Measurement of Muon Lifetime

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The average lifetime of the muon has a well known value [4] . In this paper, we find a value for the average lifetime of a muon by detecting the rate at which muons from cosmic rays decay inside a plastic scintillator. Our value for the lifetime of a muon is found to be $\tau_\mu = 2.15 \pm 0.04\,\mu$s; this value agrees with the accepted value for the muon lifetime.

I. INTRODUCTION

Muons are one of six leptons (the others being electrons, tauons, and the associated neutrinos) [1]. The main source of muons on earth is cosmic radiation, which contains pions hitting our atmosphere and decaying into muons with the two reactions shown below:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \tag{1}$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \tag{2}$$

where π^+ and π^- are plus and minus pions, μ^+ and μ^- are plus or minus muons, and ν_μ and $\bar{\nu}_\mu$ are muon neutrino and antineutrino [1]. Once the muons are created they rapidly decay over time, shown in the reactions below:

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \tag{3}$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \tag{4}$$

where e^- and e^+ are an electron and positron, and ν_e and $\bar{\nu}_e$ are electron neutrino and antineutrino. This decay can be described as a exponential decay given by

$$N(t) = N_0 e^{-t/\tau_\mu} \tag{5}$$

where $N(t)$ is the muon population, N_0 is the initial population, t is time and τ_μ is the average lifetime of a muon [1]. In this paper, we will find the average lifetime of a muon.

II. METHOD

To measure the lifetime of muons we use a Teachspin Muon Physics apparatus connected to a computer. The detector is a cylindrical plastic scintillator surrounded by a black anodized aluminum alloy tube, measuring 15 cm in diameter and 12.5 cm tall. The plastic scintillator is a material that, when hit with high energy particles, produces light. A photomultiplier tube, or PMT, is used to detect the light given off in the scintillator. We can adjust sensitivity of the PMT by changing the PMT's voltage. The PMT will amplify the signals from the light emitted in interactions and send them to the electronics box, which includes a clock and amplitude filter that triggers if the signal voltage is above a voltage V_T, and is connected to a computer.

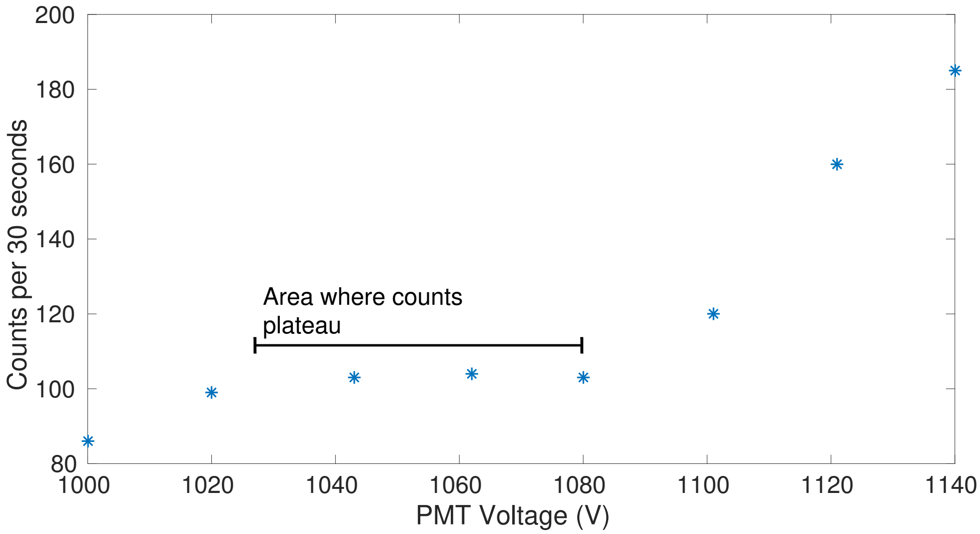

Figure 1. This plot shows the counts per 30 seconds versus different PMT voltages with the values for the detection threshold set at $V_T = 0.092\,\mathrm{V}$. The middle of the plateau is at about $V_{PMT} = 1060\,\mathrm{V}$. This data is used to find an appropriate V_{PMT} value for detecting muons.

