Measurement of the Muon Lifetime

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(Dated: November 29, 2017)

Our experiment uses a water Cherenkov detector to measure the lifetime of cosmic muons. We used scintillator panels as counters on the top and bottom of our Cherenkov detector, along with sixteen photomultiplier tubes (PMTs) attached to the Cherenkov detector. By measuring the time between signals we were able to plot the distribution of decay times and find the muon lifetime. Our final result is that the muon lifetime $\tau_\mu = 2.127 \pm 0.023\,\mu$s. This result is in close agreement with the accepted muon lifetime $\tau_\mu = 2.197\,\mu\text{s} \pm 2.2\,\text{ps}$ [1].

I. BACKGROUND

In our experiment we attempted to find the time between stopping a cosmic ray muon in our water Cherenkov detector and the muon decaying into an electron plus an electron neutrino and a muon neutrino as seen in figure 1.

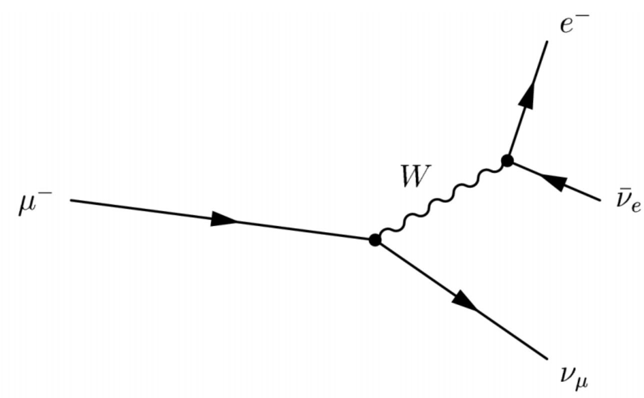

FIG. 1. Feynman diagram of a muon decay

Muon decay was first observed by scientists Williams and Roberts in 1940 and the half life was then measured by Rasetti and his team [2]. While the decay time of a muon has previously been measured to be $\tau_\mu = 2.197\,\mu\text{s} \pm 2.2\,\text{ps}$ [1], muons are able to travel into our detector because they are traveling near the speed of light. This causes the spacetime frame of the muons to be shifted compared to our lab frame, and therefore they are able to travel large distances.

The charge of a particle causes the scintillator material to ionize and give off light that is detected by a photomultiplier tube [3]. We found that our top counter was triggered around 100 Hz while our bottom counter was triggered around 30 Hz, meaning 100 muons passed through the top counter per second and 30 through the bottom per second. Our Cherenkov detector works by looking for Cherenkov radiation from the muons passing through the water. In water the muons are able to travel faster than the speed of light causing the emission of Cherenkov radiation. We can detect that light with the 16 PMTs that we have set up all around the box. We found the flux through the Cherenkov detector to be approximately 6 Hz.

Aside from looking for a muon passing through our Cherenkov detector, we also look for the electron emitted in the decay process. By measuring the time difference between a signal from a cosmic ray muon and an electron we can presumably find the lifetime of the muon.

II. APPARATUS

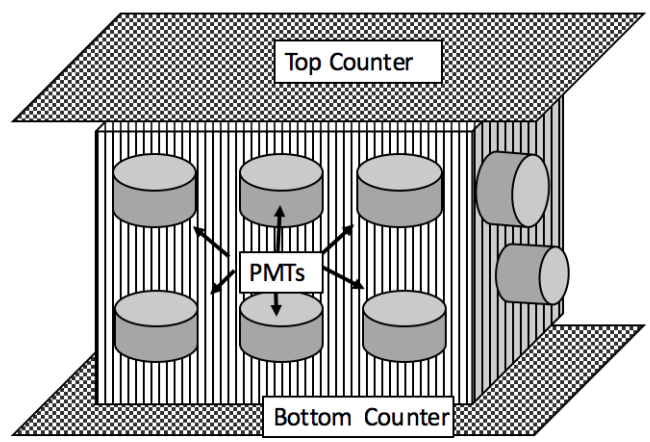

FIG. 2. Diagram of the Cherenkov detector

Our detector consisted of two scintillator panels as top and bottom counters along with 16 PMTs surrounding our tank of water. The tank has a total volume of $6.8 \times 10^4\,cm^3$. The PMTs are arranged into four zones that feed into a fan in/out so that we can control all of the Cherenkov detector PMTs as one signal.

