The Muon Lifetime Experiment

C.J. Mann, S.J. Thompson
Physics 121, Dept. of Physics and Astronomy, UCI

Utilizing the muons present in the atmosphere due to cosmic radiation, and the particles resulting from muon decay, we were able to determine the muon lifetime. Three scintillator slabs are placed on top of each other with photomultiplier tubes (PMT's) running between them. When a muon passes through one of the slabs, a signal is sent from the PMT. If a muon stops in a slab, a timer is initialized. When the muon decays, an electron is sent off along with two neutrinos. The charged electron moving through the scintillator slabs is picked up by the PMT's and a signal is sent again, this time stopping the timer. After leaving the system to collect data for a long period of time, we were able to determine the muon lifetime to be 2.535 ± .276 microseconds.

Muons were discovered by Carl D. Anderson in 1936 while studying cosmic radiation. When cosmic rays, usually consisting of protons with very high energy collide with our atmosphere, a pion is created. The pion also has a short lifetime and will quickly decay into a muon. The incoming protons are traveling at relativistic speeds when they collide with the atmosphere. This is important because if they were not, the time dilation due to special relativity, would not give the muon sufficient time to reach the Earth's surface. The muon generally travels to the surface along the same path the original cosmic ray was traveling with close to the same speed.

Most muons will pass through everything and bury themselves in the ground where they will eventually decay. However, some muons will collide with so many other molecules along the way that they will lose their energy and stop somewhere near the surface. This fact is fundamental to the success of our experiment. However, in order for us to notice the arrival of such a particle, we need one more constraint. Remembering that the incoming proton is the original source of the muon, and that the proton has charge +1e, therefore due to conservation of charge, the pion must also have charge +1e. Consequently, because the pion decays into the muon and chargeless neutrinos, the muon has charge +1e. The charge of the muon allows us to utilize the phosphoric properties of our scintillator slabs in order to track the position of the muon.

Scintillator slabs have the unique property that when excited by incoming energy they release a photon of lesser energy. This unique characteristic allows the slab to be optically transparent to the outgoing photon. We can then use our photomultiplier tubes to pick up the arriving photons. Of course this does not tell us where the muon is in the slab or even if it is still in the slab. We therefore designed our experiment in such a way to distinguish between particles that have passed through, and those that have stopped.

Fig. 1 shows a simple diagram of the experimental setup. The three slabs enable us to use digital logic to determine where the muon is. When a muon enters a slab, photons are emitted from the slab and a signal is sent to our logic circuit. The importance of using three slabs is being able to determine where a muon has stopped. For instance, if all three slabs send a signal at the same time, it is obvious the muon has passed through all three slabs. It may indeed have stopped in the third slab, but we would have no way of knowing that without a fourth, so we ignore that signal. If only the first two were to send a signal, we would know that the muon traveled through the first two but not the second, and therefore has stopped in the second slab. At this point, our logic circuit will send a signal starting a timer. Once the muon decays, an electron is emitted and will cause a second signal to be sent from whichever slab it passes through. Thus, if any of the three slabs produce a signal after the start signal has begun, a second signal stopping the timer will be sent. Of course a second muon could pass through the slabs before the first one has decayed, thus creating false data. However, the likelihood of this is so small, along with the fact that we are taking thousands of measurements, that this problem will only create a very small error, many orders of magnitude below our measurement value.

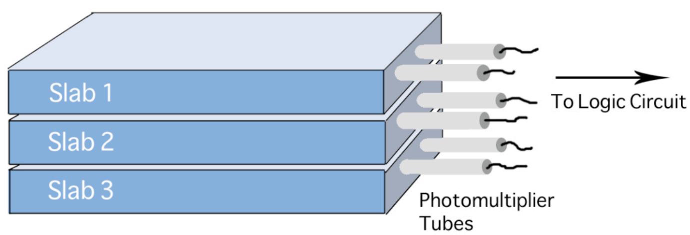

Figure 1. *Experimental setup, three scintillator slabs with photomultiplier tubes that collect the excited photons. The induced signal is used to calculate the lifetime.*

In our experiment, the logic circuit is connected to a timer which starts and stops based on incoming pulses. These start and stop signals are then sent to a computer which places the data into a histogram depending on the time of the decay. Fig. 2 shows all the collected data from a week of testing.

When measuring any kind of decay, whether it is nuclear decay or particle decay, the behavior of such a system is to follow an exponentially decaying function. In our case, the function is this:

$$N(t) = N_o e^{-\frac{t}{\tau_u}} \qquad \tau_\mu = \text{muon lifetime}$$

Equation 1. *Muon decay formula. N(t) = number of muons present after time t. N(0) = initial number of muons.*

The number of counts in this case, N(t) is the number of muons present after at time *t*. The amount, N(0) represents the initial amount of muons. For this experiment, initial number of muons is irrelevant so long as we consider it to be equal for all measurements. The important variable in the equation is in the exponential decay. Therefore, all data representing this relationship must exhibit exponential decay. This is clearly the case in Fig. 2. The decaying function represents the probability that a muon will still exist at a later time. Therefore, as time progresses, the probability that a muon will still exist gets smaller and smaller.

