, enabling conversion of analog voltage to microseconds. The resulting decay histogram was fit with an exponential model using nonlinear least squares regression in Python. The measured muon lifetime was found to be $\tau = (2.244 \pm 0.014)$ μs, in good agreement with the accepted value of 2.197 μs. Minor deviations are attributed to electronic noise, background events, and systematic effects. The result confirms the capability of a single-detector setup to accurately measure a fundamental constant of particle physics.

I. INTRODUCTION

Muons (μ) are elementary particles in the lepton family, possessing the same charge and spin as electrons but with a mass approximately 206 times greater [1]. They are produced in the upper atmosphere through high-energy collisions between primary cosmic rays—mainly protons—and atmospheric nuclei. These collisions create cascades of particles, including charged pions, which subsequently decay to produce muons [2]. Although muons are inherently unstable, with a rest-frame mean lifetime of approximately $\tau_0 = 2.197\ \mu s$ [1], they can travel significant distances due to relativistic time dilation. Moving at velocities near the speed of light, muons experience slower internal clocks from the perspective of an Earth-bound observer, enabling their detection at sea level. Muons decay via the weak interaction, following these primary decay channels shown in Equation (1) and (2) [1].

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \tag{1}$$

$$\mu^- \to e^- + \bar{\nu_e} + \nu_\mu \tag{2}$$

Here, $\mu^\pm$ represents the positive or negative muon, $e^\pm$ is the positron or electron, ν_e and $\bar{\nu}_e$ are the electron neutrino and antineutrino, and ν_μ, $\bar{\nu}_\mu$ are the muon neutrino and antineutrino, respectively. The time distribution of muon decays follows an exponential decay law described by Equation (3) [1].

$$N(t) = N_0 e^{-t/\tau} + C, \tag{3}$$

where $N(t)$ is the number of decay events observed at time t, N_0 is the number of muons at $t = 0$, τ is the mean lifetime of the muon, and C is the constant background count from random or unrelated events.

This experiment aims to measure the average muon lifetime by recording the time interval between a muon entering a detector and its subsequent decay. By analyzing the distribution of these time intervals, we extract *tau* through exponential curve fitting and compare it to the accepted value.

II. PROCEDURE & METHODS

A. Experimental Setup

The primary detection system for this experiment consists of a plastic scintillator coupled to a photomultiplier tube (PMT). The PMT was biased at approximately -2.2 kV to ensure optimal photoelectron gain. The required operating voltage varies by PMT model. In this experiment, a discrepancy was noted regarding the appropriate bias voltage for the Hamamatsu H6410 PMT. While the initial assumption was that −1.7 kV would suffice, it was later determined that this voltage was insufficient to produce detectable signals. The manufacturer's specifications indicate an maximum rated anode-to-cathode voltage of -2.7 kV. However, operating the PMT near its maximum voltage can induce field emission, leading to increased dark current and noise [4]. This is what factored into the decision to operate the PMT at -2.2 kV.

When a muon enters the scintillator and deposits energy, scintillation light is produced and directed into the PMT, which converts the light signal into a corresponding electrical pulse [5].

This electrical pulse—our initial event—may originate from either a passing or stopping muon. If the muon decays within the scintillator volume, a second pulse is generated from the resulting decay electron. These two pulses form the basis of our timing measurement. To discriminate valid muon events from background noise or low-energy particles, the PMT output is fed into a Constant Fraction Discriminator (CFD). The CFD was set at the threshold of 40 mV. This value was determined by the apparent amplitude of the muon decay signals as seen on the oscilloscope. A corresponding image is shown in Figure 1. This threshold allows only signals above this level to pass to the timing system. This reduces the influence of noise while preserving genuine muon and decay events.

