The Muon Lifetime

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1 Introduction

Cosmic rays are high-energy charged particles that originate from space and constantly bombard our Earth. These particles typically have energies of around 10^{10} eV, but some have been detected with energies as high as 10^{20} eV, hence we believe cosmic rays are a product of the explosions of stars. In the upper atmosphere, they collide with oxygen and nitrogen molecules, forming unstable particles not commonly found in nature such as pions. One example of this is described by the following scattering event

$$p + p \to p + p + \pi^+ + \pi^- \tag{1}$$

This could be a cosmic ray in the form of a proton colliding with another proton in a nitrogen nucleus, producing two pions. These pions then usually decay into a muon and a neutrino via the following processes

$$\pi^+ \to \mu^+ + \nu_\mu \tag{2}$$

for a positively charged pion π^+ and

$$\pi^- \to \mu^- + \bar{\nu}_\mu \tag{3}$$

for a negatively charged pion π^-. Pions have a short mean lifetime of $2.6 \cdot 10^{-8}$ seconds, which means they decay long before they reach the surface of the Earth. Their decay products, the muon and muon neutrino, do not interact via the strong force and thus traverse the remainder of the atmosphere.

In 1938, Carl Anderson and Seth Neddermeyer discovered the muon by observing the trails of pions left by energetic particles passing through their cloud chamber. During their studies, they identified a particle that came to a halt within the chamber. By examining the curvature of the particle's path in the presence of an external magnetic field, its range, and the level of ionization it produced, they found that the mass of this particle was approximately 10% of the mass of a proton. Since this value falls between that of an electron and a proton, they to concluded that it was a newly discovered particle, and further study was required to identify and understand its properties.

2 Experimental Setup

In this experiment, we measure the lifetime of the μ^- and μ^+. To do this, we design our apparatus with enough matter to reduce the kinetic energy of the passing muons. Once the muons are brought to a stop, we can observe their lifetime. This also makes calculations of the muon lifetime much easier, as once at rest, there will be no time dilation experienced. The halted muons will decay through the reactions:

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu_\mu} \tag{4}$$

$$\mu^- \longrightarrow e^- + \nu_e + \nu_\mu \tag{5}$$

The apparatus is composed of three slabs of plastic scintillators. Scintillators are materils that convert deposited energy from high energy particle interactions into emitted photons.

A diagram of the experimental setup is provided below. Here, the three scintillator slabs are labeled T, V, and AB. A slab of steel is placed between the T and AB scintillators to increase the stopping power of the setup. When a muon is stopped by the detector, it will pass through the top scintillator T, and will reach the detector body AB. It will NOT, however, pass through the bottom scintillator, V. So to identify events when the muon is halted by the detector volume, we must look for instances when coincident flashes are observed by PMTs A, B, and T, but not the bottom PMT V. This

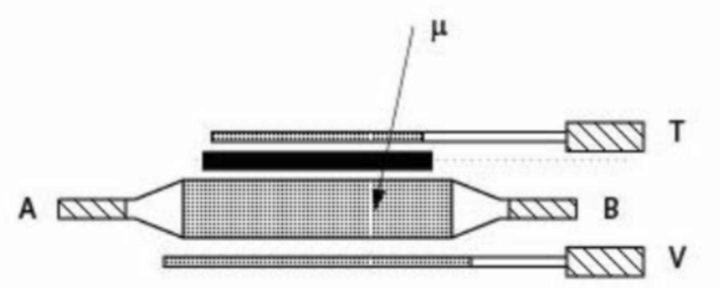

Figure 1: Experimental setup, as shown in the lab handout

coincidence setup is run by an electronics rack operating logic gates. It is designed to select signals given the condition $A \wedge B \wedge T \wedge \bar{V}$. To ensure timing, we use long cables to delay the signals and ensure they reach the logic gate at identical times, despite the fact that the events occur sequentially.

The output of this coincidence logic circuit is sent to an ORTEC TAC. The TAC is designed to convert the duration of the coincidence pulse to an analog voltage signal. The analog signal is proportional to the duration of the input pulse (hence the name "time-analog-converter"). We use the AB signal to stop the TAC protocol. Due to the timing of the logic, events with short muon lifetime may be lost. This does not impact the quality of our data, however, since the any portion of the exponential decay plot can be fit to yield the same predicted lifetime.