By using a delay box we were able to make sure that all three signals coincided. All three were then discriminated and the top and Cherenkov signals were made into signals of width 50 ns while the bottom was made to be 200 ns. These widths were chosen because of our trigger. The top and Cherenkov signals are then sent into a coincidence box (coincidence 1) along with a veto on the bottom counter. The signal from coincidence 1 is then delayed by 100 ns and becomes our start trigger on a time-to-height converter. For our second coincidence we take the signal from the Cherenkov detector along with a 500 ns veto pulse made by the triggering of coincidence 1. The signal from coincidence 2 is then sent into the time-to-height converter as the stop trigger. The signal from the time-to-height converter is then amplified and sent into our multichannel analyzer (MCA) in our computer. Additionally, the signal of coincidence 2 is sent to another pulse generator that creates a 2.2 μs pulse. This pulse is our gate and is fed into the MCA as well. The gate is what signals to the MCA to record data. Therefore the pulse from the time-to-height converter is under the gate pulse. This data is then sent into our computer where we can collect the data. A diagram of our electrical setup is in figure 3.

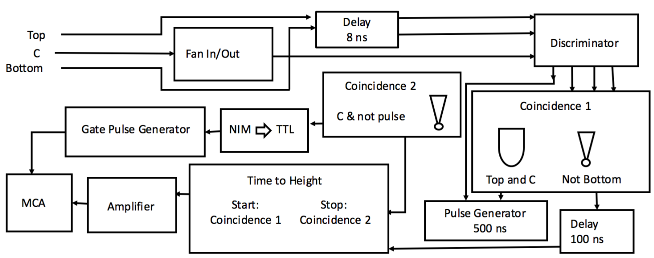

FIG. 3. Diagram of our electronics setup for our muon detector.

By using a pulse generator we were able to send pulses delayed by different amounts of time into our time-to-height converter and then into our computer software in order to calibrate the software. We found that there was a liner relationship between the time and histogram binning in the software from 0 to 8.1 μs. A graph of this calibration is shown in figure 4 where the axis labeled marker is the software's bins.

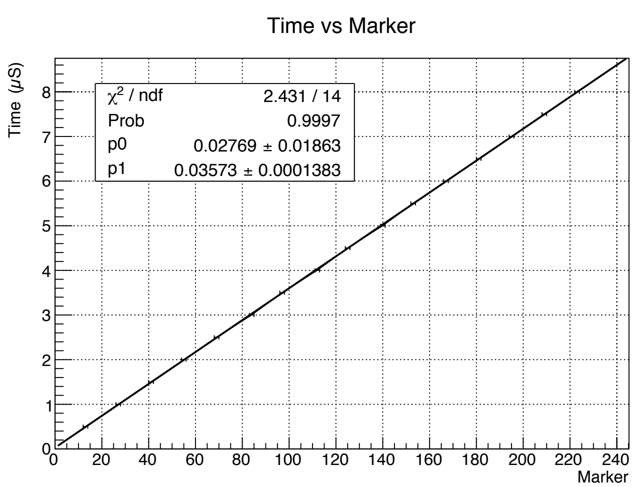

FIG. 4. Graph of Time Lengths vs Histogram Bin. Error is due to small changes in pulse height due to the pulse generator

A. Trigger

The trigger is a two part system consisting of a start and a stop trigger. Our start trigger is made with the intention of seeing a cosmic ray muon traveling through the top counter and stopping inside the Cherenkov detector. Therefore the start trigger is made to require a signal from the top counter as well as the Cherenkov detector. We also require that the start trigger is suppressed if there is a signal from the bottom counter, because we do not want our muon to pass through the Cherenkov detector. The start trigger is made using our first coincidence.

The stop trigger is based on the idea that we are looking for the decay products of the muon decay, therefore we look for a muon exiting the Cherenkov detector. This trigger is set up to send a signal when there is a signal from the Cherenkov detector. Additionally, we set up an anti-coincidence with requirement that the trigger must wait 500 ns after the start trigger has fired. This ensures that we are not stopping on either noise, or obtaining an immediate start followed by a stop trigger. The stop trigger is made using our second coincidence.

