Lab N-17: Lifetime of cosmic ray muons with with on-line data acquisition on a computer

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We measure the muon lifetime using scintillation and delayed coincidence techniques. Cosmic ray muons entering a scintillator radiate photons as they slow to non-relativistic velocities. These muons decay to neutrinos and an electron, the latter of which also scintillates. The scintillation photons are detected with a photomultiplier tube and the distribution of times between these signals is used to extract the muon lifetime. Further care is taken to statistically disentangle the μ^+ and μ^- decay distributions, as the μ^- displays a lower effective lifetime in media due to nuclear capture processes. We find $\tau = 2.36 \pm .01_{\text{thy}} \pm .09_{\text{stat}}$ μs.

Keywords: 510 Lab, muon lifetime, scintillation, delayed coincidence

I. INTRODUCTION

Muons are produced when cosmic rays strike the upper atmosphere. Though the muon lifetime is on the order of 2 μs, they are highly boosted and time dilation allows these muons to reach sea-level. These muons can be observed through their interactions with a scintillator, a material with a high index of refraction that radiates photons when energetic particles pass through them. In this paper we present a measurement of the muon lifetime via the detection of scintillation radiation and delayed coincidence techniques first proposed in [1].

The basic process is presented in Figure 1. When a relativistic muon enters a scintillator, it loses its kinetic energy to scintillation radiation via ionization. The muon then comes to rest and decays to an electron, electron anti-neutrino, and a muon neutrino following the usual exponential decay distribution of unstable particles. The latter two particles go undetected, but the electron has a large kinetic energy and produces scintillation radiation. The time between the two radiation pulses is a measure of the muon lifetime.

There is a subtlety, however. Though charge-parity symmetry in the lepton sector sets the muon (μ^-) and anti-muon (μ^+) lifetimes equal to one another in vacuum, the two particles behave differently in media. Muons can be captured by high-Z nuclei via the process

$$\mu^- + p^+ \to n + \nu_\mu, \tag{1}$$

where the outgoing neutron scintillates. Thus the measured μ^- lifetime is shorter than the true value which, by charge-parity symmetry, is equivalent to the μ^+ lifetime. Fitting to a single exponential distribution would then underestimate the μ lifetime in vacuum. In order to be able to extract this lifetime one must fit the distribution of decay times to two exponentials representing the decays of the μ^- and μ^+.

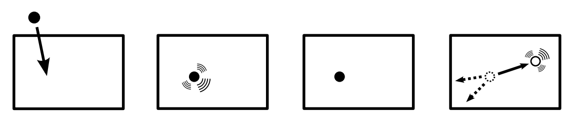

FIG. 1: Physical process being studied. (a) A relativistic muon enters the scintillator, (b) interacting with the medium via ionization and eventually losing its kinetic energy as scintillation radiation. (c) The now *non*relativistic muon survives on the order of τ before (d) decaying into two neutrinos and an electron, the latter of which also scintillates.

With sufficient statistics, we show that it is possible to determine both the μ^+ and μ^- decay distributions and hence determine the muon lifetime.

II. EXPERIMENTAL PROCEDURE

A schematic of the experimental set up is shown in Figure 2. An array of organic scintillators are connected to photomultiplier tubes (PMT) that detect and amplify photon signals. From these signals we would like to identify pairs which come from a muon entering the scintillator and the electron produced from the subsequent decay. Thus incidental signals from noise amplified in the PMT must be removed from the data set.

A discriminator vetoes any signal below a critical threshold characteristic of the scintillation radiation. In order to remove noise above this threshold voltage, we limit our accepted data to those in which a pair of signals occur within 25 μs of one another. This provides an ample range of decay times to fit the exponential decay of particles whose effective lifetimes are on the order of 2 μs. Signals that pass the discriminator initiate (1) a coincidence unit, (2) a 25 μs delayed pulse, and (3) a time

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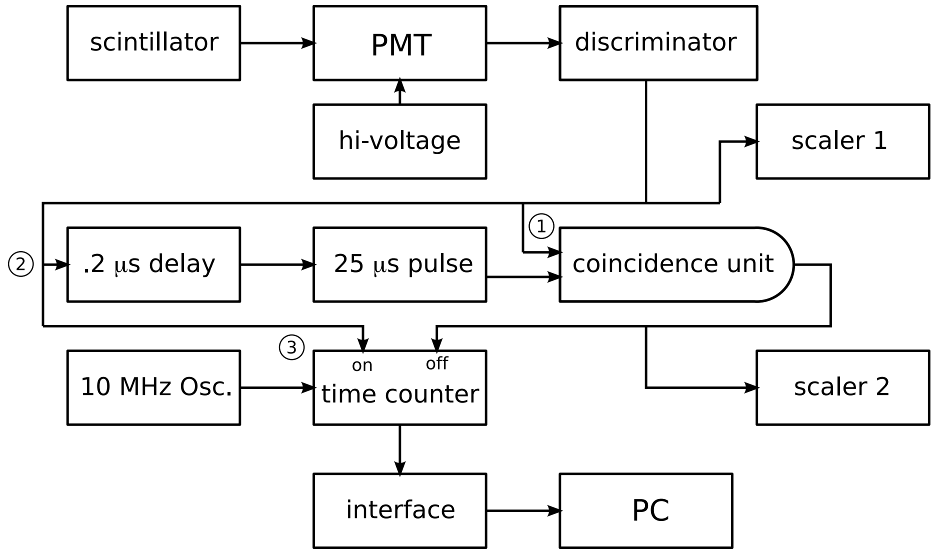

