Muon Lifetime and Muon Flux

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By using a plastic scintillator and measuring the time between two pulses, the average muon lifetime was measured to be $1.67 \pm 0.07 \mu s$. The muon flux was measured to be $23.9 \pm 0.5 m^{-2} str^{-1} s^{-1}$ near sea level. This value is 3.5 times lower than accepted values due to measurements inside a multi-story building. Even so, the intensity of flux was found to decrease as the angle made with the zenith increased and followed closely to the theoretical decay of $\cos^2\theta$.

INTRODUCTION

Muons are elementary particles that are formed from the interactions of cosmic rays and our atmosphere. As cosmic ray particles approach Earth, these protons interact through collisions with atmospheric particles. Traveling at relativistic speeds, muons are found to have traveled much farther than expected without the effect of time dilation. Because of this, muons are able to be detected at sea-level of an average rate of 1 detection per minute per cm^2. The mean production height of muons in the atmosphere is 15000 meters above sea level. Traveling at the speed of light would take 50 μs, but muons have mass so this speed is impossible. Even so, the average lifetime of an at rest muon is more than 20 times smaller, without relativistic effects would never reach sea level at the observed rate.

In this experiment a plastic scintillator is used to detect muons that become trapped and decay in the apparatus. By recording the time between capture and decay, the average muon lifetime can be determined. The decay rate of the muon follows the standard decay of

$$D(t) = \frac{1}{\tau} e^{-t/\tau},$$

where $D(t)$ is the exponential probability distribution function and τ is the lifetime of the muon.

To see the effect angle of muon flux, two scintillators are setup a fixed distance apart. This creates a measure of flux due to the area of the detector and the steradian subtended by the detectors from a common origin. The rate of muons passing through both detectors is a function of rate, steradians, detector area, and angle from zenith. Keeping steradians, time elapsed, and detector area constant, the flux as a function of angle is:

$$\Phi(\theta) = \Phi_0 \cos^2\theta,$$

where Φ_0 is the flux at 0° relative to the zenith. Since the mean muon production occurs 15,000 m above the Earth's surface, we can expect the highest flux aligned with the zenith. As this angle increases, the path length is increased extending the time that muons must exist before entering the detector.

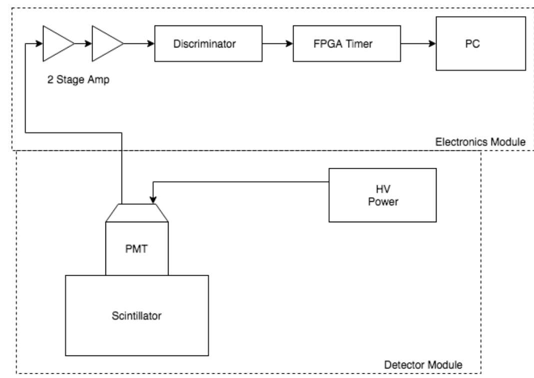

FIG. 1. Block diagram of Muon Lifetime detector. Muons caught in the scintillator and allowed to decay in scintillator send two pulses. The first is when it is slowed by interaction with the scintillator, it releases kinetic energy amplified by the PMT. Another pulse is sent through the PMT as the muon decays. As long as two pulses occur within a 20 ns time span, the data is recorded by the PC.

EXPERIMENTAL

The TeachSpin muon physics package was used in the muon lifetime determination. A block diagram of the apparatus is shown in Figure 1. Setup included high voltage adjustment and discriminator settings. An oscilloscope was used to monitor expected behavior of inputs at all stages of the process. Two data runs were made to determine the average lifetime of the muon.

For the flux as a function of angle based off of the zenith measurement, two scintillators were used, see Figure 1. A paddle scintillator in conjunction with a cylindrical one. Measuring the radius of the spheres from the center of the lower scintillator, the radius was held constant as several 10 minute detections were recorded using a LeCroy 623B discriminator, LRS 35AL -fold logic unit, and an Ortec 776 Counter & Timer NIM modules. Measurements were made at 15° increments. Adjustments were made to the discriminator, pulse width, and pulse timing.

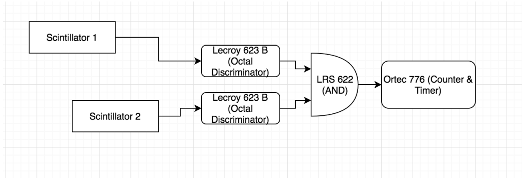

FIG. 2. The setup of the NIM modules utilized to count muon detections occurring nearly simultaneously across the scintillators. One scintillator was positioned above the second at various angles measured from zenith.