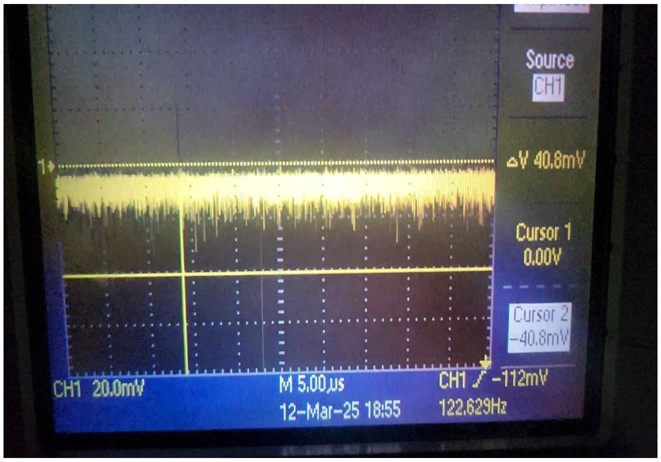

FIG. 1: Capture of muon decay signal on oscilloscope.

The filtered signals are routed to a Time-to-Amplitude Converter (TAC), which measures the time interval between two pulses. To enable a single-detector configuration, we split the signal path using a coaxial splitter: one copy is sent through a short cable to the TAC's STOP input, while the other travels through a longer, delayed cable to the START input. In the case of a valid muon stop-decay sequence, the second pulse (decay) arrives at the STOP input first, followed by the delayed initial pulse arriving at the START input. The TAC, upon receiving these signals in this order, generates a voltage output proportional to the elapsed time between them.

This analog voltage signal from the TAC is digitized by a Multi-Channel Analyzer (MCA), which converts it into a corresponding digital value using an Analog-to-Digital Converter (ADC). The ADC assigns each voltage to a discrete channel number, creating a one-to-one mapping between voltage amplitude and digital bin. These channel numbers represent the time intervals between muon arrival and decay, and the MCA compiles them into a histogram of event counts versus ADC channel. This histogram forms the raw data used in the calibration and decay analysis. The MCA is connected to a computer running MAESTRO-32 software, which enables real-time data acquisition, visualization, and export for post-processing.

To ensure proper signal integrity, the detector was wrapped in light-tight black foil and enclosed within a blackout material to eliminate light interference. An image of this is shown in Figure 2.

FIG. 2: Photo of detector setup.

B. Time Calibration

To convert the muon decay data from ADC channels into physical time units, a calibration was performed using a pulse generator. The generator produced pairs of pulses with controlled time delays, simulating muon arrival and decay signals. These artificial events were processed by the full detector system, including the Time-to-Amplitude Converter (TAC) and Multi-Channel Analyzer (MCA), just as actual muon decays would be.

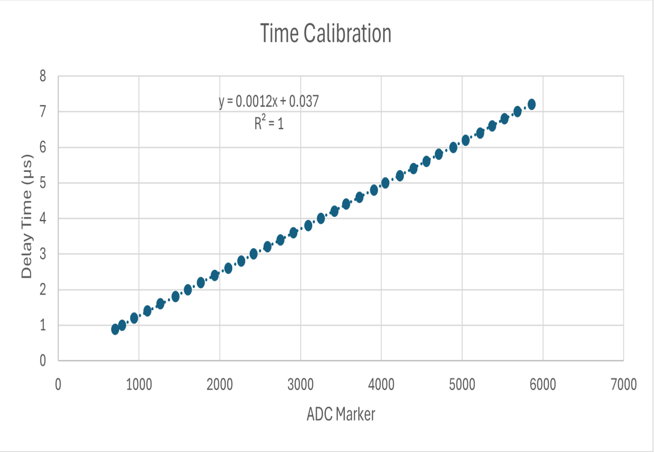

FIG. 3: Time calibration curve, with the conversion factor given by the slope of the line.

The resulting ADC channel numbers were plotted against the corresponding delay times, producing a highly linear relationship. This data is shown in Figure 3. A least-squares regression yielded the following calibration equation:

$$t = (1.22 \pm 0.001) \times 10^{-3} \cdot \gamma + (0.0361 \pm 0.0042), \quad (4)$$

where t is the time in microseconds and γ is the MCA bin number. The uncertainties in the slope and intercept were obtained directly from the standard errors provided by the regression analysis using Excel's LINEST function. The coefficient of determination for the fit was R^2=0.99997, indicating excellent linearity and consistency in the calibration data. This equation was used to convert the decay histogram from channel space to time space, enabling an accurate exponential fit to determine the muon mean lifetime.

