Muon Physics

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Abstract

This experiment was conducted in order to measure the lifetime of a muon and the rate at which they descend. We used a method of experimental physics called detector physics, the detector used consisted of a scintillator in the shape of a right circular cylinder, placed at the bottom of the black anodized aluminum alloy tube. We measured their lifetime to be $\tau_\mu = (2.19396 \pm 0.11424)\mu s$ with an error 0.02 σ from the accepted value of $\tau_\mu = (2.19703 \pm 0.00004)\mu s$. In order to find the direction of flux we collected data using two different detectors, with the upper detector facing flat relative to the zenith angle, and changing the relative angle between the two. We found that at 90° the measurements were most accurate, with an average value of $\Phi_\mu = 0.9858$ muons $cm^{-2}min^{-1}$, a 1.4 % difference from the accepted value of $\Phi_\mu = 1$ muon $cm^{-2}min^{-1}$.

INTRODUCTION

When physicists Carl D. Anderson and Seth Neddermayer were researching cosmic rays at Caltech, they encountered a particle that resembled an electron but responded differently when subjected to a magnetic field. The particle was soon after identified as a muon, it carries a charge equal to that of an electron but is 200 times as massive. As primary cosmic rays collide with the nuclei of air molecules, a variety of particles are produced, including the pion. Through the weak force some of these charged pions will spontaneously decay into a muon and a neutrino or antineutrino (Fig. 1). Relative to an observer on Earth, it takes the muon approximately 50 μs to travel to the Earth's surface from the moment muons are created in the upper atmosphere. Being that the current accepted lifetime of a muon is approximately 2.2 μs, it is no coincidence that they are reaching the Earth's surface at 1 muon $min^{-1}cm^2$, in fact this is evidence of time dilation in the theory of special relativity.

METHODS

Charged particles passing through a scintillator lose some of its kinetic energy through ionization and atomic excitation of the solvent molecules. A portion of this energy excites the fluor molecules in the scintillator and their electrons are pushed into excited states, this process is known as radiative de-excitation and results in a photon being emitted.

A Muon's Lifetime

As a muon enters the plastic scintillator, the photon that is emitted is detected by a photomultiplier tube (PMT) and produces a signal that, when amplified and fed through a voltage comparator, produces an output pulse that triggers a timing clock. Once the muon begins to decay it produces an electron, a neutrino and an antineutrino (Fig. 2), the electron has enough energy to produce a second scintillator light that triggers the timing clock to stop counting. The time interval between the start and stop timing pulses, or the muon decay rate (λ_{obs}), is the data sent to the PC where it gets collected via the Muon program. The time clock will sometimes get triggered from random noise followed by no second scintillator flash, in these instances the time clock automatically stops counting at around 40000 ns. In order to account for this we allowed the detector to run through the night to acquire a substantial amount of valid data, and later ran our data through a sifter that deleted all entries 40000 and above. Our measurements of the muon lifetime is an average over both negatively and positively charged particles, let N^+ and N^- represent the number of positively and negatively charged muons respectively, [1]

$$\tau_{obs} = \frac{\tau^- N^- + \tau^+ N^+}{N^- + N^+} \tag{1}$$

Where $\tau_{obs} = \lambda_{obs}^{-1}$, which was found by running our data through a Python program. When negatively charged muons pass through the scintillator they quickly decay due to weak interactions with protons in the scintillator nuclei, and due to the nature of the of the interaction probability being proportional to Z^4, we expect the lifetime of negative muons to be nearly equal to that of carbon, $\tau_c = \tau^- = 2.043 \pm 0.003 \mu s$. Since positive muons are not captured by the scintillator nuclei, and just pass through, we can set the lifetime of positive muons equal to the free space lifetime value, $\tau^+ = \tau_\mu$. Taking this into consideration our final results for muon lifetime is,

$$\tau_\mu = \frac{\tau_{obs}(N^- + N^+)}{N^+} - \frac{\tau^- N^-}{N^+} = 2\tau_{obs} - \tau^- \tag{2}$$

Here we assume that the ratio of positively and negatively charged muons are equal so that, $N^-/N^+ = 1$ and $(N^- + N^+)/N^+ = 2$.