3 Results

Our results are summarized in **Figures 1 and 2**.

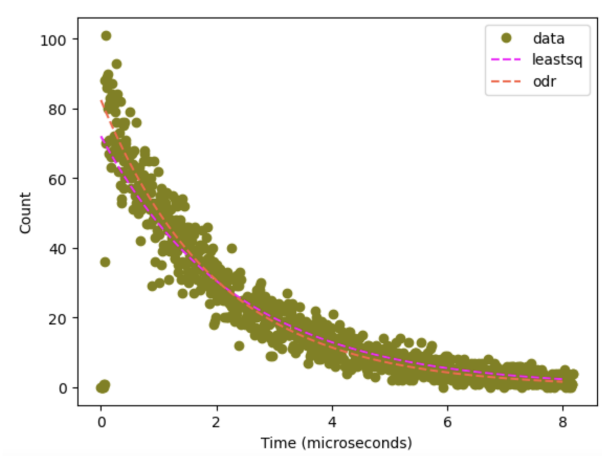

Figure 2: New data from 2023

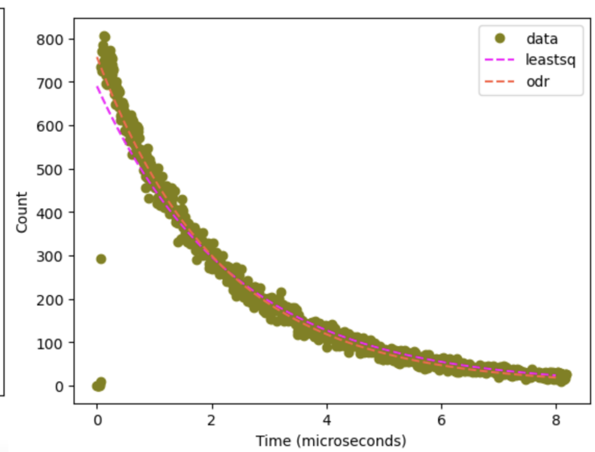

Figure 3: Old data from last 5 years

We obtained a τ_1 of $1.9344\mu s$ with an uncertainty of $0.02888\mu s$ for the new data and a τ_2 of $2.1562\mu s$ with an uncertainty of $0.02295\mu s$. We exclude the first 9 channels from our data due to the presence of outliers. There are two fits per graph, a least squares fit and an orthogonal distance regression fit, which better incorporates the uncertainties in our counts. We use a Poisson distribution for the standard deviations of each count, where a Gaussian distribution can be used as an approximation for large n.

4 Analysis

There will be error due to background since the TAC stops on any $A \cdot B$ signal. Thus, if the TAC is caused to stop prematurely, this will underestimate the amount of time a muon took to decay. The original function we fit to our data is

$$N = N_0 e^{-\frac{t}{\tau}} \tag{6}$$

where $\frac{1}{\tau}$ represents the rate of our exponential decay. However, if we split up the rate into two parts,

$$N = N_0 e^{-(\frac{1}{\tau}+\alpha)t} \tag{7}$$

and force $\frac{1}{\tau}$ to be the theoretical decay rate, we can approximate the decay rate due to background, α. Since the theoretical decay rate is

$$\frac{1}{\tau_{theor}} = \frac{1}{2.197 \cdot 10^{-6}} = 455166.1356 s^{-1} \tag{8}$$

Then, **Equation 7** becomes

$$N = N_0 e^{-(455166.1356+\alpha)t} \tag{9}$$

Fitting this function to our data, we retrieve

$$\alpha_1 = 3.8551 \cdot 10^{-2} s^{-1} \tag{10}$$

for the new data and

$$\alpha_2 = 2.0640 \cdot 10^{-2} s^{-1} \tag{11}$$

for the old data. Now we can fit the function described by **Equation 7** to our data, using the appropriate value of α. We obtain similar plots:

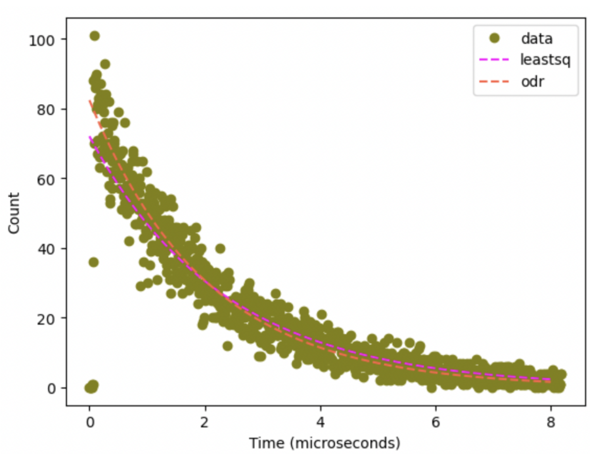

Figure 4: New data from 2023

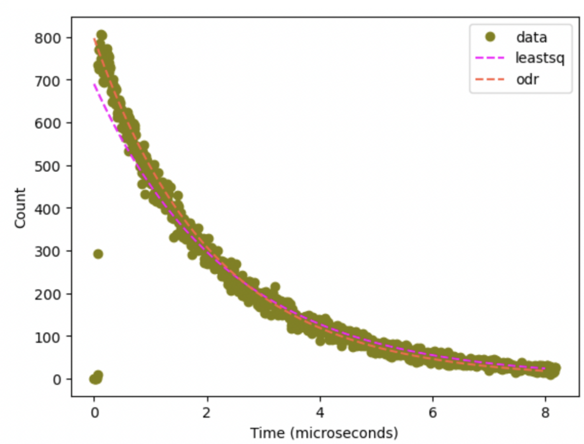

Figure 5: Old data from last 5 years

From these plots, we obtain a τ_1 of $2.0254\mu s$ with an uncertainty of $0.02871\mu s$ for the new data and a τ_2 of $2.1562\mu s$ with an uncertainty of $0.02295\mu s$ for the old data. Although our estimate for τ_2 remains unchanged, our estimate for τ_1 improved significantly.

5 Discussion

In this experiment, the mean lifetime of muons was determined to be $2.0254\mu s$ with an uncertainty of $0.02871\mu s$ for the new data and a τ_2 of $2.1562\mu s$ with an uncertainty of $0.02295\mu s$ for the old data. Evidently, the old data gives us a more accurate experimental value of τ. The theoretical lifetime of a muon, $2.197\mu s$ falls just outside of our uncertainty range. Thus, it is important to analyze the results in more detail and consider possible sources of error and their impact on the obtained value.

Firstly, let us consider the experimental setup. The experiment involved detecting the decay of muons using a particle detector and recording the time intervals between decay events. The decay process of muons is governed by exponential decay, where the probability of decay is constant over time. In the previous section, we determined an experimental value for the mean lifetime by plotting two large datasets of decay events.

The uncertainty in the mean lifetime value arises from several sources. One significant source of uncertainty is the statistical nature of radioactive decay. Even though a large number of decay events were recorded, there is still inherent randomness in the decay process. This randomness contributes to the uncertainty in the measured mean lifetime value. We attempted to minimize this source of uncertainty by analyzing a large volume of data accumulated over many years. Regardless, statistical chance could play a role in our error.

Another source of uncertainty is the measurement error associated with the particle detector and the timing apparatus used. Imperfections in the detector's sensitivity and the timing apparatus can introduce systematic errors in the recorded decay times. If the PMTs are poorly coupled to the scintillators, some photons may escape detection. This could explain why we're seeing a lower than expected lifetime. Similarly, environmental factors could also influence the quality of the scitillators. Variations in temperature and humidity can degrade scintillator quality. This is an issue that many large experiments face (notably Mu2e at fermilab). Any degradation to the scintillation efficiency will lead to an underestimate of our muon lifetime. We would expect that this sort of issue would only get worse with time. This prediction is consistent with the observation that newer datasets tend to yield less accurate predictions of τ. This is likely not the only factor that causes accuracy to vary across datasets (increased counts will also increase accuracy), but it's worth acknowledging.

6 Conclusion

In conclusion, while the experiment yielded a mean lifetime value less than the theoretical value, further refinement and investigation are necessary to fully understand the factors influencing muon decay. To improve the experiment in the future, increasing the number of decay events recorded and conducting multiple trials could enhance the statistical precision. Additionally, careful calibration and characterization of the experimental setup, as well as conducting the experiment in a controlled environment, would help minimize systematic errors and environmental influences.