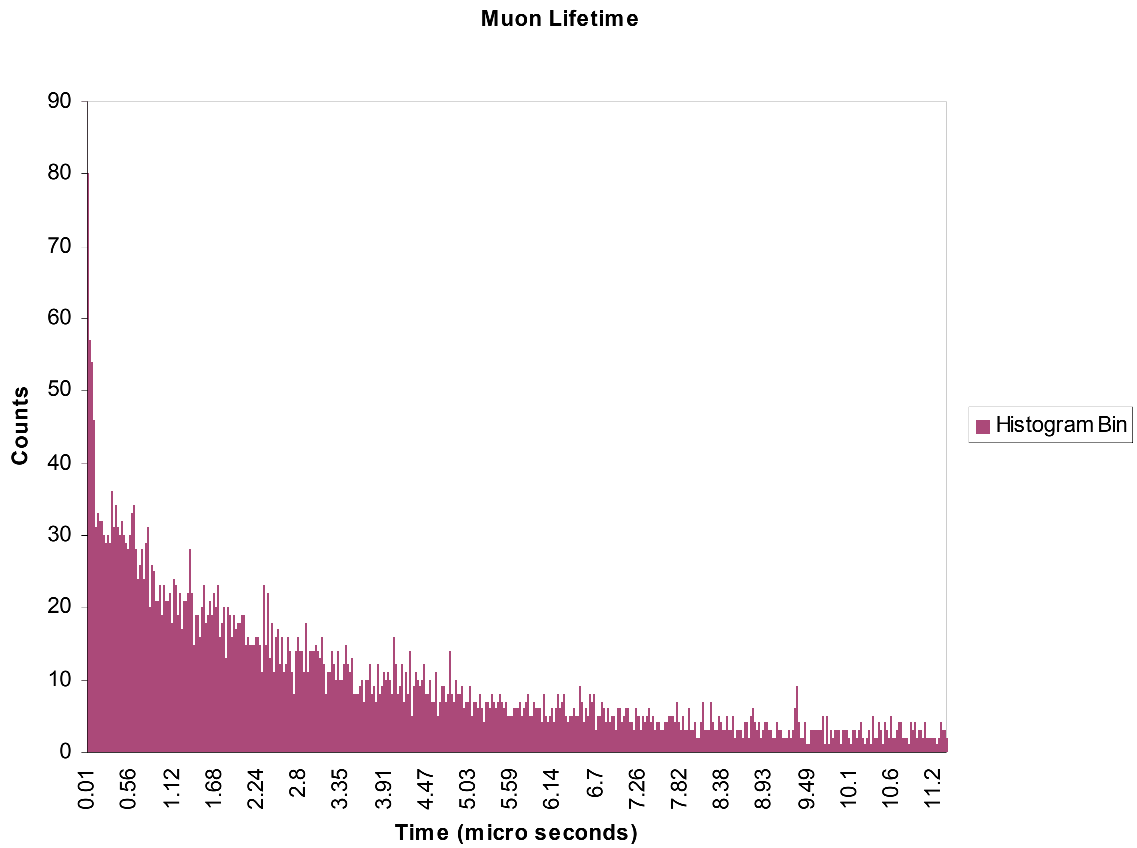

Figure 2. *Histogram data taken from muon lifetime. Each bar represents a bin in a histogram. Bin width was approximately 5 nanoseconds apart. The height of the bin corresponds to the number of counts in that range.*

In order to obtain the lifetime from this data, we needed to fit the data to a curve. To fit a nonlinear equation we used a regression on the formula:

$$y = Ae^{-\frac{x}{B}}$$

Equation 2. *Exponentially decaying function used in regression analysis. y = number of counts in a bin, x = corresponding bin, expressed in time (microseconds).*

This gave us a value of 2.535 for B, corresponding to τ for the muon lifetime. The uncertainty in B is given by:

$$\sigma_B = \sigma_y \sqrt{\frac{N}{\Delta}}$$

$$\sigma_y = \sqrt{\frac{1}{N-2}\sum_{i=1}^{N}\left(y_i - Ae^{-\frac{x}{B}}\right)^2} \qquad \Delta = N\sum x^2 - \left(\sum x\right)^2$$

Equation 3. *Equation for* σ_B*, the uncertainty in the constant B, corresponding to the constant τ. The equations below are necessary in defining the first equation. The terms for each, y and x, are the same terms defined in Eqn. 2, with the exception of N. In this equation, N represents the number of measurements, or in our case the number of bins. (N = 2057).*

This gave us a value of .276 for σ_B, this is the uncertainty in B, thus the uncertainty in our value for the muon lifetime.

There are different methods in fitting a nonlinear equation. One method is to reduce the nonlinear equation to a linear one, using logarithms. We chose not to use this method because it depends on the uncertainty in y being equal for all measurements. Due to the setup of our experiment, we cannot know that for sure. On the other hand, the method we chose does provide to a good approximation the correct values of A and B.

The uncertainties in the y values, which in our case are the number of counts per bin, arise from our varying source of muons. We assumed at the beginning that the number of muons at sea level is a constant. However, there is no way of knowing from one moment to the next what the initial number of muons is, the constant A in Eqn. 2. More specifically, while the number of muons at the surface may be very regular, we also need the amount that will stop in one of our two slabs to be nearly constant; this creates even more irregularity. Thus, if there were an abundance of muons for a given period of time, the counts would increase. Of course the lifetime of all these muons is the same, however, when fitting the data we are using the number of counts as to find B, under the assumption that A is a constant as well. This uncertainty in A is responsible for the large uncertainty in our final value for τ.

From the analysis of our data we can conclude that the value of 2.535±.276 microseconds is a good estimate for the lifetime of the muon, however, measurement from a more direct source would likely be a better alternative. With a constant source of muons, more precision can be gained.