Muon Flux

In order to detect the direction and magnitude of muon flux, we had to interface two scintillators directly with the rack of equipment housing the Nuclear Instrumentation Modules (NIM) electronics. Figure 3 illustrates our set up, we connected both scintillators to a discriminator where we adjusted the width and threshold, setting the voltage threshold to its minimum value. We then connected both detectors to an AND logic gate, so that the counter would tally the muons that passed through both scintillators. The scintillators were placed parallel to each other and collected data at different angles at which the upper PMT was placed (Fig. 4). We used this equation to calculate flux (Φ_μ):

$$\Phi_\mu = \frac{N_\mu}{\Delta t \, A \, \Omega} \tag{3}$$

Where N_μ is the count of muons passing through both scintillators, Δt is the time interval, and constant $A \cdot \Omega$ is the effective area times the solid angle in which we derived from the idealized geometry of detectors array.

$$A \cdot \Omega = \int_{-\frac{L}{2}}^{\frac{L}{2}} \int_{-\frac{\beta}{2}}^{\frac{\beta}{2}} \int_{-a+\frac{L}{2}}^{\frac{L}{2}-m} \int_{-\frac{b}{2}}^{\frac{b}{2}} \frac{\gamma dy_0 dx_0 dy dx}{(\gamma^2 + (x-x_0)^2 + (y-y_0)^2)^{3/2}} = 83.0584 cm^2 sr \tag{4}$$

The elements in this equation are demonstrated in Figure 4.

RESULTS AND DISCUSSION

Our results for muon lifetime were very accurate, measuring a value of $\tau_\mu = (2.19396 \pm 0.11424)\mu s$ with a deviation of $\sigma = 0.02$, only a 0.15% from the accepted value of $\tau_\mu = (2.19703 \pm 0.00004)\mu s$[2]. Since the scintillator detects any charged or neutral particle that passes through, it has no way of identifying specific particles. Since this is an environmental systematic error out of our control, we had to set the threshold voltage in between 180 mV and 220 mV, to only record particles losing enough of its kinetic energy to trigger the time clock. In spite of doing this, the data from the first couple of days were not usable due to the majority of the time intervals being 40000 ns and above. We concluded that there was a random instrumental error, and although we were unable to figure out what was wrong with the detector, the problem was solved by lowering the threshold voltage to 125 mV. Our final results (Fig. 5) gave us a value of $\tau_{obs} = (2.06710 \pm 0.22086)\mu s$, and an exponential distribution of the decay time, which is typical of radioactive decay.

$$N(t) = Ae^{-\lambda_{obs}t} + B \tag{5}$$

Upper and lower boundaries for our exponential model were carefully chosen in order to reduce the effect of noise. In Fig 6. we illustrate the correlation between the decay time and muons events through a linear regression model. At larger decay times our data exhibited larger margins of error, this is expected as there is still noise that is not easily repaired without taking multitudes of data. We corrected some of this noise by subtracting the background noise constant B (Eqn. 5), this made sure that both algorithms gave reliable results.

We made a few approximations when measuring the flux of muons. We used a meter stick to measure the dimensions of the instruments which may have caused slight inaccuracies. In attempt to counteract any physical variations, we averaged over a few measurements. It was possible to simply take physical measurements for $A \cdot \Omega$, but we instead derived a formula it (Eqn. 4) and attempted to keep the separation distant constant. Thus there is some error in $A \cdot \Omega$ but can be ignored as it is minimal. To establish the direction of flux, we made measurements at different angles and concluded that the flux was most accurate in the vertical direction. Figure 7. shows how the flux decreases as the angle between the separation distance and the horizontal axis decreases. Our final result for muon flux in the vertical direction is $(26.1499 \pm 1.6716) cm^{-2} min^{-1} sr^{-1}$ with an uncertainty of 1.67 σ (Table. II), which corrects to $\Phi_\mu = 0.9858$ muons $cm^{-2} min^{-1}$. Being that our final result yielded an uncertainty greater than 1 σ, it can be concluded that our approximations in some measurements were the result of this inaccuracy. This could be resolved by using a more accurate measuring tool and collecting more data.