III. RESULTS

After one week of data taking we collected our results. Our data was plotted on a histogram in thirteen bins because that achieved the best exponential fit. We also decided to makes cuts and take only the data between 500 ns and 6.5 μs. We chose these cuts because we had a large pile up before 500 ns that distorted the curve. We believe this was due to imperfections in our stop trigger coincidence. We cut after 6.5 μs because from approximately 5.5 to 6.5 μs there were zero counts, making it a natural place to stop measuring. After 6.5 μs there was a large increase in events due to the fact that a start trigger without a stop trigger will send a signal after 10 μs. We wanted to eliminate all of those signals because they were not our data.

Muon decay follows the normal decay equation: $N(t) = N_0 e^{-t/\tau}$. Therefore following our exponential fit, the muon lifetime is $\tau_\mu = 1/slope$. We obtained $\tau_\mu = 2.127 \pm 0.023\,\mu$s.

IV. ERRORS

Our errors are all calculated statistically. For a chi squared test we obtained $\chi^2 = 20.29$ over 10 degrees of freedom. Our main statistical error comes from a spike in counts from 3.5 to 5.5 μs which we believe to be statistical fluctuations.

We did not find any systematic errors because our experiment consists of many electronic components that we were unable to find any errors with. Our pulse generator would give small changes in pulse length during our calibration of the Time vs. Marker curve, however this

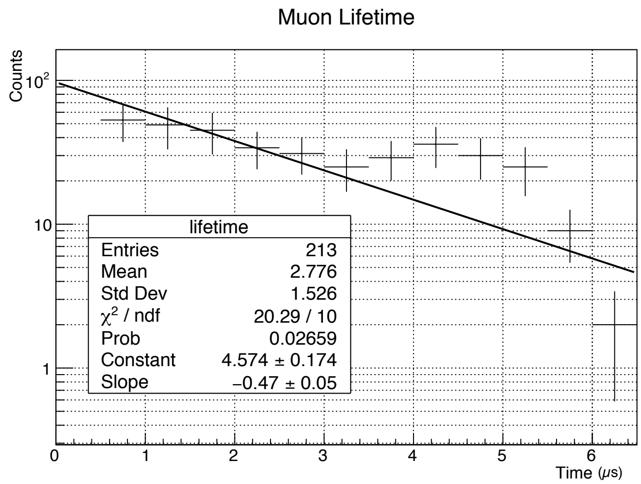

FIG. 5. Exponential graph of muon lifetime vs counts with an exponential best fit curve.

error only occurred when the pulse generator was fired many times consecutively during a short period of time. Therefore with careful testing we eliminated that error. Testing the different components more thoroughly is one of the suggestions discussed further in the future steps section.

V. CONCLUSION

We found that the muon lifetime is $\tau_\mu = 2.127 \pm 0.023\mu s$, which is in close agreement with the accepted value $\tau_\mu = 2.197\mu s \pm 2.2ps$ achieved by the MuLan Collaboration [1].

VI. FUTURE STEPS

In the future we believe it would be most helpful to improve the stop trigger by adding in another veto to the coincidence 2. Because we are looking for an electron leaving the Cherenkov detector, we believe it would be beneficial to include an anti-coincidence for the top and bottom counters. That would increase the likelihood that the signal from the second coincidence is actually an electron exiting the Cherenkov detector rather than another particle entering.

We also suggest further trials with a pulse generator to test for errors in our electronics. We saw no fluctuations through our testing, however it was brief testing because we ran out of time.

VII. ACKNOWLEDGEMENTS

I would like to thank the lab helpers Situ and Dan for their help on this project. I also want to thank Professor Sulak who was extremely helpful throughout this project.

[1] V. Tishchenko, S. Battu, R. M. Carey, D. B. Chitwood, J. Crnkovic, P. T. Debevec, S. Dhamija, W. Earle, A. Gafarov, K. Giovanetti, T. P. Gorringe, F. E. Gray, Z. Hartwig, D. W. Hertzog, B. Johnson, P. Kammel, B. Kiburg, S. Kizilgul, J. Kunkle, B. Lauss, I. Logashenko, K. R. Lynch, R. McNabb, J. P. Miller, F. Mulhauser, C. J. G. Onderwater, Q. Peng, J. Phillips, S. Rath, B. L. Roberts, D. M. Webber, P. Winter, and B. Wolfe. Detailed report of the mulan measurement of the positive muon lifetime and determination of the fermi constant. *Phys. Rev. D*, 87:052003, Mar 2013.

[2] Vanderbilt University. What is a muon. Published by Vanderbilt HEP.

[3] Johann Zmeskal. Detector and detector systems for particle and nuclear physics i, Jan 2016.