Muon Lifetime Determination

James Monaco
HWS Physics and Chemistry, ’20
Dartmouth Engineering, ’21

October 29th, 2019

Abstract

Mean muon lifetime was calculated based off of data collected showing the distribution of observed muon lifetimes in a scintillator. Due to an additional method of decomposition, μ^- was expected to have an observably shorter lifetime than μ^+. Results showed that to be true, with μ^- and μ^+ having lifetimes of 2.217 ± 0.025 μs and 2.744 ± 0.087 μs, respectively. The expected lifetime of μ^- falls within this observed value. This was then used to calculate the Fermi coupling constant: $G_F = (1.586 \pm 0.131) * 10^{-5} GeV^{-2}$, which was also agrees with the literature.

1 Introduction

High energy cosmic rays strike the earth continuously, cascading into many other particles, as shown in figure 1. One product of these cosmic rays striking an upper-atmosphere nucleus are pions $(\pi^+\text{and}\pi^-\ )$, which decay into muons and neutrinos. Muons aren’t fundamental, but are a building block of matter much like protons, electrons, and neutrons, with several unique properties. They can be described as ”heavy electrons” with the same charge as an electron (-1e for μ^-, +1e for μ^+), but with about 207 times the mass of an electron. It is also unstable, decaying into more fundamental particles.

Both μ^+ and μ^- can spontaneously decay into more stable particles: an electron, a neutrino and an anti-neutrino. But, because μ^- has the same charge as an electron, it can also decay through its stronger interactions with matter. In fact, because the muon is not an electron but has the same charge, it can violate the Pauli exclusion principle and occupy and already occupied atomic or orbital. Once bound in an orbital, it interacts with a proton to decay:

$$\mu^- + \mathrm{p} \longrightarrow \mathrm{n} + \nu_\mu$$

Because μ^- has an additional mechanism of decay in matter than μ^+, it is expected to have a shorter mean lifetime. Both these lifetimes is less than the time it takes for a muon to travel from the upper atmosphere to ground level, but due the particles relativistic speed, time dilation causes it to perceive less time than observed from a stationary frame, allowing it to survive and be observed at ground level.

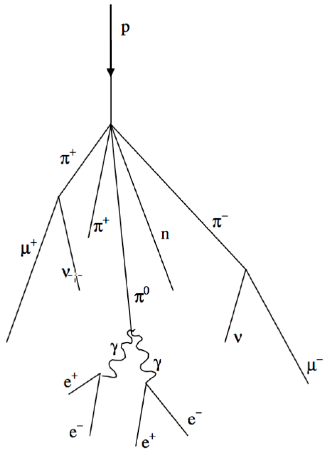

Figure 1: Cosmic Ray Cascade from a high-energy proton striking a nucleus in the upper atmosphere. Taken from the Advanced Lab Manual [1].

The decay time distribution of muon lifetimes observed at ground level, $D(t)$, can be expressed as:

$$D(t) = \lambda e^{-\lambda t} \tag{1}$$

Where λ is the rate constant such that the mean lifetime of a muon, τ, is the inverse of λ. In reality, this expression exists for two different λ, that of μ^+ and μ^-.

To experimentally measure the lifetime of the muon, the time distribution of muon lifetimes can be measured. From equation 1 for both μ^+ and μ^-, the resulting graph of lifetime vs. number of muons measured should have two distinct slopes on a semi-log scale, as it’s the sum of two exponential functions. Because μ^+ has a slightly longer lifetime, it should start to dominate at higher measured lifetimes, creating a region of a distinctly different slope. Fitting the slopes will give λ, and from that the lifetimes (τ) of both muon particles can be calculated.

2 Experimental Set-up

A block diagram is shown in figure 2 of the experimental set-up. The set-up can be broken down into two subsections: the scintillator, and the signal processing.

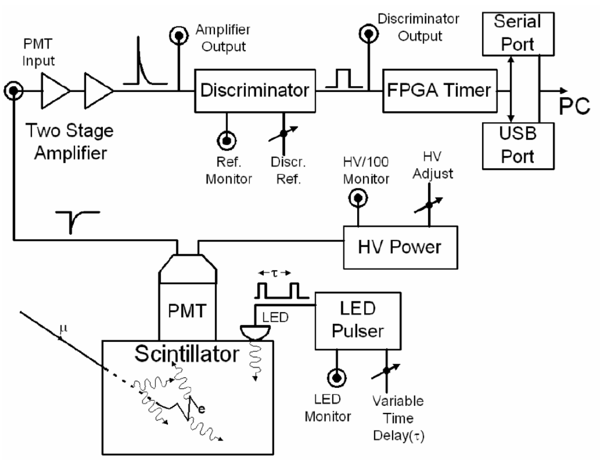

Figure 2: A diagram of the experimental set-up, showing muon decay creating photons that are recorded by the PMT. Taken from the Advanced Lab Manual [1].

2.1 Scintillator

The scintillator is a polyvinyltoluene based plastic cylinder (15 cm height by 12.5 cm diameter) mixed with fluor molecules. The scintillator has the property that it fluoresces light when charged particles travel through it, giving 1 photon for every 100eV of deposited energy. A photomultiplier tube (PMT) then gives a negative voltage pulse each time a photon is observed. Muons are energetic charged particles, and therefore this material can be used to detect a muon [1].