[1] T.E. Coan and J. Ye *Muon Physics Lab Manual v051110.0*

[2] Particle Data Group *http://pdg.lbl.gov/*

FIGURES

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

FIG. 1. A schematic of a charged pion (π^+, π^-) decaying into a charged muon (μ^+, μ^-) and a muon neutrino (ν_μ) or muon antineutrino ($\bar{\nu_\mu}$). Pions decay due to the weak force.

$$\mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

FIG. 2. A schematic of a muon (μ^-, μ^+) decaying into an electron (e^-, e^+), a muon antineutrino ($\bar{\nu_\mu}$) or a muon neutrino (ν_μ), and an electron neutrino (ν_e) or an electron antneutrino ($\bar{\nu_e}$). The negatively charged muon is more representative of what occurs inside the scintillator, while the positively charged muons are more likely to pass through the scintillator and decay elsewhere.

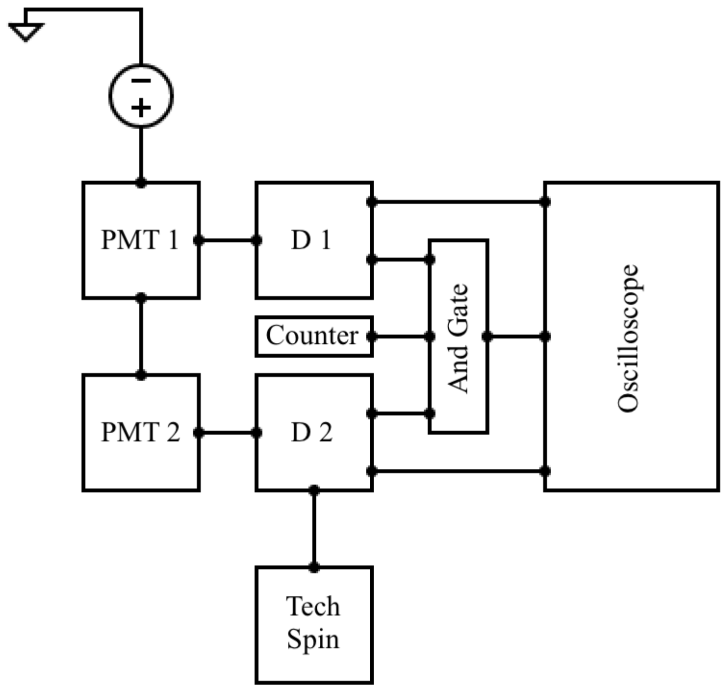

FIG. 3. Here is a rough schematic of the setup used to determine muon flux. Both PMT's are connected to separate discriminators whose outputs go to the oscilloscope and the logic/coincidence gate. The coincident gate is connected to a counter in the NIM electronics.

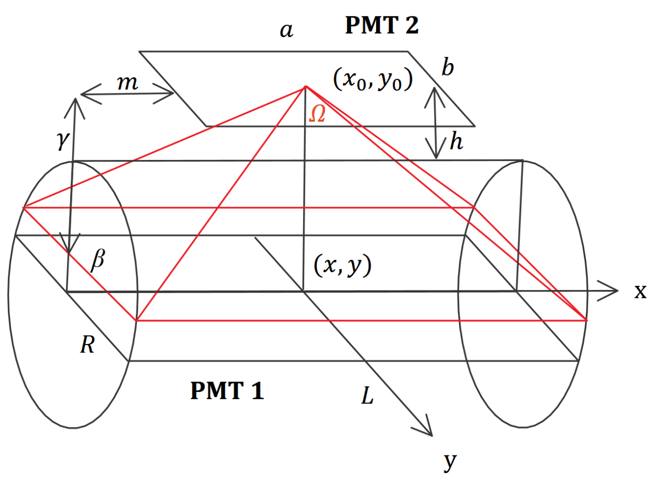

FIG. 4. This picture shows the set up and geometry of PMT array.

