Cosmic Ray Sourced Muon Lifetime Measurement in a Liquid Scintillator Detector

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A measurement of the muon lifetime was performed using a liquid scintillator detector and oscilloscope setup connected with Python for automatic muon decay detection. Over multiple days, cosmic-ray muons were recorded, and intervals between arrivals and decays were analyzed. An exponential fit yielded a lifetime of $\tau = 2.03 \pm 0.19\,\mu$s, consistent with expected value of $\tau = 2.1969811 \pm 0.0000022\,\mu$s. The results support the reliability of cosmic-ray muon detection for weak interaction studies and confirm previous muon lifetime measurements.

INTRODUCTION

The Standard Model of Particle Physics is the most successful theoretical framework for describing the fundamental building blocks of matter and their interactions. It classifies elementary particles into *fermions* (matter particles) and *bosons* (force carriers). Fermions are further divided into *quarks* and *leptons*, whereby each of these has three generations of particles. The first generation contains the commonly known electron and its neutrino. The second generation includes the muon and its neutrino, often called the electron's heavier cousin, and the third generation consists of the tau lepton and its neutrino. The muon (μ^+/μ^-) is simply a heavier version of the electron, possessing the same charge and spin but with a much shorter lifetime.

Among the four fundamental forces—gravitational, electromagnetic, strong nuclear, and weak nuclear—the muon's decay is mediated by the *weak force*. Mediated by the massive W and Z bosons, the weak force is the only one that can be characterized by the violation of parity symmetry, making it important to many phenomena in subatomic physics.

Commonly, modern particle physics experiments make use of high-energy accelerators such as the Large Hadron Collider to produce new particles by producing particle collisions at relativistic speeds. However, in this experiment, this is not necessary as cosmic rays act as the source of muons, continuously striking the Earth's atmosphere. Cosmic rays are primarily high-energy hydrogen and helium atoms that travel around the universe and are thought to be generated by events such as supernovas, galaxy collisions, solar flares, and matter falling into super-massive black holes. [2] When these high-energy atoms or particles collide with other atoms in Earth's atmosphere, they generate secondary particles such as pions ($\pi^{\pm}$), which quickly decay into muons and neutrinos via the weak interaction:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \quad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \tag{1}$$

Although muons have a mean lifetime of about $2.2\,\mu$s in their rest frame, they reach sea level in large numbers due to relativistic time dilation.

The muon lifetime is not only an important quantitative result from weak interactions but also an important experimental test of the Standard Model and quantum field theory. Although the Standard Model successfully predicts many physical observables, its predictions must be verified through precise measurements to confirm or challenge the theoretical framework. Demonstrating agreement between the measured muon lifetime and the predicted value is therefore a crucial step in validating our current understanding of particle physics.

Muons have been found experimentally to have a vacuum lifetime of $2.1969811 \pm 0.000022\,\mu$s. [5] In this experiment, this experimental value was tested; by detecting the time interval between a muon's arrival in a detector and its subsequent decay, one can experimentally determine this lifetime.

The most common mode of Muon decay [3] is shown below:

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu, \tag{2}$$

Liquid scintillators are made of materials that are able to absorb and then emit energy from charged particles such as muons and electrons. When either an electron or muon travels through the scintillator, some of the electrons from the scintillator material absorb energy. What makes a material be a scintillator is the fact that shortly after this energy is absorbed, the excited electrons go back down to their original state and re-emit the energy as visible light. When connected with a photomultiplier tube (PMT), this emitted light turns into an electrical pulse which can be recorded to an oscilloscope. [1, 4]

Because muon decay is inherently a quantum mechanical process, its decay or lifetime is not a certainty at any moment. Rather, once a muon is observed, there is a given probability that it will decay at any given moment. This probability follows the laws of quantum mechanics and, as such, it has an associated probability distribution function. By recording decay times for a large population of muons and plotting a histogram of these intervals, one can fit the resulting data to an exponential function and extract from it the characteristic decay constant that is the inverse of the muon's mean lifetime.