FIG. 2: Schematic of the experimental set up, adapted from the lab manual [2]. See Section II for a description.

counter. The coincidence unit waits for a secondary pulse before outputting a signal to stop the timer. The delayed pulse will restart the coincidence unit after 25 μs if it has not yet observed a second signal, suggesting that the initial pulse was a background event. The time counter is driven by a 10 MHz oscillator, allowing a resolution of 0.1 μs.

Upon a second signal within 25 μs, the coincidence unit outputs a stop signal to the counter, which then outputs the recorded time to a data acquisition system (DAQ) interfacing with a PC. Two scalers count the total number of single pulses passing the discriminator and the total number of muon candidate paired pulses within 25 μs.

The output file contains the total number of counts per 0.1 μs time bin over 256 such bins.

III. RESULTS AND DISCUSSION

We imposed cuts restricting our data to times within $0.7\ \mu\text{s} \le t \le 16.0\ \mu\text{s}$. For short times the 0.2 μs delay in Figure 2 leads to unreliable counts, while at long times we suspect a systematic error with the electronics system. This latter anomaly can be seen by looking at a logarithmic plot of a subset of the muon candidate data, shown in Figure 3. To verify this cut we compare the points around the bins $t \sim 16.0\ \mu$s to the expected number of background pair events given by a Poisson distribution

$$N_e = N_t \ P_{\Delta t R}(2), \tag{2}$$

where δt is the bin size, R is the rate of singles counts, and N_t is the total number of singles counts. We find a distinct drop below this background rate and cut the data above $t = 16.0\ \mu$s.

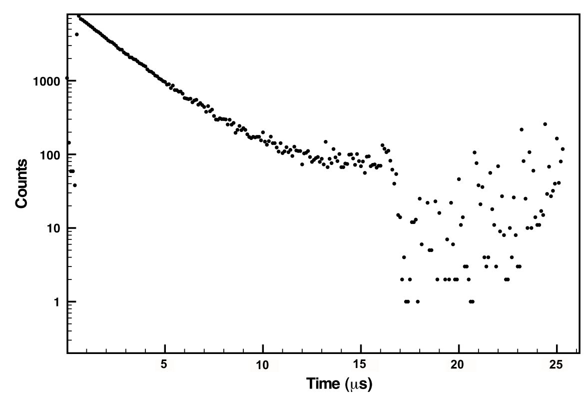

FIG. 3: A subset of the muon candidate data displaying undercounting for times less than 0.7 μs and an experimental anomaly for times above 16.0 μs.

After these cuts the data contained 166,415 muon candidates over 154 bins of size $\Delta t = 0.1\ \mu$s. We fit these points using a maximum likelihood analysis over four parameters; the muon lifetime τ_-, the anti-muon lifetime τ_+, the background rate B, and the total number of muon candidates (muons + background) N. The normalized probability distribution for muon events takes the form

$$f(t|\tau_-,\tau_+) = \frac{1}{\tau_- + R\,\tau_+}\left(e^{-t/\tau_-} + R\,e^{-t/\tau_+}\right), \tag{3}$$

where

$$R = 1.18 \pm 0.12 \tag{4}$$

is the ratio of μ^+ to μ^- at sea-level [3]. Thus the expected number of events in a given bin t_i is given by

$$N_i = N\ f(t_i|\tau_-,\tau_+)\,\Delta t + B\,\Delta t. \tag{5}$$

The binned likelihood function $\mathcal{L}$ is given by the product of the Poisson distributions from each bin with expected count N_i and measured count n_i,

$$\mathcal{L}(\tau_-,\tau_+,B,N) = \prod_{i=1}^{\#\text{ bins}} P_{N_i}(n_i). \tag{6}$$

The maximum of this function gives the maximum likelihood estimator of the parameters τ_-, τ_+, B, N. The location of this maximum is unchanged when $\mathcal{L}$ is transformed by a monotonic function, so it is often convenient to work with the log-likelihood function,

$$\ell = \log\mathcal{L} \tag{7}$$

$$= \sum_{i=1}^{\#\text{ bins}} -\log(n_i!) + n_i!\log(N_i) - N_i. \tag{8}$$

This replaces the product with a sum and the has the benefit of taking values that are not exponentially small. Thus the log-likelihood can more readily be optimized using computer mathematics systems[1].

