The Lifetime of a Muon

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An attempt was made to detect muons in order to measure their average lifetime using various combinations of amplifiers and discriminators with a scintillator and personal computer. We were aware that the current setup of this lab was problematic, and thoroughly tested all parts of our apparatus using various techniques. We were unsuccessful in getting the apparatus to collect data of muon lifetimes as intended but were able to draw some conclusions about the flaw in the setup.

Every day numerous high-energy cosmic rays bombard the upper atmosphere of the earth. These rays, mainly composed of protons and alpha particles at extremely high energy, collide with the nuclei of atoms high above the earth creating pions and anti-pions. These particles quickly decay into muons, anti-muons, and and an array of other particles. This is represented by the equations below.[2]

$$\Pi^- \rightarrow \mu^- + \overline{\nu_\mu} \tag{1}$$

$$\Pi^+ \rightarrow \mu^+ + \nu_\mu \tag{2}$$

Muons are fundamental particles in the standard model of particle physics. They have the charge of an electron as well as an associated antiparticle known as the anti-muon with opposite charge. Muons, however, are about 207 times as heavy as an electron. They are unstable as well, and decay into an electron, muon neutrino, and anti electron neutrino as shown below [2].

$$\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu_e} \tag{3}$$

$$\mu^+ \rightarrow e^+ + \overline{\nu_\mu} + \overline{\nu_e} \tag{4}$$

The average lifetime of a muon is 2.2 microseconds and its decay is governed by the same equation as radioactive decay, namely,

$$N(t) = N_0 e^{\lambda t} \tag{5}$$

$$\lambda = \frac{\ln 2}{t_{\frac{1}{2}}} \tag{6}$$

In this case $t_{\frac{1}{2}}$ is the half life of a muon, about 1.56 microseconds.

At the speed of light, neglecting the capture of muons in air, it would take a muon 50 microseconds to reach the surface of the earth from 15km cite, the approximate height of its creation. Using the decay equation, we see that only about 2.44×10^{-9} percent would actually survive, or about 1 out of 400,000,000. The reality is, however, that the average lifetime of a muon is extended due to time dilatation as a consequence of special relativity [1].

$$t = \frac{t_{rest}}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{7}$$

Using the time dilation equation, we see that the average lifetime of a muon moving at 98 percent the speed of light will actually be 16 microseconds in the earth's reference frame, over seven times longer, again, neglecting the earth's atmosphere. This increases the amount of muons that survive the trip through the atmosphere to 4 percent making the probability of detection enormously greater.

Our apparatus for the detection of muons and the measure of their lifetime consists of a scintillator, photomultiplier tube, amplifier, discriminator, and personal computer equipped with a data acquisition card. See figure 1. The experiment works in the following way. Muons travel into the scintillator depositing energy by exciting atoms in the scintillator fluid as they decelerate. These excited atoms quickly fluoresce, giving off photons that are detected by the photomultiplier tube (PMT). The PMT converts the photons' energy to a voltage proportional to the amount of energy deposited, which can be measured. After the muon dumps all of its kinetic energy into the tank, and comes to rest, it obeys the exponential decay law, as it does at every other time. Upon decay, the released electron or positron has an energy up to about 50 MeV cite which is also deposited into the scintillator, ultimately producing a voltage pulse as well. These 2 pulses can be measured as well as the time between them, which, is the lifetime of that muon. After many muon detections have been recorded, one can then statistically formulate the average lifetime of a muon.

cite the pic The voltage pulses from the PMT are then amplified and sent to a discriminator, a device that only allows a voltage above a certain level to pass. From the discriminator runs 2 coaxial cables one long, one short which then attach to the start and stop inputs respectively of the data acquisition card in a personal computer. The purpose of sending the same pulse through these two

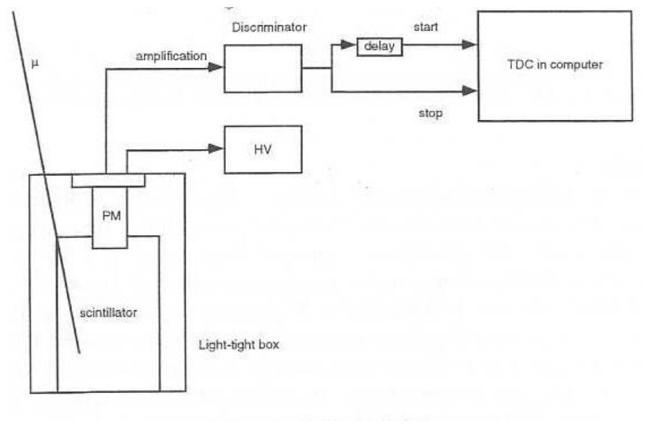

FIG. 1: This is the schematic of our apparatus as stated by the lab manual [2]

