Muon Decay

(Based on T.E. Coan and J. Ye's Muon Physics)

Introduction

The muon is one of nature's fundamental "building blocks of matter" and acts in many ways as if it were an unstable heavy electron, for reasons no one fully understands. Discovered in 1937 by C.W. Anderson and S.H. Neddermeyer when they exposed a cloud chamber to cosmic rays, its finite lifetime was first demonstrated in 1941 by F. Rasetti. This experiment permits you to measure the averaged mean muon lifetime in plastic scintillator, to measure the relative flux of muons as a function of height above sea-level and to demonstrate the time dilation effect of special relativity.

You will be concerned with measuring the mean muon lifetime.

Our Muon Source

The top of earth's atmosphere is bombarded by a flux of high energy charged particles produced in other parts of the universe by mechanisms that are not yet fully understood. The composition of these "primary cosmic rays" is somewhat energy dependent but a useful approximation is that 87% of these particles are protons 11% are heavier nuclei, mostly He nuclei, and 2% are electrons.

The primary cosmic rays collide with the nuclei of air molecules and produce a shower of particles that include protons, neutrons, pions, kaons, photons, electrons and positrons. These secondary particles then undergo electromagnetic and nuclear interactions to produce yet additional particles in a cascade process. Figure 1 in yhr manual indicates the general idea. Of particular interest is the fate of the charged pions produced in the cascade. Some of these will interact via the strong force with air molecule nuclei but others will spontaneously decay via the weak force into a muon plus a neutrino or antineutrino.

$$\pi^+ \rightarrow \mu^+ + \nu$$
$$\pi^+ \rightarrow \mu^- + \bar{\nu}$$

The muon does not interact with matter via the strong force but only through the weak and electromagnetic forces, so it travels a relatively long instance while losing its kinetic energy and decays by the weak force into an electron plus a neutrino and antineutrino. The typical energy of the muons produced in the upper atmosphere is on the order of a few GeV. These muons will lose energy as they interact with the atoms in the atmosphere and finally, with the scintillator in the detector. Primarily they lose energy as they scatter off of the electrons in the matter they pass through. By the time they reach sea level they lose on the order of 2 GeV of energy to the atoms in the atmosphere. The mean production height in the atmosphere of the muons detected at sea-level is approximately 15 km. Travelling at the speed of light, the transit time from production point to sea-level is about 50 μsec. Since the lifetime of at-rest muons is more than a factor of 20 smaller, the appearance of an appreciable sea-level muon flux is qualitative evidence for the time dilation effect of special relativity.

The lifetime of both muons in a vacuum is about 2.197 μs. In matter the lifetime of the μ^- is shorter because the μ^- can be captured by a nucleus and combine with a proton to form a neutron plus a neutrino and release energy. (This is similar to electron capture in radioactive decay.) In our detector, mostly carbon, it is likely to be around 2.0 μs. (It depends on the atomic number of the material. The higher the atomic number, the shorter the lifetime.) As a result you will measure some average lifetime of the two muons. (See the manual.)

