Muon Lifetime

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1 Goal

To measure the muon lifetime with a plastic scintillator and determine if the detected muons, which are generated by cosmic rays, arrive in correlated manner.

2 Introduction/Background

When cosmic rays (high energy protons) collide with Oxygen or Nitrogen in Earth's upper atmosphere, muons can be generated which soar to Earth at relativistic speeds. Upon entering a scintillator, muons immediately radiate a light pulse, due to the abrupt change in refractive index, that can be detected by a PMT, but the majority of such muons are too energetic to be captured by a hand-held scintillator and will pass through without triggering another PMT event. The eventual muons that are halted within the scintillator undergo a weak decay, as seen in Figure

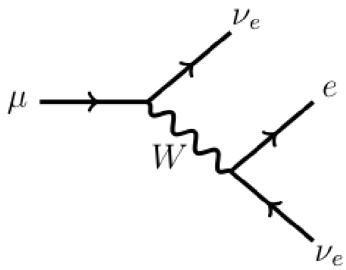

Figure 1: Feynman diagram of muon weak decay.

which results in an electron carrying enough kinetic energy to cause more ionizations within the scintillator, creating a second light pulse that is visible with the PMT. Since the muons are highly relativistic, the amount of time they experience before stopping is negligible compared to the time delay t_i between the PMT event of a muon entry and the secondary electron ionization signal. Therefore, t_i provides a measurement of the lifetime of the muon, since the muon is in the lab frame after stopping. So, an average over many samples of t_i provides the mean lifetime τ of the muon, since the distribution of decay times t_i follows the exponential decay law

$$N = N_o e^{-t/tau} \tag{1}$$

Since the majority of incident muons are too energetic to be trapped by the detector, single-pulse events greatly outnumber double pulse events and it is necessary to separate these signals in order to measure only the delay time between a muon and its subsequent decay, which can be achieved by noting that our detector has a hit rate of $\sim$ 20,000 hits per hour, which amounts to 5.5 per second, and 5.5×10^{-6} per μs. Therefore, it is highly improbable for an unwelcome muon to enter the detector (creating a pulse) while another trapped muon is waiting to decay. In this unlikely case, the electrons would measure t_i to be the time between each muon's entry and would not capture the decay pulse.

Additionally, the muon detection rate can be compared with models of counting statistics in order to determine if muon arrivals are random or correlated. It is possible for many muons to be generated in a single cosmic ray collision event, so by comparing the muon detection rate with models of counting statistics, we may find insight into the muon production mechanisms.

3 Procedure and Data

In order to measure the lifetime of the muon, we used the upper portion of the electronics shown in Figure 2, which features a plastic scintillator as a detector, coupled with a PMT, which feeds a stop line and a delay line into a Time to Amplitude Converter (TAC). The TAC converts the time difference t_i between start-stop signals by outputting a square signal of height proportional to t_i, which was binned and sorted according to height by a multichannel-analyzer (MCA). The delay line, which adds 30 ns, is connected to the start input on the TAC, so that when a muon enters, its signal resets the TAC clock (stop line) before starting the timer through the delay line, then the decay signal will stop the timer after t_i. The delay line is necessary because we must be able to restart the timer upon entry of each muon, and if the delay line wasn't connected to start, then the TAC would measure 30 ns always, this is how we measured the time delay for the longer line.