When a muon enters the scintillator it interacts, slows down and stops (since it stops we do not have to worry about relativistic effects), releasing light which is picked up by the PMT. Then, when the muon decays it releases an electron that has much more kinetic energy than the muon, so it releases another burst of light (it also releases two neutrinos, but those can be ignored) [2]. The electron has more kinetic energy since the mass of the electron, $m_e = 9.109 \times 10^{-31}$ Kg, is much smaller than the mass of the muon, $m_\mu = 1.883 \times 10^{-28}$ Kg, and so the extra mass turns into kinetic energy [1][3]. Measuring the difference between these two light emissions allows us to measure the muon lifetime. Even though we do not know the time at which each muon is created, the decay times we measure will still fit equation 5. This is possible since the decay time is exponentially distributed. If there is no second light detection after a little more than $40\,\mu s$, the timer is reset.

To find settings for the PMT voltage V_{PMT} and the trigger voltage V_T that would only send a signal if a muon was detected, we set $V_T = 0.092\,\mathrm{V}$ and made measurements of counts per second measured by our equipment for different V_{PMT} values. This data was then plotted shown in figure 1. The V_{PMT} values we want to use are when the counts per 30 seconds plateaus. This happens after the voltage is high enough to detect all of the muons and before it is too high, causing it to detect noise from things such as electrons. The values

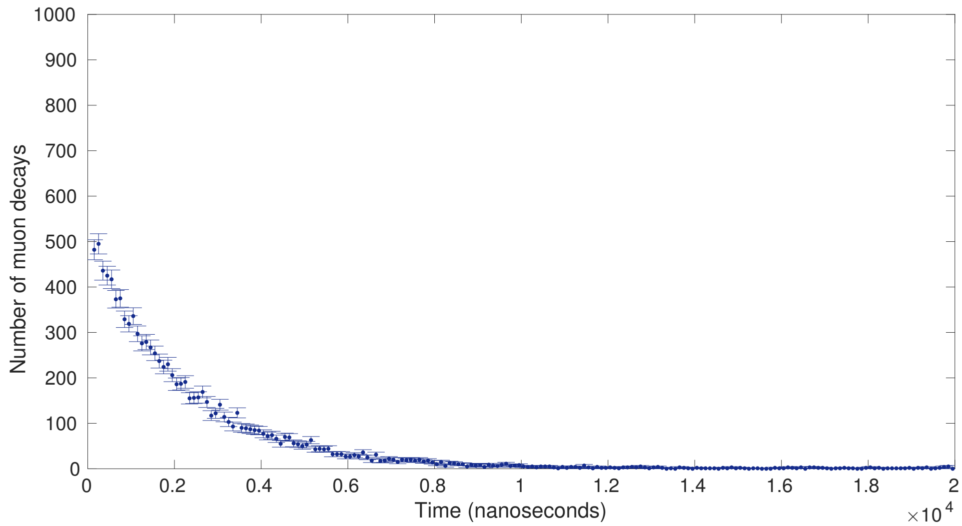

Figure 2. Counts per 100 ns width bins; this is equivalent to plotting equation 5.

we decided on for our V_{PMT} was $V_{PMT} = 1061\,\mathrm{V}$. The apparatus was then left running for 10 days.