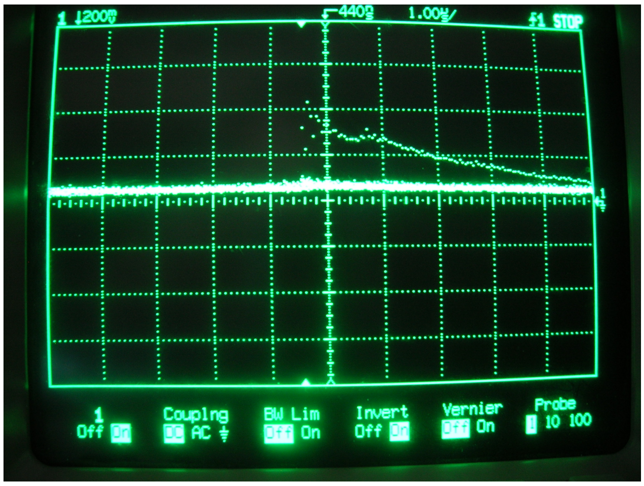

FIG. 2: This is a pulse, probably a muon, as it looks coming directly from the scintillator and PMT without amplification or discrimination. These pulses were difficult to photograph due to how quickly they appear and then leave on the scope; this one does not show the sharply peaked decaying exponential of other more pronounced strikes. Notice the relatively long duration of the pulse..

cables is well founded. The voltage pulse travels through the shorter cable arriving at the data acquisition card telling it to stop (and reset) its counter. This is necessary in case any random event or perhaps a muon capture for some reason or another caused the counter to start and did not have a pulse to stop it. The pulse through the shorter cable reaches the card a few nanoseconds before the one through the longer start cable preparing the counter to measure the time until the next pulse from the muon decay to stop the counter. A program written in Quick C records the count number and time between the muon decelerating in the scintillator and the decay of the muon after it stops.

We were unable to successfully get our apparatus to work as described above. As mentioned before, we were aware that there was a problem with the equipment we were using, and so spent our allotted time attempting to determine the fault.

The first logical thing we did in testing our equipment was to test the scintillator and photomultiplier tube. We did this by setting our power source on the recommended value of 1.2 kV [2] and connecting our scintillator and photomultiplier tube to the oscilloscope. We adjusted the volts/div scale to 200mV and 1 microsecond per division for the time scale. With these settings we were clearly able to see pulses every few seconds of about 200mV or greater that probably correspond to muon strikes and decays. We noticed that the pulses were up to about 4 microseconds long in the shape of an exponential decay. See figure 2. We adjusted the voltage to the PMT from 1kV to 2kV. The only change in signal as the voltage was varied from low to high through this range was an increase in baseline voltage and the counts registering at a proportionally higher voltage. Any voltage significantly above 2 kV causes the baseline voltage to be above two volts. However, the highest threshold setting on the discriminator is 2 volts. Because of this, the discriminator would be triggered continuously and not filter out the lower energy background noise. Hence any power supply setting much greater than 2 kV will not work in our setup.

The next components we tested were the various amplifiers. We found that some worked, some did not work at all, and others only did so when set to certain amplifications. We tested them by using a function generator to transmit pulses through the amplifier. The output of the amplifier was then observed using an oscilloscope in order to test the amount amplification each amplifier produces and detect any distortion of the signal. Depending upon the amplifier and amplification combination, we found many irregularities in the results of our tests. For example some channels of one of the amplifiers did not transmit a signal whatsoever let alone amplify it. The lower half of the LRS Model 333 amplifier did not work at amplifications of 6 dB and 8 dB but worked fine when set to 20 dB. Additionally, we observed noteworthy ringing in all amplifiers for all channels at all levels of amplification. See Figure 3. In the end we decided that the amplifier that was most reliable was the LRS Model 333 when set at the amplification of 20 dB.