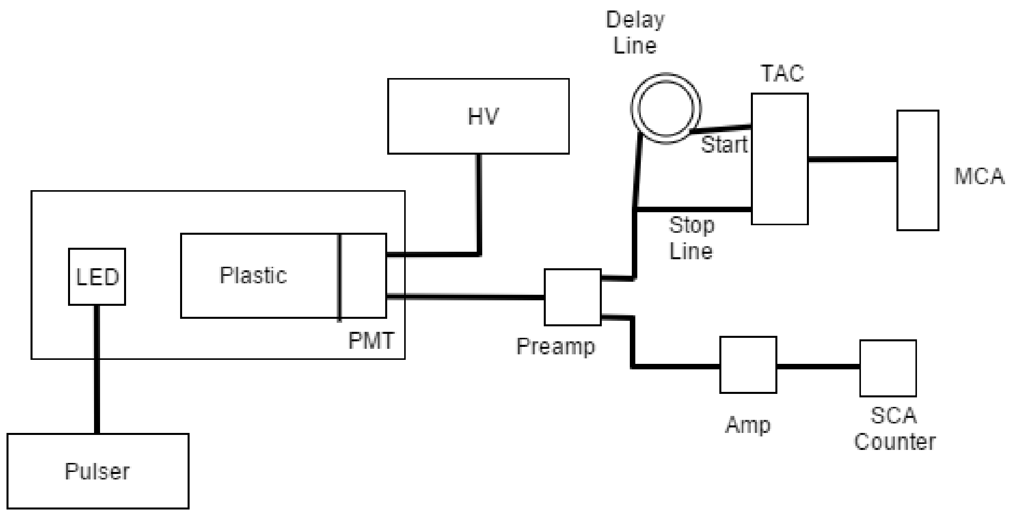

Figure 2: Block diagram of the experimental apparatus.

From the MCA generated histogram, we built a calibration relation between the MCA channel number (which is proportional to the TAC output voltage and is therefore proportional to t_i) and t_i by using a pulse generator to determine the channel corresponding to pulses of known separation, which we generated with an LED, and performing the fit seen in Figure 3 to determine the linear relationship between t_i and channel number.

Then we let the experiment run for three days, where we detected 1,831 muon decays with various delay times, which are plotted according to occurrence number in Figure 4.

In order to measure the arrival rate of muons, we adjusted the PMT voltage and preamp gain so that the measured muon flux was about 5.5 per second, ensuring that we were registering only muon events, and used the MCA in MCS mode to record the number of muon

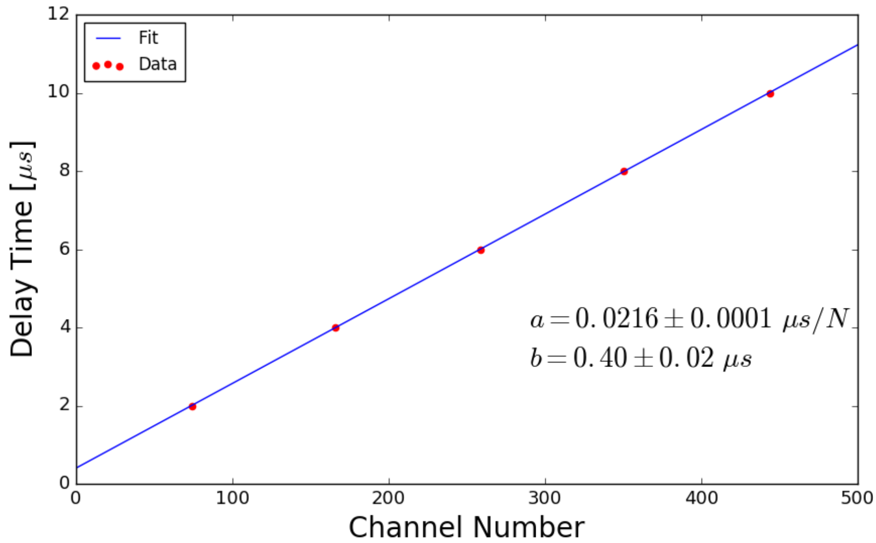

Figure 3: Calibration line relating the delay time of a double-pulse event and the MCA channel number.

events in 512 consecutive one second intervals, which is plotted as a histogram in Figure 5. We measured $n_{av} = 5.3 \pm 0.3$ muons per second.

4 Analysis and Discussion

We found the muon lifetime $\tau = 2.15 \pm 0.14\ \mu s$ by applying a weighted exponential fit of the form $Ae^{-t/\tau} + c$ to the curve in Figure 1, where we grouped the 512 channels of the MCA into 510/5 averaged channels and calculated the uncertainty of the bunched channel by adding in quadrature. Our result is in agreement, less than one standard deviation, with the accepted value of 2.2 μs. We also performed an alternative measurement of the mean lifetime of the muon by averaging all of the measured time delays, where we found $\tau 2.8 = 0.2 \pm$, which is reasonably close to our previous measurement, although more prone to systematic offsets.

For random arrivals we expect the count rate to behave according to the low rate counting of Poisson statistics, while if the arrivals are correlated, a histogram of the event rate would be bimodal.