We use the *Mathematica* computer algebra system [4] to optimize the four-parameter log-likelihood function and find that the best fit values are given by

$$\tau_- = 1.74 \pm .02_{\text{thy}} \pm .18_{\text{stat}}\ \mu\text{s} \tag{9}$$

$$\tau_+ = 2.36 \pm .01_{\text{thy}} \pm .09_{\text{stat}}\ \mu\text{s}, \tag{10}$$

where τ_+ estimates the muon lifetime in vacuum. This fit is plotted in Figure 4. The theoretical errors come from the errors on the ratio of anti-muons to muons at sea-level given in equation (4). The statistical errors are calculated using the large n_i assumption that the Poisson distribution approaches a Gaussian distribution since bin with the smallest count has $n_i = 66$ and the Gaussian approximation is conventionally valid for $n_i > 5$ [5].The error ellipses for $\tau_\pm$ are shown in Figure 5.

The accepted value of τ_μ is given by [6],

$$\tau_\mu = 2.197019 \pm .000021, \tag{11}$$

where the most recent measurements are also based on scintillation detection [7]. The 1.5σ discrepancy with our measured value τ_+ is suggestive of a systematic error, possibly connected the apparent systematic errors for the larger time bins $t_i > 1.60\ \mu$s. Our measured value for τ_- is also 1σ lower than the value measured in carbon [1].

One may further refer to past literature to check the sensibility of our result. As summarized in [1], measurements of both τ_+ in large-Z media tend to be larger than those in low-Z media, while measurements of τ_i in large-Z media tend to be smaller than those in low-Z media. While this qualitatively seems to fit the data presented above and suggest a that the scintillation medium has a large Z value, we note that for the 'garden-variety' organic scintillator used in our experiment we expect the main contribution to the effective Z would come from carbon and hydrogen, for which our measured values disagree with past results.

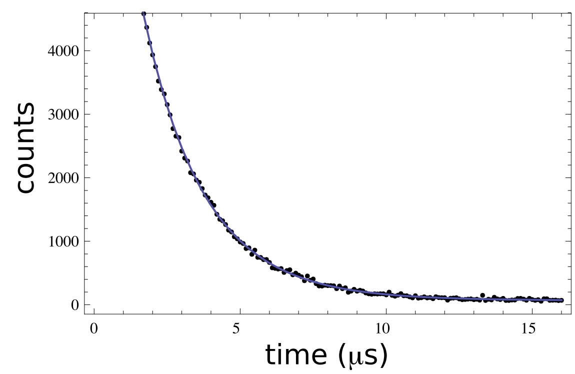

FIG. 4: Muon candidate data with maximum likelihood fit, error bars are smaller than the data points.

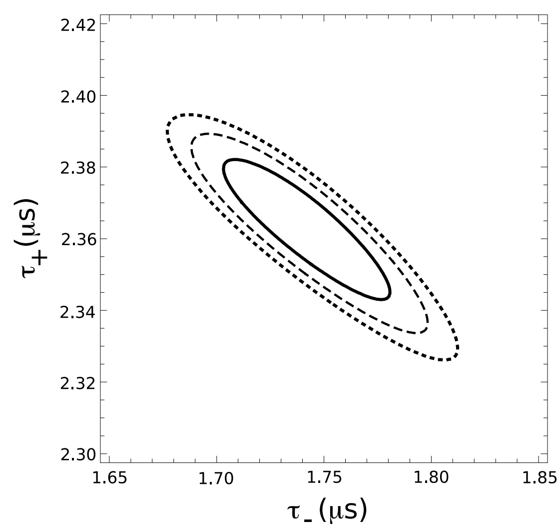

FIG. 5: Ellipses representing the 1σ (solid), 2σ (dashed), and 3σ (dotted) statistical errors for $\tau_\pm$.

IV. CONCLUSION

We have presented an analysis of the muon lifetime using delayed coincidence observation of scintillation radiation from its decay. Even though muons interact with matter and have a lower effective lifetime, we are able to fit the data to two nearly-equal exponential decays representing the μ^+ and μ^- decays separately. The ex-

[1] For particularly slow computers one may further use Stirling's approximation to simplify the $\log n!$ term in ℓ.

tracted value of the μ^+ lifetime is representative of the μ vacuum lifetime. Though the values for $\tau^\pm$ differ on the order of 1σ from our expected results, we have demonstrated the feasibility of maximum likelihood technique to distinguish between two very similar decays.

Anomalously low values at the large-time tail of the distributions are suggestive of systematic errors that may affect the data even after this tail is cut. Further study of possible systematic errors is required to better understand the measurement.

During the preparation of this document [8] appeared, suggesting the possibility of nonstandard muon interactions with a hidden sector. While it's unlikely that this has any effect on the present experiment, it's still a really neat paper that I'll to spend more time reading as this lab is completed.

Acknowledgments

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