RESULTS AND DISCUSSION

The experimental value observed for the average lifetime of a muon was determined as $1.67 \pm 0.07\mu s$. The distribution and exponential curve fit of the histogram is represented in Figure 3. This accepted value of the average muon lifetime is $2.2\mu s$, so it falls within 8σ of the experimental measurement. The count size may have been too low to get an accurate determination, and the number of bins greatly influences the measure of the exponential fit distribution.

Compared to the accepted value of muon flux $83m^{-2}str^{-1}s^{-1}$, the value measured was $23.9 \pm 0.5m^{-2}str^{-1}s^{-1}$. This value is well below expected, and the uncertainties do not make up for the discrepancy. This leaves the responsibility to systemic and environmental errors. On this concern, the experiment was performed on the third floor of a six story building. The behavior of the flux does follow the expected formula of $\Phi(\theta) = (23.9 \pm .5)\cos^2\theta + 1.55$, where 1.55 is taken to be the background detections due to a busy physics department.

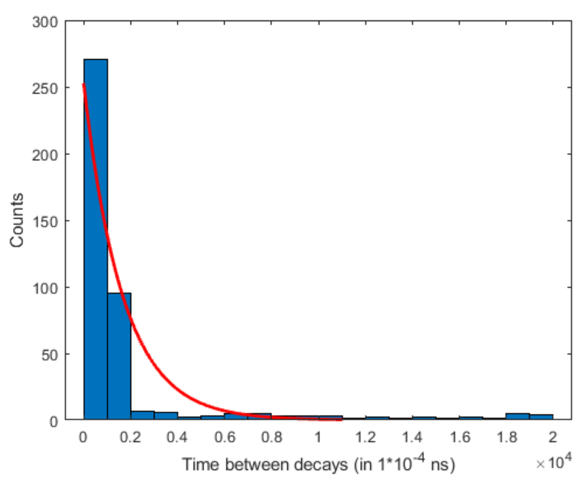

FIG. 3. Histogram of muon decay counts verses the time to decay. Bins of histogram determined from software data collection. Values above $20\mu s$ were thrown out. The value of 1.67 $\pm 0.07\mu s$ was determined from data analysis(Matlab).

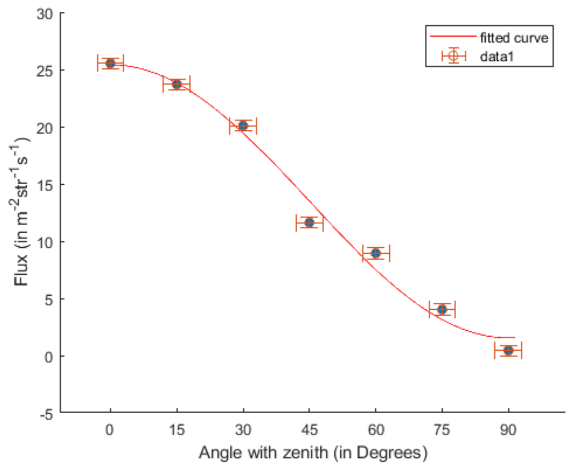

FIG. 4. Flux vs the degrees from zenith. Error bars for Flux axis determined by standard propagation of errors those being rate, steradians, and area. Error on Angle axis from measuring the angle relative to the zenith. Curve is $\Phi(\theta) = 23.9cos^2(\theta) + 1.55$. We take the scalar value as the background detections.

CONCLUSIONS

The measurement of the muon lifetime depended mainly on the Teachspin Module. Analyzing the given data showed large amount of detections within the first two bins of the histogram, 250 for the first bin and just under 100 for the second, while the rest of bins had about 4-5 counts. Having having the module run for a longer time period would provide a larger distribution and would reduce the error observed in our analysis. The longer time duration should also provide a more accurate result. A larger bin size would greatly effect the quality of the results by giving better resolution during the majority of the critical data collection $(0 - 0.5\mu s)$. The flux value measured, $23.9 \pm 0.5m^{-2}str^{-1}s^{-1}$, was well below the accepted value of $83m^{-2}str^{-1}s^{-1}$, but the experiment took place on the third floor of six. It is estimated that muons lose kinetic energy at a rate of $2MeV/g/cm^2$, so going through several floors of the physics building before entering the scintillators will have an impact on the intensity of detections.

Running the experiment outside and away from obstructions would significantly improve the max flux measured. Fixing the distance between the detectors with a cardboard tube and having the detectors rotate through a fixed point would greatly decrease the uncertainties in steradians and area. Of course, getting a measurement of the area of the scintillator would also help. But the largest error that occurred was in the rate of detections, so running the experiment multiple times would greatly improve the precision of the results.