Apparatus and Data Acquisition

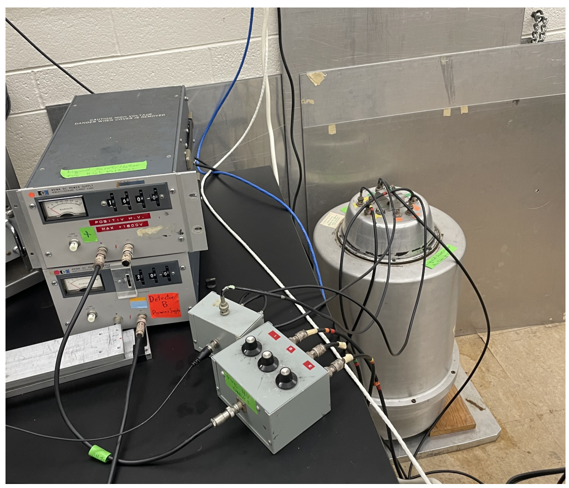

FIG. 1. Power Supply, Liquid Scintillator, PMTs and Potentiometer used to detect muons in the experiment.

The experimental setup consists of a liquid scintillator detector (cylindrical object on the right in Fig. 1) coupled to three separate photomultiplier tubes (PMT), with data acquisition performed using a Siglent SDS1204X-E oscilloscope. A positive high voltage HP6516A power supply set to the recommended value of +1600 V was used to power the liquid scintillator. This positive voltage passed in series through a potentiometer that allowed for varying the gains of each of the three PMTs. For the purposes of this experiment, the gains of the PMTs were equalized. This was done to ensure that the sensitivity of the system to detect muon decay is as homogeneous as possible throughout the entire liquid scintillator.

The lab setup includes several different scintillators that can be used in conjunction to form a muon telescope, which can be used to perform other experiments related to muon physics. However, for muon lifetime measurements, the large liquid scintillator is the only one used since it has the highest detection rate, and for lifetime measurement, there is no need to have more than one scintillator.

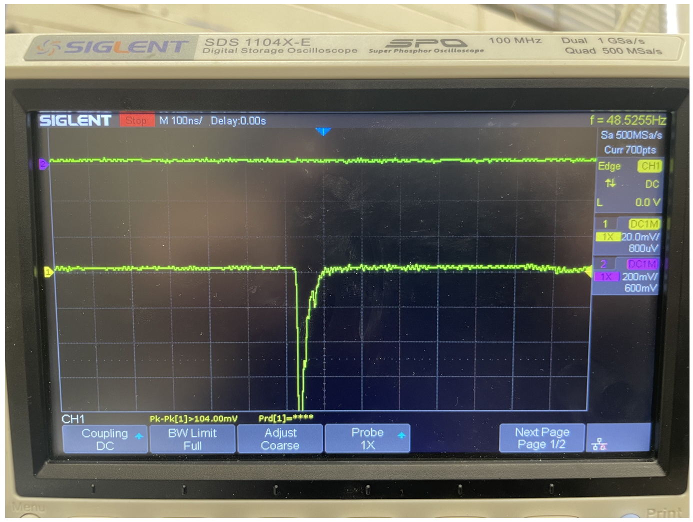

FIG. 2. Example oscilloscope capture showing voltage spikes consistent with a detected muon event.

Besides being connected to the summed output of the PMTs, the oscilloscope was also connected via USB to a lab computer running NI LabVIEW software. LabVIEW communicated with the instrument in real time, fetching waveforms each time the scope triggered. A Python script connected to LabVIEW on the backend and performed a peak-finding algorithm on every frame captured by the oscilloscope. Specifically, it scanned for two different voltage pulses that surpassed a given amplitude threshold and appeared within the expected time interval for muon decay (0 ns–8 µs). If these conditions were met, the event was identified as a muon decay and recorded in a text file. Due to this automatic processing with the Python script a key component of this experiment was adjusting the configuration of the oscilloscope such that the script would be able to process the frames correctly. If the sampling rate or memory depth were set to higher levels the Python script would crash after a few seconds. If the time division was set too low then each frame passed into the peak finding algorithm in Python would not be long enough to have a muon decay in the frame and no events would be detected. Similar consideration was given to Trigger level, if it was too low then noise or even variations within a single particle detected could trigger the oscilloscope and be incorrectly recorded as a decay event. However, if the voltage threshold was set too high then the muon decays would not be recorded as events at all.