Some muons that enter the chamber slow down. This initial slow down causes the scintillator to emit a pulse of light. Then, the muon decays into an electron and a neutrino/anti-neutrino pair. The neutrinos are uncharged and have no effect on the scintillator, but the electron is highly energetic due to the rest mass of the muon becoming kinetic energy. This electron causes the scintillator to produce light all along its path within the plastic. In short, one photon is produced when the muon slows down, and then many photons are produced when it decays, resulting in negative pulses for each photon.

2.2 Signal Processing

The output of the PMT are then sent through two-stage amplification that also inverts the signal; the measured gain was -20, both amplifiying and inverting the signal. This amplified pulse is then sent to a discriminator to give a square wave for each photon.

The discriminator signal is then sent to a field- programmable gate array (FPGA) timing circuit. The purpose of this circuit is to filter out signals that are not muons, and to output the lifetime of the muons in the detector. Each discriminator pulse starts a timer, and if a second pulse is received within 21 μs but greater than 1 μs, then the time between pulses is recorded and sent to the computer as valid data. If a second pulse is not recorded within this interval, the circuit is reset.

3 Data Acquisition and Analysis

The data from the FPGA is stored an a histogram is created to show the distribution of observed muon lifetimes. There are 60 bins in 20 μs intervals. The first bin must be discarded: the electron traveling through the scintillator produces many photons within a small time interval that is then recorded as valid data, artificially inflating the value of counts for the first bin. The entire data set, excluding the first bin, is shown in figure 3.

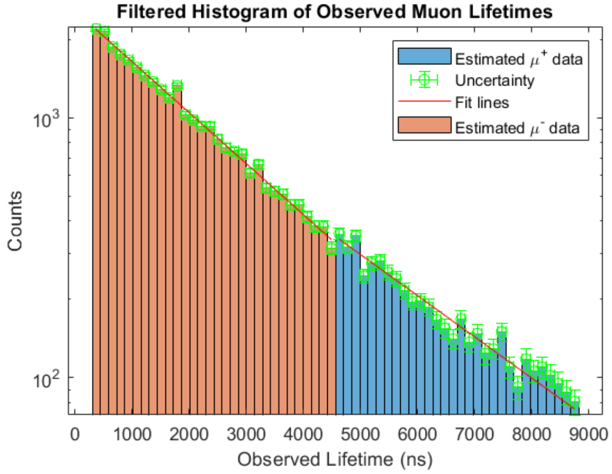

Figure 3: A diagram of the experimental set-up, showing muon decay creating photons that are recorded by the PMT. Taken from the Advanced Lab Manual [1].

The distribution seems to be linear with the log of observed lifetimes, as expected. But, there's clearly a discontinuity of slopes around halfway through the histogram. The muons with longer observed lifetimes seem to have a shallower slope, indicating a longer average lifetime. This makes sense, as μ^+ is expected to have a longer average lifetime as explained. The data with smaller observed lifetimes ($\tau \geq 4.5$ μs) and longer observed lifetimes ($\tau \leq 4.5$ μs) are then fit to their own exponential

	μ^+	μ^-
Expected Lifetime (μs)	2.19	2.19
Measured Lifetime (μs)	2.744 ± 0.087	2.217 ± 0.025

equations of the form of equation 1. The results are shown in table 3.

4 Conclusions

The measured lifetime of μ^- matches the expected literature value. However, the literature says there should be little difference between μ^+ and μ^- [2], with there is a significant difference in lifetime between μ^- and μ^+ observed.

This discrepancy may be material-dependant, as some materials may have orbitals that interact more strongly with μ^- than others, causing μ^- to have a shorter observed lifetime and therefore μ^+ and μ^- to have a greater difference in mean lifetimes.

4.1 Calculating the Fermi Coupling Constant

Muons decay via the weak force, and the Fermi coupling constant (G_F) is a measure of the weak force. The relationship between muon lifetime and G_F is as follows:

$$\tau = \frac{192\pi^3\hbar^7}{G_F^2 m^5 c^4}$$

Isolating for G_F gives:

$$G_F = \sqrt{\frac{192\pi^3\hbar^7}{\tau m^5 c^4}}$$

With $\tau = 2.217 \pm 0.025\mu s$ and $m = 105.65 MeV/c^2$ [3], G_F is calculated to be $G_F = (1.586 \pm 0.131) * 10^{-5} GeV^{-2}$. The literature value is $1.166 * 10^{-5} GeV^{-2}$ [4]. These values are in agreement.

References

[1] HWS Physics. *Advanced Laboratory Manual*. Hobart and William Smith Colleges, 2019.

[2] M. Tanabashi and Et al (Particle Data Group). Mean life ratio $\mu + / \mu$. 98(03001), 2018.

[3] J. C. Street and E. C. Stevenson. New evidence for the existence of a particle of mass intermediate between the proton and electron. *Physical Review*, 52(9):1003–1004, Nov 1937.

[4] P.J. Mohr and D.B. Newell. *Physical Constants*. 2019.