Muon Lifetime Measurement

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The muon decay is a unique process in that it allows for the measurement of the strength of the weak interaction. In this experiment, we used 2 photomultiplier tubes to detect muon decays. The signals from the PMTs were processed through a series of electronics and produced data that was fit to an exponential decay model, allowing us to measure the muon lifetime. We measured it to be $2.5(5)\cdot 10^{-6}$ s, which is in accordance with the accepted value of $2.197\cdot 10^{-6}$ s.

Introduction

Muons are elementary spin 1/2 particles similar to electrons with a charge of –e, but with about 200 times the mass of an electron. Muons are typically found in the form of cosmic radiation. Unlike other cosmic particles, muons do not interact via the strong interaction. Because of their high energy, muons will reach the Earth and decay before they have an opportunity interact. Muons decay by the following process (Matthews & Schwoebel):

$$\mu^{\pm} \rightarrow \nu_{\mu} + e^{\pm} + \nu_{e} \qquad (1)$$

Historically, the muon decay process was used to experimentally confirm the time dilation effect of special relativity by looking at the decay rate (Frisch & Smith, 1963). But it is also has the property that it only involves the weak interaction. The muon lifetime is related to the Fermi coupling constant:

$$r_{\mu} = \frac{1}{\tau_{\mu}} = \frac{G_F^2 m_{\mu}^5}{192\pi^3} \qquad (2)$$

The Fermi coupling constant G_F is a measure of the strength of the weak interaction, and can be determined by measuring the muon decay rate, or the reciprocal of the lifetime (Matthews & Schwoebel).

The measurement of the muon decay rate or lifetime can be done with a tank of scintillator. As a muon goes through the scintillation material, it may interact and emit a photon. After some amount of time, the muon will decay and emit another photon. By measuring the time between these two photon emissions, the lifetime of the muon can be determined. As with all decays, the muon decay follows the exponential model (Matthews & Schwoebel):

$$N(t) = N_0 e^{-t/\tau_{\mu}} \qquad (3)$$

In this experiment, we measured the muon lifetime.

Method

The experimental setup, shown in **Figure 1**, involved 2 photomultiplier tubes (PMTs) attached to a tank of scintillator., where the muons interacted and decayed. Each PMT was attached to a Phillips Scientific Model 705 discriminator. When the PMT's detected a photon emission, they emitted a pulse. When one of these pulses reached or exceeded the threshold voltage of its

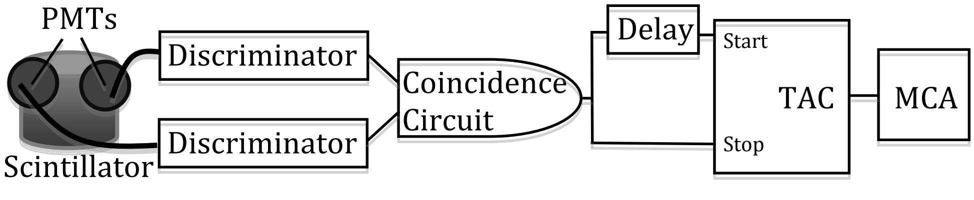

Figure 1: The experimental setup consisted of the scintillator with 2 PMTs attached. The pulses from the PMTs corresponded to photon emissions from muon events. When a PMT pulse met the set threshold voltage, its discriminator sent a pulse to the coincidence circuit. If both discriminators sent pulses within a set time window, the coincidence circuit sent an output pulse. This pulse traveled to the inputs of the TAC, with the start pulse going through a delay module. The TAC converted the time between consecutive PMT pulses to a voltage, and a pulse of that voltage was set to the MCA for analysis.

corresponding discriminator, the discriminator to send an output pulse. The discriminator for PMT 1 had its threshold voltage set at 19 mV and PMT 2 was set at 24 mV. The pulses from the discriminators were sent to a coincidence circuit (Phillips Scientific Model 755 Quad Four-Fold Logic Unit). When the two discriminator pulses were within a set time window, the coincidence circuit sent an output pulse. If they were not, no pulse was sent. The pulses emitted from the coincidence circuit were sent to the 2 inputs of an Ortec 567 time-amplitude converter (TAC). The pulse going to the start input first went through a Chronetics Inc. Model 21 Dual Delay unit, while the other pulse traveled directly to the stop input of the TAC. The delay module was set to 32 ns. When a pulse arrived at the TAC, it triggered the TAC to start measuring the time between the pulse it just received and the next. If the next pulse arrived within 10 μs of the first, the time between pulses was measured and converted to a voltage. The TAC then sent a pulse of this voltage to the computer to be measured by a multichannel analyzer (MCA).

The purpose of the delay module must be stressed. When the coincidence circuit emitted a pulse corresponding to a photon emission, the delay module slowed the pulse going to the start input by 32 ns. Thus, the stop input saw the pulse before the start input. When the TAC finally received the start input pulse, it began measuring the time to the next pulse. After the next photon emission, this pulse again reached the stop input before the start, due to the 32 ns delay. This time, the TAC saw the stop input, stopped the time, and converted this to a voltage to be sent as an output pulse. After the stop signal was received and converted to a voltage, the start input sees this pulse, resetting the TAC. The TAC is now measuring the time to the next pulse, and the cycle has been completed.