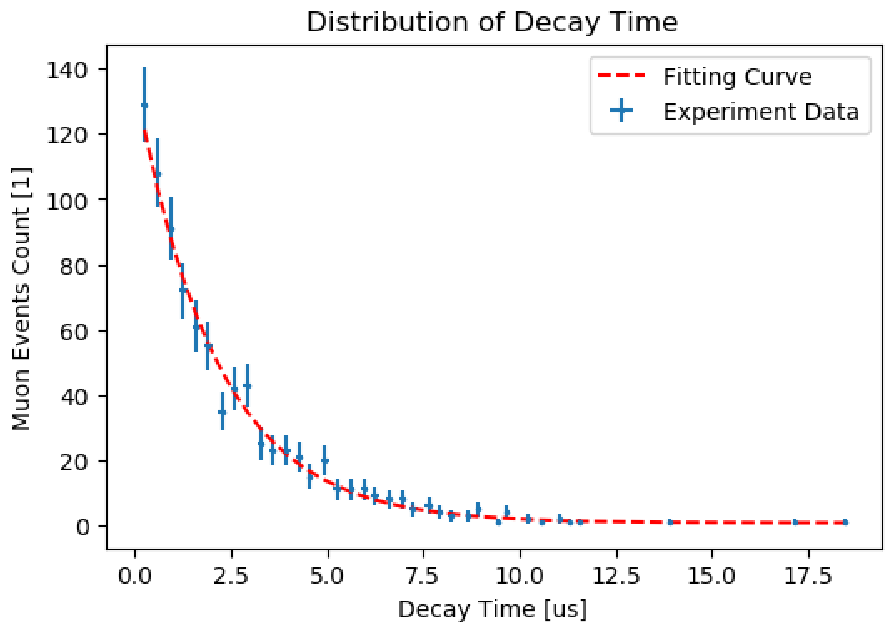

FIG. 5. This plot shows the exponential fitting for the muons events time distribution.

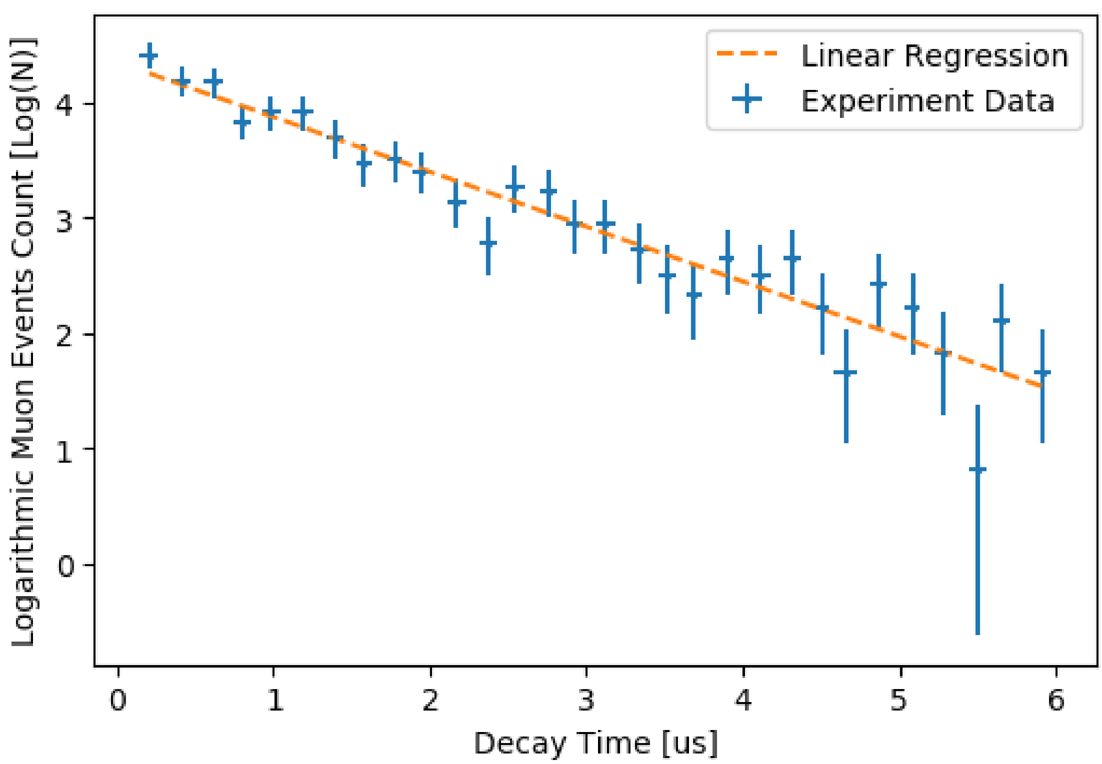

FIG. 6. This plot shows the linear regression for the muons events time distribution in logarithmic scale.

