Muon Lifetime

Saumil Nalin, Dan Beckstrand, and Rylee Palos

Department of Physics, The University of Texas at Dallas, Richardson, Texas 75080-3021, USA

ABSTRACT

Muons are a type of fundamental particle that belong to the lepton family. They are produced through interactions in the Earth's upper atmosphere where primary cosmic rays interact with air molecules to produce pions and kaons that then decay. Both of these decays produce a muon and neutrino or antineutrino through interactions with the weak force. These muons can be positively or negatively charged. Once produced, muons have a average lifetime of $2.2\ \mu s$, but they are able to reach the Earth's surface due to the relativistic effect of time dilation. The average lifetime of a muon can be experimentally determined through a use of a scintillator that detects the excitation of a muon entering the medium and decaying into an electron. The time difference in these two events is the muon lifetime. We find the average lifetime to be $2.186\ \mu s$, which is 0.45% from the accepted value. Once the average lifetime is experimentally determined, another interesting quantity is the ratio of positively to negatively charged muons that interact with the scintillator. We find this value to be 14.04, which is 940% from the accepted value. This error is likely due to the detector not being able to meet the precision needed for the equation.

1 Introduction

Muons belong to the lepton family of fundamental particles. Primary cosmic rays enter Earth's upper atmosphere and interact with air molecules to produce secondary and tertiary particles. Atmospheric muons originate from the decay of secondary pions and kaons produced in the atmosphere by incoming cosmic rays, shown in Fig. 1.

$$\pi^{\pm} \rightarrow \mu^{\pm} \overset{(-)}{\nu}_{\mu} (\sim 100\,\%)$$

$$K^{\pm} \rightarrow \mu^{\pm} \overset{(-)}{\nu}_{\mu} (\sim 63.5\,\%).$$

Figure 1. Charged pion and kaon decay. Both decay models produce a muon as shown, with the (-) above the neutrino indicating that sometimes the decay produces an antineutrino. The percentages in parentheses indicate the branching ratios for each decay model. Branching ratios estimate the rate of decay, meaning charged pions almost always decay into muons and kaons decay into muons 63.5 % of the time.[1]

This spontaneous decay results from the pions' interaction with the weak force. Once produced, muons only exist for a short time before they decay into an electron and a neutrino or an antineutrino due to the weak force. Unlike pions and kaons, muons do not interact with strong force - only with weak and electromagnetic forces. Not all muons produced in the atmosphere will make it to sea-level to be detected, some will continue to interact with atmospheric particles and some decay before reaching the ground.

$$e^{+} + e^{-} \rightarrow \mu^{+} + \mu^{-}.$$

Figure 2. Electron-positron collision. The result of this collision is the production of a positive and negative muon. This shows how muons can be produced through electromagnetic interactions.[2]

Muons can also be produced through electromagnetic interactions, such as in electron-positron collisions, shown in Fig, 2. Most of the muons observed in laboratory settings come from the interactions of the weak force, as discussed above. Since muons undergo radioactive decay, we use an exponential relation for the decay of a muon population,

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

where τ is the lifetime of the muon[3] and N_0 is the theoretical initial population of muons that we had.

The average lifetime of a muon is 2.2 μs.[3]. Despite this, we can experimentally detect muons. This is possible because of the effect of time-dilation, which is only possible because muons travel close to the speed of light. Without relativistic effects, muons would not be able to reach the surface of the Earth.[4].

Another interesting quantity to consider when dealing with the muon lifetime is the charge ratio, $\rho = \frac{N_+}{N_-}$, where N_+ is the number of positive muons that decay and N_- is the number of negative muons that decay. Since the detector cannot distinguish between negative and positive species of muons, we must use

$$\rho = -\frac{\tau^+}{\tau^-}\frac{\tau^- - \tau_{obs}}{\tau^+ - \tau_{obs}}, \tag{2}$$

where $\tau^+ = 1.19703 \pm 0.00004\ \mu s$ represents the average lifetime of a positive muon, $\tau^- = 2.043 \pm 0.003\ \mu s$ represents the average lifetime of a negative muon, and τ_{obs} is our experimentally found lifetime.