Next, we tested the accuracy of the discriminator available to us. To test the discrimator we used a function generator set to produce 2 pulses that would bear resemblance to a muon incoming and decaying in a scintillator. These manufactured pulses were fed into the discriminator and observed on an oscilloscope. We set the generator to make 2 pulses, 2 micro seconds apart with each pulse 8 nano-seconds in length. By varying the amplitude of these pulses and adjusting the threshold voltage of the discriminator, we determined that the threshold-

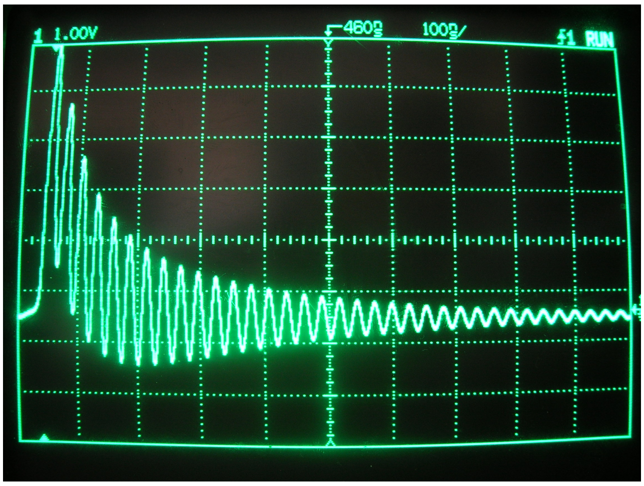

FIG. 3: This figure shows the ringing characteristic of the amplifiers we had available. Such ringing as this could perhaps have been what caused the very fast recorded lifetimes that were sometimes observed.

ing of the LRS Model 108D discriminator was working properly. Additionally, we also checked the output width adjustment, which was also appeared to be working correctly. However, the discriminator also produced considerable ringing similar to that of the amplifiers after it had thresholded our signal.

In addition, it is imperative that a more accurate oscilloscope is bought. We were certain that set the function generator to make 1.0 V pulse. However our oscilloscope was only reading about 750 mV. Unfortunately we used this exact oscilloscope to test all of our equipment. This may be one of the greatest problems in attempting to get our equipment working properly. Our only option was to press on using this oscilloscope because it was the best one available to us.

We then tested the output signal produced when the PMT was connected to the amplifier and then to the discriminator. We did this with the hope that the discriminator would eliminate some of the noise caused by the ringing of the amplifier with the threshold setting. However, the ringing from the discriminator still significantly distorted our output signal.

Next, we connected the function generator directly to the computer with the intent of testing the acquisition card and the computer program. Again, we used the same setting on the function generator with the intent of mimicking muons. It was determined that the card only registers for voltages of a greater magnitude than 1.5 V. The program and card appeared to be working correctly, measuring "lifetimes" down to an accuracy of a few nanoseconds.

After such preliminary testing of components, we tried to amplify our signal correctly so that the discriminator would have an output signal great enough to trip the start/stop card. We tried sending the PMT signal first to the discriminator and then amplifying its output as well as amplifying before discriminating. We also tried amplifying the signal before and after the discriminator. In all trials, we made sure that the voltage going in to the discriminator was of an acceptable level to usefully set the threshold level. Care was also taken to make sure that the input to the computer was at least 1.5 volts. Different combinations of amplification, scintillator voltage and threshold level were tried. In all these attempts we consistently observed the output signal of each component on the oscilloscope before doing and actual data collection in order to determine which if any combinations should have produced usable results.

In a sense, all results with different settings were consistently similar. It was commonplace for the computer to either record counts at an extremely fast rate with lifetimes routinely of the order of tens of nanoseconds and very uniform or no counts at all. The data collected during these runs were clearly not muons.

We were unable to get our apparatus to measure the lifetime of muons despite testing each piece of our equipment and assembling several variations of the original apparatus. We believe thorough testing with more capable equipment is needed to determine what is exactly the fault of our device. There appears to be several contributing factors to our lack of success, however. The relatively long pulses up to 4 micro seconds of the incoming muons could potentially be problematic. Since we expect an average lifetime of 2.2 micro seconds, these long pulses may be too energetic at the time of muon decay and hence still have the discriminator tripped for the decay pulse causing this lifetime to not be recorded. Additionally, we believe that the ringing of the amplifier and discriminator caused many counts to be stopped prematurely as well as producing additional counts as the attenuated wave shown in Figure 2 reaches its crest and drops off. This effect could possibly explain the reason why during many trial runs we received a multitude of counts with extremely short lifetimes of the same order as the period of the ringing observed in the amplified signal.

We believe that it may be possible to get this muon lab working properly after a thorough testing of components and stages of the apparatus with more capable equipment. The distortion caused by ringing in the amplifiers and discriminator used as well as possibly the seemingly long pulses coming from the scintillator could all be contributing factors in prohibiting a successful experiment.

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[1] Nave, R., "Muon Experiment in Relativity",http://hyperphysics.phy-astr.gsu.edu/hbase/Relativ/muon.html (2000)
[2] University of Rochester Department of Physics and Astronomy, *The Lifetime of Cosmic Ray Muons* (Rochester, NY)