From Figure 5 we see that the muon arrival rate is well described by the Poisson distribution, which is evidence for muon arrivals being uncorrelated at the two sigma confidence level, as only 83% of our measurements are within one sigma of the Poisson line, while 100% of our measurements are within two sigma of the Poisson line. Further supporting evidence for the validity of the Poisson description of muon arrivals in our computed $\chi^2 = 0.78$ value, which is near one, and therefore reflects agreement between model and data.

5 Conclusion

We measured the lifetime of muons generated in the upper atmosphere by cosmic ray collisions with a scintillator device and found $\tau = 2.15 \pm 0.14\ \mu s$, which is in agreement within one standard deviation with the accepted value of 2.2 μs. Additionally, we found evidence that muon arrivals are uncorrelated by showing that our measured count rate is described by inherently random Poisson statistics. This indicates that there is no complex process by which muons are produced in the upper atmosphere.

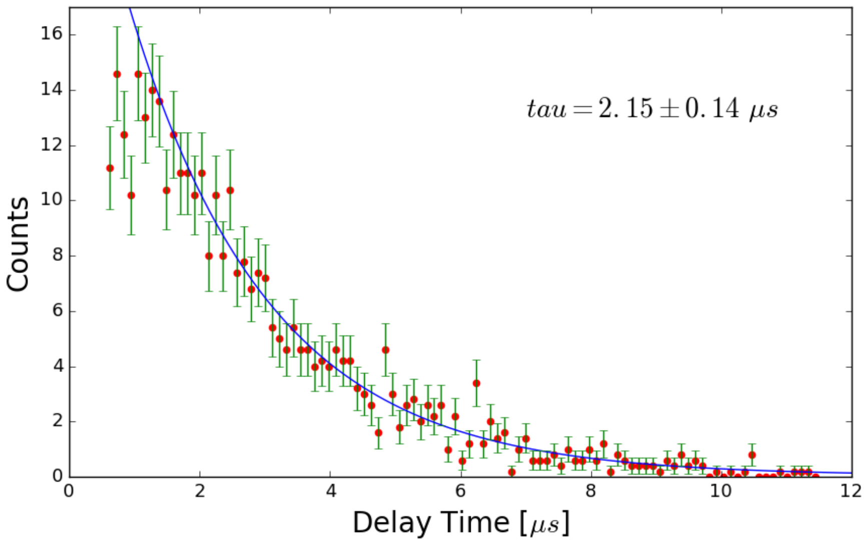

Figure 4: Number of double-pulse events for each delay time. These 510/5 data points come from grouping the original 510 channel data (after removing two) into bunches of five.

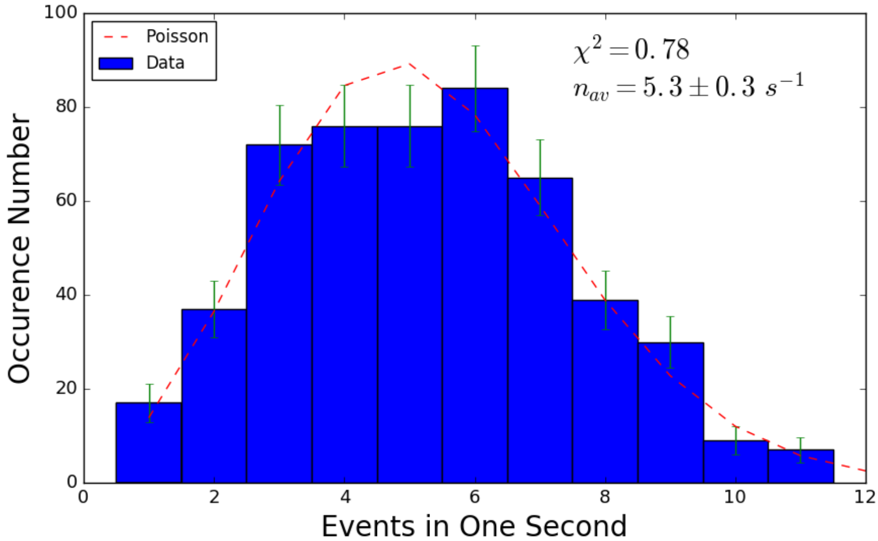

Figure 5: Histogram of the number of muon events detected within 512 one second intervals.