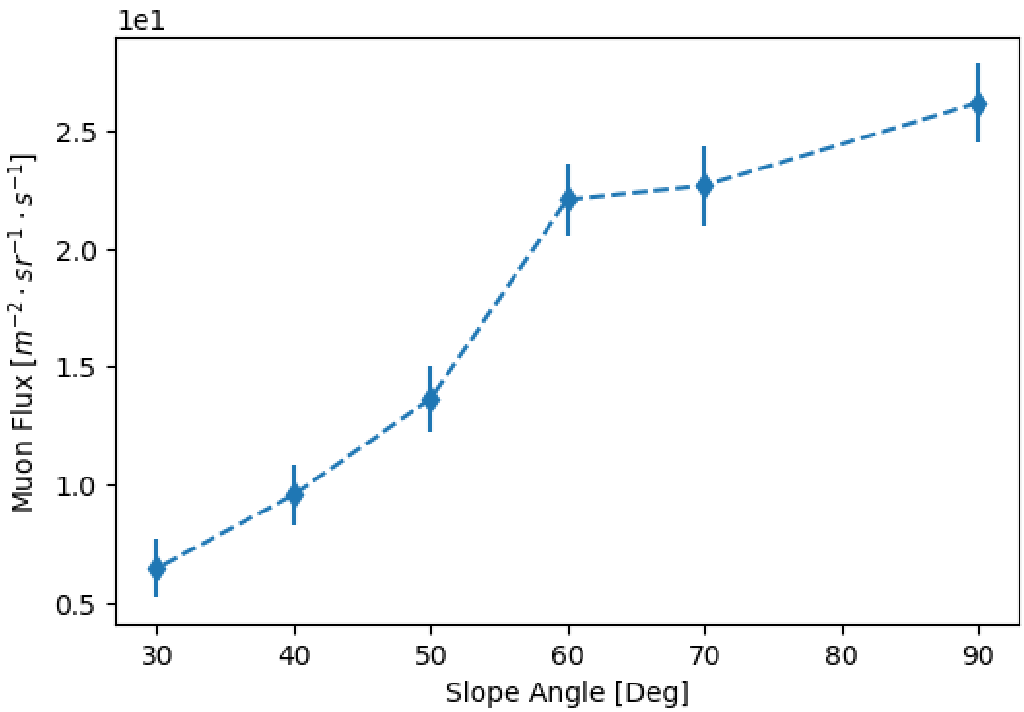

FIG. 7. This plot shows the change in muon flux as the angle between 'r' (from the solid angle) and the horizontal axis changes.

TABLES

Angle[Deg]	Start Time	End Time	Time Delta	Time Delta [Sec]	Muon Count [1]	Flux[1/Sec]
90	17:05:21	17:19:18	0:13:57	837	170	0.203106
90	17:19:18	17:35:12	0:15:54	954	219	0.22956
70	16:36:30	17:01:23	0:24:53	1493	281	0.188212
60	17:37:20	17:46:55	0:09:35	575	104	0.18087
60	17:46:55	17:56:45	0:09:50	590	115	0.194915
60	11:40:45	11:57:20	0:16:35	995	177	0.177889
50	11:59:55	12:14:15	0:14:20	860	104	0.12093
50	12:14:15	12:29:55	0:15:40	940	100	0.106383
40	12:32:19	13:01:39	0:29:20	1760	140	0.079545
30	13:03:11	13:31:43	0:28:32	1712	92	0.053738

TABLE I. This is a table of the values collected to determine flux of muons. The angle is representative of how the upper PMT is titlted relative to the lower PMT. Using the measured values of numbers of muons passing through both scintillators over a period of time we were able to calculate muon flux.

Angle[deg]	Flux[$cm^{-2}min^{-1}sr^{-1}$]	Flux[$cm^{-2}min^{-1}$]	Uncertainty[$cm^{-2}min^{-1}sr^{-1}$]
90	26.149925	0.985829	1.671650
70	22.660159	0.854268	1.692297
60	22.072823	0.832126	1.505607
50	13.645018	0.514405	1.396140
40	9.577051	0.361046	1.300642
30	6.469944	0.243911	1.221282

TABLE II. This table gives the muon flux against different slop angles. Also the flux are converted into $cm^{-2}min^{-1}$ dimension for comparison with standard value.