III. DATA ANALYSIS

First, we sorted out the decays by getting rid of the measured time intervals greater than $40\,\mu$s, since this is just less than the cut off time. In total, we got 12891 ± 113 total decays. We sorted the decays into 100 ns width bins in the range from 50 ns to 20050 ns, allowing us to plot the counts as a function of time as shown in figure 2. Figure 2 is the same plot we would get from plotting equation 5, replacing counts with muon population. To find τ_μ we take the log of the counts and find the slope of the linearized equation given below:

$$\log N = -\frac{1}{\tau_{mu}} t + \log N_0 \tag{6}$$

where the slope is

$$m = -\frac{1}{\tau_\mu}. \tag{7}$$

Taking the log of our counts data and plotting gives us figure 3. We used least squares fitting to fit the data to a line with the slope $m_{measured} = -0.464 \pm 0.008\,\mu\mathrm{s}^{-1}$. Using equation 7 and the expression $\delta\tau_\mu = \tau_\mu^2 \delta m$, we can get an experimental value for the average lifetime of a muon, which is $\tau_\mu = 2.15 \pm 0.04\,\mu$s. This value is in agreement with the accepted value

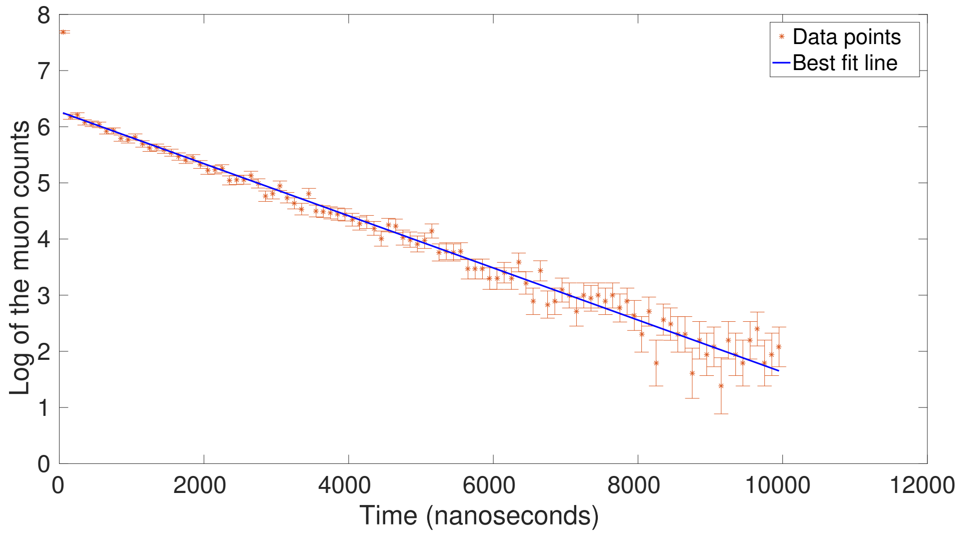

Figure 3. Linearized counts vs time data, with a linear fit line given by the equation $-0.000464x + 6.2696$; the error of the slope is 8×10^{-6}.

of $2.1969811 \pm 0.0000022\,\mu$s[4]. Though our value is in agreement, it is still lower than the expected value. One reason it may be lower is that the μ^- has an extra decay path where the μ^- interacts with a proton, shown in the interaction given below:

$$\mu^- + p \rightarrow n + \nu_\mu \tag{8}$$

where p is a proton and n is a neutron. This extra path gives μ^- two ways to decay, giving it a shorter average lifetime. This could account for our measured value for muon lifetime being shorter than the expected value.

IV. CONCLUSION

In this paper we found the average lifetime of a muon to be $\tau_\mu = 2.15 \pm 0.04\,\mu$s. Our value is 2.1% lower than the accepted value of $\tau_\mu = 2.1969811 \pm 0.0000022\,\mu$s, though our value is still within 2σ of the accepted value. The difference is likely caused the by extra decay path of the μ^-.

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[1] R. Eisberg, R. Resnick, *Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles* (John Wiley & Sons, United States of America)

[2] *Lifetime of Cosmic Ray Muons Appendix A*

[3] P.J. Mohr, D.B. Newell, and B.N. Taylor, *The 2014 CODATA Recommended Values of the Fundamental Physical Constants* (National Institute of Standards and Technology, Gaithersburg 2016) p. 56

[4] C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).