This method of delaying the start input by 32 ns resulted in a measurement of the time between pulses that was 32 ns shorter than the actual time. Because this delay was held constant, the effect of this shortening of time was a shift in the time domain of the exponential, or in channels on the multichannel analyzer.

To correct for this shift, the MCA was calibrated using a Berkeley Nucleonics Corp. Model 8010 pulse generator that emitted 2 pulses. These pulses went through the same electronics as the PMT pulses, including the delay module, and thus had the same 32 ns time shift. However, since we were able to measure the original signal coming out of the pulse generator on an oscilloscope, we were able to calibrate the MCA using the known delay of the original signal and the corresponding channel on the MCA.

Since muons were only detected by both PMTs every few seconds, the experiment was run for 48 hours to get adequate data.

Results

To get a calibration for the time between pulses corresponding to each channel on the MCA, pulses emitted from the pulse generator were measured. The time between pulses varied between 200 ns and 4.1 μs in 100 ns steps. The result was a line of best fit using the least squares method:

$$Delay = 9.46 \cdot 10^{-9} * \mathrm{Channel} + 1.67 \cdot 10^{-7} \qquad (4)$$

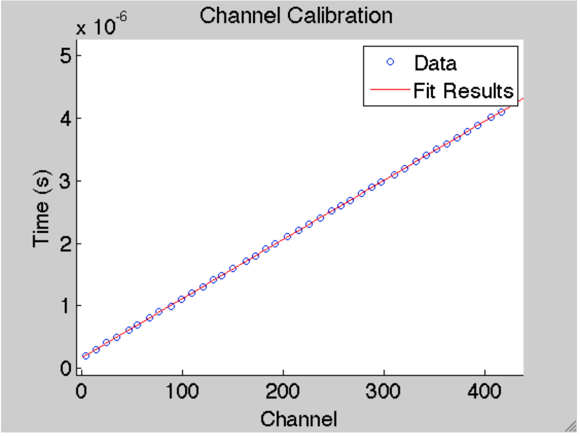

Figure 2: A calibration to convert channels to time was found by using a pulse generator and known times between pulses. Each time was correlated to a channel on the MCA, and from these data points, a line of best fit was found using the least squares technique.

Figure 2 shows the line of best fit. Using this line, the channels for the muon decay data were converted to times. The resulting data from the muon decay is shown in **Figure 3**. The plot of the time vs. counts data resembled an exponential decay and was fit using the Poisson Maximum Likelihood estimator to a model:

$$N(t) = 350(37) \cdot \mathrm{e}^{-t/2.5(5)\cdot 10^{-6}} + 1.992 \cdot 10^{-7} \quad (5)$$

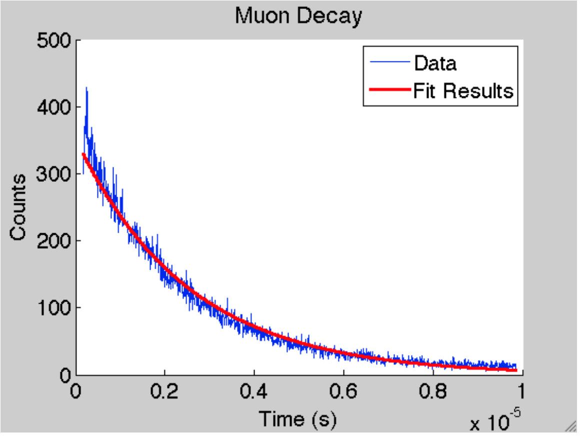

Figure 3: The muon decay data is shown with the exponential fit. The data has been converted from channels to time using the calibration line.

The muon lifetime we measured was $2.5(5) \cdot 10^{-6}$ s. The standard error of $5 \cdot 10^{-7}$ s was found by taking the square root of the inverse of the Fisher's Information matrix and using the appropriate diagonal element.

This experiment had several sources of error. Each instrument has tolerances that limit the sensitivity, introducing some error. Also, the TAC measured all time events between 0 and 10 μs. If 2 muons interacted with the scintillator and one interacted before the other had time to decay, this may introduce error into the setup. It is small because due to the low frequency of muon events, the time between them was typically on the scale of seconds and not microseconds. Nevertheless, over the course of the 48 hours in which data was collected, there was some small probability of such an event occurring.

Conclusion

Our measured value for the muon lifetime was $2.5(5) \cdot 10^{-6}$ s, which is in accordance with the accepted value of $2.197 \cdot 10^{-6}$ s.

For future experiments, several improvements could be made. Adding an extra PMT could help eliminate false positives. Also, the data could be filtered to eliminate cases where the TAC saw 2 consecutive muon interactions, rather than an interaction followed by a decay. The experiment could also be run for a longer period of time to increase the number of events measured. The time window of the coincidence circuit might also be reduced to eliminate help false positives.

References

1. Frisch, D. H., & Smith, J. A. (1963). Measurement of the Relativistic Time Dilaton Using Muons. *American Journal of Physics* , *31*, 342.

2. Matthews, J. A., & Schwoebel, P. R. *LAB 2: Experiments in Nuclear Physics.* University of New Mexico.