2 Experimental Setup

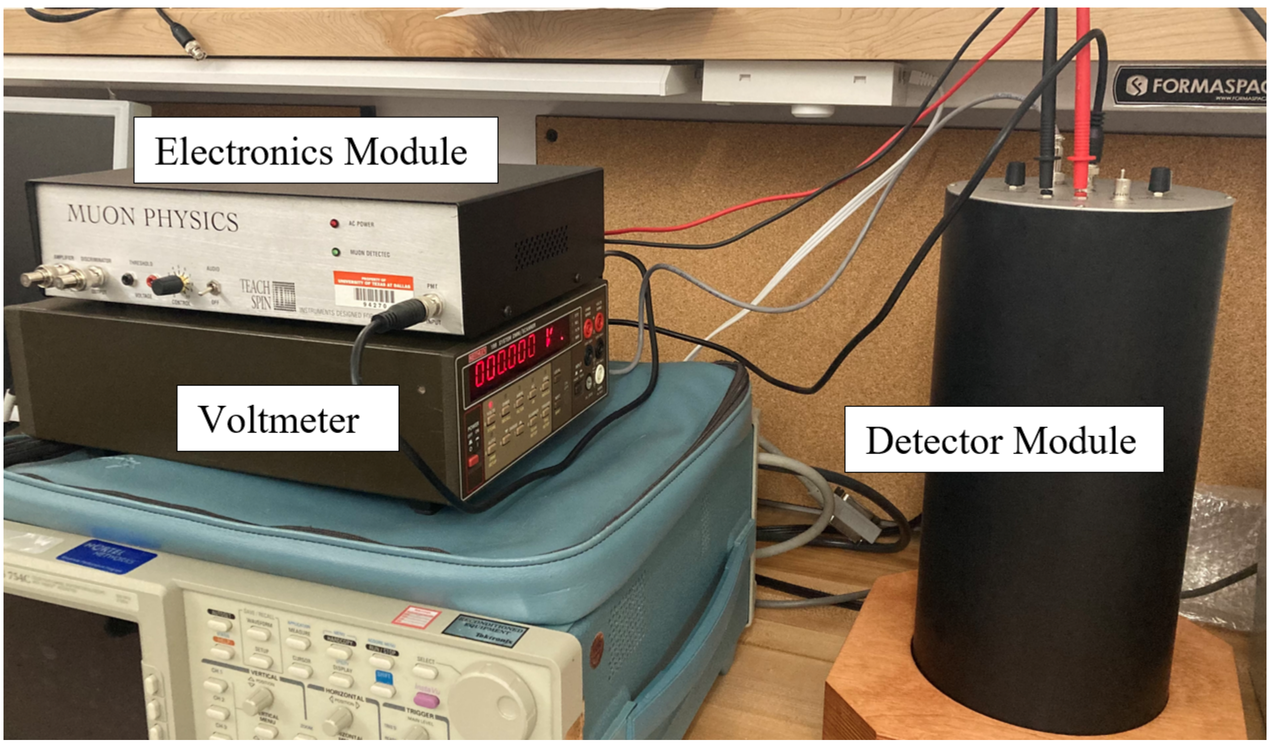

Figure 3. Our setup includes a voltmeter and both the electronics and detector modules. The electronics module interprets the signal from the detector module and outputs that data to the computer. The detector module houses a plastic scintillator and photomultiplier tube which together detect muon decay.[5]

When charged particles enter the detector and collide with the plastic scintillator, some kinetic energy is lost by the incoming particle to the excitation of electrons in the scintillator material which causes photon emission. That light is detected by the photomultiplier tube and starts a timing clock. A second light signal is produced when the muon decays into an electron, and this second signal stops the timing clock. If a second signal does not occur within 20 μs, then the incident particle is not considered a muon. Thus the detector module records the decay rate of muons that collide with the scintillator within. By virtue of the exponential distribution of decay times, it does not matter for our analysis how long the muon existed before entering the detector.

Muon decay within the detector occurrs about once every minute, so to obtain a meaningful amount of data points, we record data over the course of 233.345 hours. During this time, the detector module recorded 15080 muon decays.

3 Results

The range of our decay times was 0 to 20 μs. Instead of plotting each decay against its lifetime, we separated our time axis into 60 bins of 1/3 μs and separated the decay data into the number of decays that occurred within each time bin. Thus we now have 60 data points of decay count vs. lifetime.

The detector module outputs the number of muons that decayed and the time it took for each muon to decay. We take this raw data and convert it to give us the number of decayed muons for each chosen time: 'bin'. We find these bins by separating the range of our decay times into 60 sections. We plot the number of decayed muons vs the bin number and find it to be an exponential curve, shown in Fig. 4.

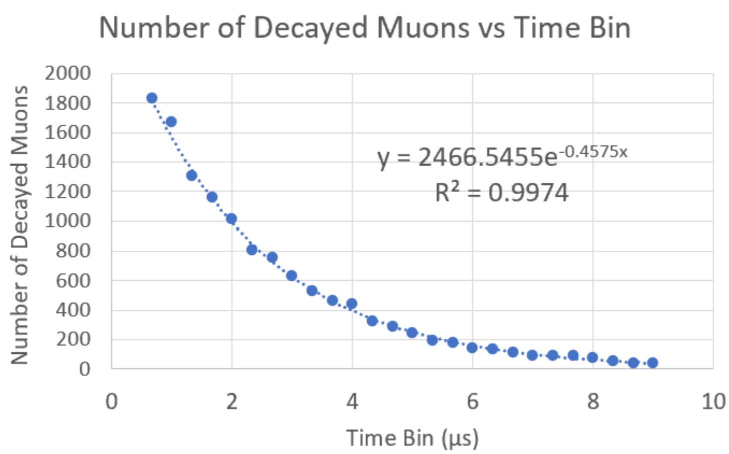

Figure 4. Experimental data plotted as number of decayed muons vs bin number. The range of the bins is chosen so that the data resembles an exponential curve, since muon decay time is distributed exponentially. Data points outside of this range result from noise. The lifetime of a muon, τ, is found from taking the reciprocal of the coefficient of the exponential, 0.4575. So, we find that $\tau = 2.186\ \mu s$.

We find the average lifetime of a muon, τ, to be 2.186 μs, which is within 0.45% of the accepted value[3].

Once we establish our average lifetime, we use Eq. 2 to find that $\rho = 14.04$.

4 Conclusions

The experimentally determined value for muon lifetime had a systematic error of 0.45% when compared to the expected value of $\tau = 2.2\ \mu s$.[3] When compared to the expected value of $\rho = 1.18$[6], our ρ value gives an error of 940%, which is likely due to the sensitivity of the equipment. Due to the limitations of the detector, our τ_{obs} has a precision that is too low to get a better ρ.

Our results for the muon lifetime were conclusive, but our results for the positive muon to negative muon ratio, ρ, were not conclusive. The goal of the experiment is to find the a viable value for the lifetime of the muon and we were able to do that with nothing more than 0.45% error. So it is sufficient to say that the goal was met. We can improve the experiment by increasing the sensitivity of our equipment to help with the precision of the values and lower our error. There are many applications of muons, particularly in particle physics. Muons can be used as test particles in hadron physics for high-energy experiments[3]. Muons can also be used to test the theories in

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