III. ANALYSIS & RESULTS

Following calibration, data collection was initiated and continued over approximately seven days to accumulate sufficient statistics. The resulting distribution of decay intervals was later analyzed and fit with Equation (3) to extract the mean lifetime of the muon. This data is shown in Figure 4.

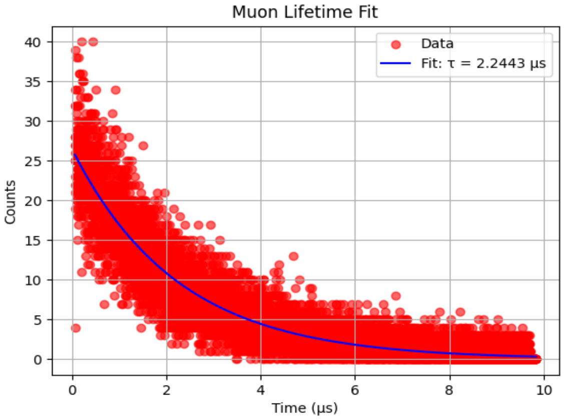

FIG. 4: Muon lifetime exponential fit.

The fitting was performed using a Python script that employed nonlinear least squares regression (via the scipy.optimize.curve_fit function). The resulting best-fit value for the muon lifetime was:

$$\tau = (2.2443 \pm 0.014)\,\mu s \tag{5}$$

The uncertainty was extracted from the square root of the corresponding diagonal element of the covariance matrix returned by the fit. While the majority of the data conformed well to the expected exponential behavior, several early-time bins displayed unusually high or scattered counts. These points, likely influenced by electronic noise, pile-up, or timing artifacts, can heavily bias the exponential fit. To minimize this effect, a small subset of these early-time outliers was excluded from the fit. This exclusion was limited to only those points that clearly deviated from the trend and was justified by their disproportionate influence on the fitted result.

IV. DISCUSSION & CONCLUSION

The accepted value for the muon lifetime is $\tau_{accepted} = 2.197\ \mu s$ [1], giving us a measured deviation of:

$$\Delta\tau = 2.244 - 2.197 = 0.047\mu s \tag{6}$$

This corresponds to a relative error of approximately 2.1% , which is well within reasonable experimental expectations for a single-scintillator setup. The remaining discrepancy may stem from background noise, timing resolution limits of the detector electronics, or residual systematic bias introduced by early-time signal artifacts, even after outlier removal. Nevertheless, the agreement with the accepted value is strong, and the result demonstrates the effectiveness of the experimental technique in capturing a fundamental constant of nature. In future experiments under similar conditions, it may be beneficial to slightly increase the discriminator threshold to approximately 42 - 45 mV. This could help further suppress low-energy background noise while preserving valid muon decay events.

V. ACKNOWLEDGMENTS

I would like to acknowledge the Louisiana State University Department of Physics and Astronomy for providing the equipment for this experiment. I would also like to thank my lab partner Preeti Sharma for her assistance in this experiment.

---

[1] Particle Data Group, *Review of Particle Physics*, Prog. Theor. Exp. Phys. **2024**, 083C01 (2024).
[2] P. L. Biermann, "The Origin of Cosmic Rays," *Space Science Reviews*, **74**, 385–396 (1995).
[3] University Physics Lab, *Muon Lifetime Measurement Manual*, PHYS7398 Lab Course, Spring 2022.
[4] Hamamatsu Photonics, *H6410 Series Photomultiplier Tube Datasheet*, available at: `https://www.hamamatsu.com`.
[5] University Physics Lab, *Scintillation and Electronics Manual*, Internal Course Document, 2022.