Through a combination of analysis and trial and error the following configurations were chosen for the oscilloscope:

- **Sampling rate**: 500 MSa/s
- **Memory depth**: $7,000$ points
- **Time division**: 1 µs/div
- **Triggering mode**: Interval trigger with window [0 ns, 8 µs]
- **Trigger level**: -4.8 mV (DC coupling)

Data collection was allowed to run for approximately three days, accumulating all recorded events into a text file for further processing. Afterward, the provided Python data-analysis code was used to read these events, generate a histogram with 50 bins of the measured time intervals, and produce a plot of detection count versus separation time. The binned data of detection count versus separation time was then processed with curve fitting code to fit it to the theoretical exponential decay function that models muon decay. This post-acquisition analysis enabled the extraction of the muon lifetime from the full distribution of observed events.

RESULTS AND DISCUSSION

The histogram of measured decay times is shown in Fig. 3. An exponential decay model of the form

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

was fitted to the data, yielding a measured lifetime of $\tau = 2.03 \pm 0.19$ µs.

The main source of error is thought to be due to muon nuclear capture. [3] A process where the negative muons interact with nuclei of atoms present in the medium of the liquid scintillator, causing the negative muons to have a shorter apparent lifetime. This is consistent with the expected result obtained in the experiment being close to but shorter than the expected muon lifetime. Other sources of error that are thought to be negligible compared to the effects of muon nuclear capture include possible reflections in the oscilloscope cable causing false double pulses that could be potentially recorded as a decay event although

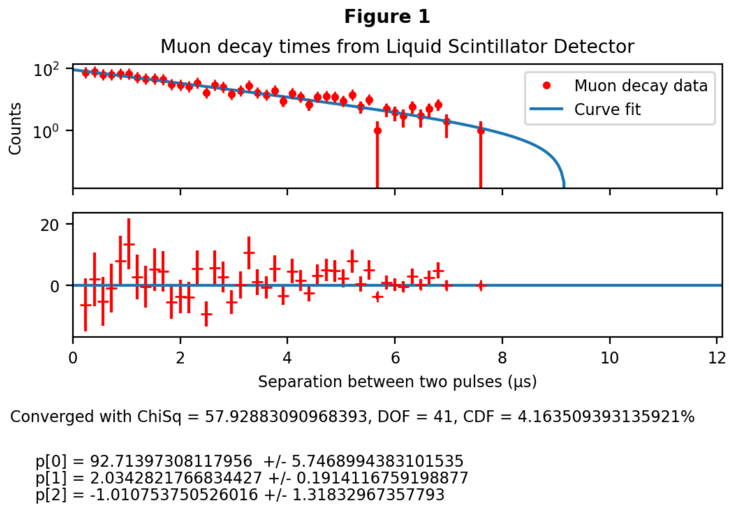

FIG. 3. Histogram of muon decay times fitted to Eq 3, where p[0] = N_0, p[1] = τ, and p[2] = b.

it's unlikely they would meet the voltage trigger threshold. Additionally, there is some uncertainty associated with the curve fitting results which is reported in Fig. 3, and there is a time uncertainty from the peak separation software.

CONCLUSION

A measurement of the muon lifetime was performed using a liquid scintillator detector. The result, $\tau = 2.03 \pm 0.19$ μs, is in agreement with the accepted experimental result within uncertainties. Especially when taking into account the fact that the muon lifetime is given in vacuum and in this experiment the muons were not detected in vacuum, but in a liquid material where negative muons have a shortened lifetime due to interactions with atomic nuclei from the scintillator medium.

CITATIONS

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