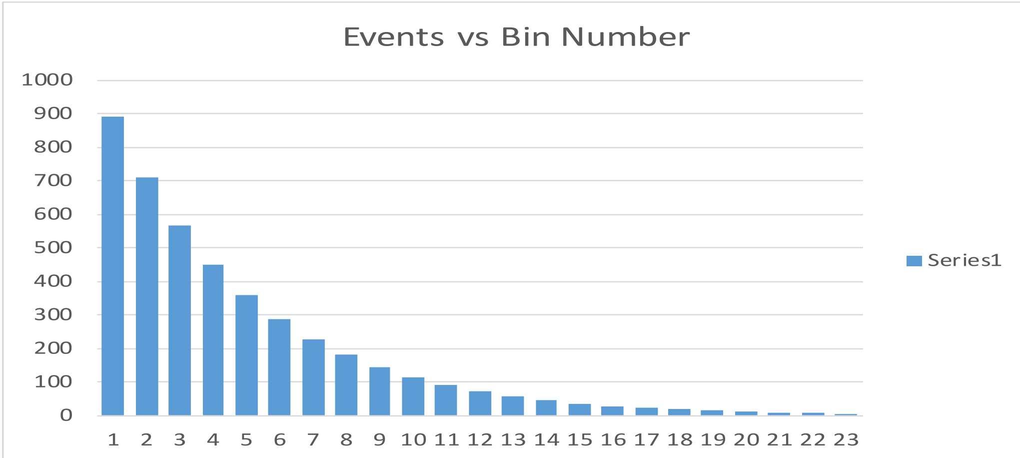
Detector

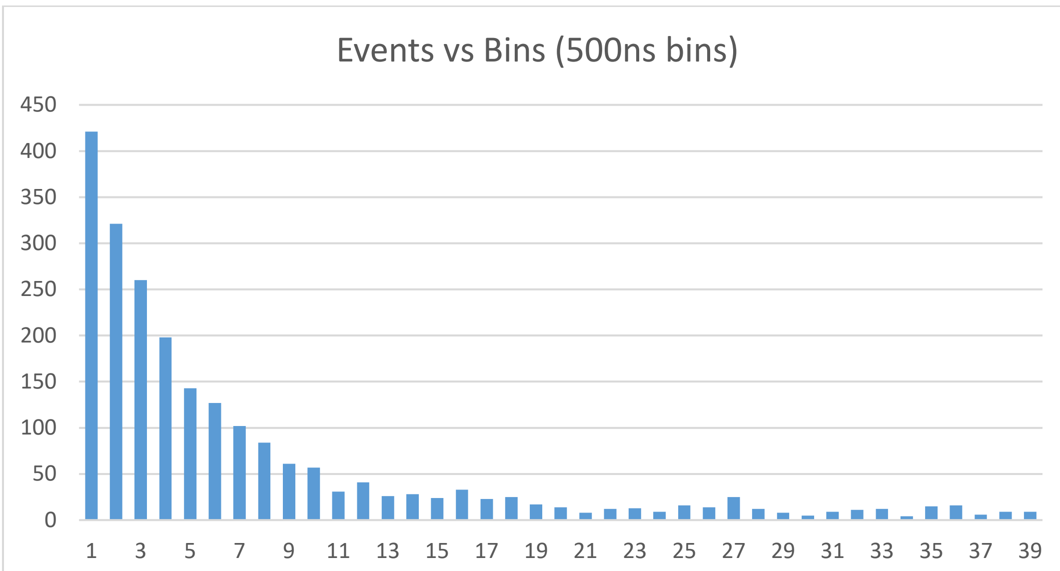
The detector is a plastic scintillator in the shape of a right circular cylinder of 15 cm diameter and 12.5 cm height placed at the bottom of a black anodized aluminum tube. The plastic scintillator is a transparent organic material made by mixing together one or more fluors with a solid plastic solvent. A charged particle passing through the scintillator will lose some of its kinetic energy by ionization and atomic excitation of the solvent molecules. Some of this deposited energy is then transferred to the fluor molecules whose electrons are excited and emit light when they de-excite. These plastic scintillators are quite fast, the light being emitted in a few ns. (Sodium iodide doped with thallium, another common scintillator, takes a couple of hundred nanoseconds to emit its light.) A photomultiplier tube detects this light and produces a pulse output whose height (voltage) is proportional to the energy deposited in the scintillator. A computer then records these pulses.

The muon flux at sea level is about one muon per minute per square centimeter. Therefore only a few muons hit the scintillators per second. Most pass through without decaying, but they will excite the scintillator and produce a pulse. The muons we are interested in are the ones that have been slowed by their passage through the atmosphere, enter the scintillator and lose the rest of their energy to the scintillator, producing a pulse. They will then stop and eventually decay, producing an energetic electron and two neutrinos. The electron will leave most of its energy in the scintillator, producing another pulse. The time between these two pulses is how long it took the muon to decay. The computer records two different things. It records the total number of pulses, or events, produced in the scintillator. Second it records the time between pulses that occur within 20μs of each other. The pulses that occur within 20μs of each other primarily consist of two groups.

1. Some of these are events where a muon stops and decays within the detector. These are the events we are interested in.
2. Others are due to two different muons passing through the detector within 20μs of each other. These are "accidental" coincidences and are called a background.

In order to analyze these events and find the lifetime for the muons, one makes a histogram of how many events occur within various time intervals of each other. One might make a histogram by looking at how many occur between 0 to 499ns of each other, how many occur between 500 – 999 ns of each other, how many occur between 1000ns and 1499ns of each other, etc. Each of these intervals is called a **bin**. (I strongly recommend equal length bins, otherwise you will need to use the rate = (count/bin length). If there were no background events, these would be expected to follow and exponential decay. A plot of events vs bin number would look like the histogram below. However, this plot assumes no randomness due to the random nature of the decays. This looks like exponential decay. However the background and the random nature of the decay will make it look a little messier. The second graph below shows the result of an actual run of about 23 hours. Note that the exponential decay is fairly clear, but that there are fluctuations that become more noticeable after four or five microseconds. (For example bin 11 is at 5.5 μs.)





You can reasonably assume that any events at times greater than 12μs are background events. You can estimate the background rate but averaging the last 12 to 15 bins, say bins 25 through 39. A better way to do it would be to use a curve fitting routine and fit the data to an exponential plus a constant or

$$A\exp(-\lambda t) + C$$

Where you would fit A, λ, and C to the data.

Operating the Experiment

Read the manual pages 14 – 24. It contains the operating instructions and information about the file format. (If you are thinking of going to graduate school, you need to be able to read the manual and be able to operate the equipment!! Many jobs in physics also expect this level of competence.) I have a couple of recommendations about the settings for the experiment.

1. The high voltage for the PM tube (photomultiplier tube) should be low enough so that there are only about 4-7 muon events per second. Higher rates indicate that the tube is “firing” on other types of “events”.
2. Set the discriminator to about 200mV = 0.200V.
3. You will have to run the experiment for <u>at least</u> 48 hours (two days), but longer is better. Four or five days is better.

<u>File Format and Data Analysis</u>

You will find that the files contain two columns of data. The first column consists of two types of numbers. If there are no decays, or an accidental coincidence, the number will be 40,000 or greater. If the number is 40,006, it indicates that over the last second there were 6 events recorded, but that none of them were within 20μs of each other, i.e. no coincidences. If the number is < 40,000, e.g. 1400, it is indicative of a coincidence and that the time between the two events is 1400ns or 1.400μs. The data sequence shows a few columns of data from a run done on Jan. 7, 2019. The first row, first column is 40017. That means that there were no coincidences in the 1546890914th second. (The second column measures time in seconds from a reference date. Can you determine that date?) The seventh entry is 6120 in the first column. This means that there was a coincidence of two events 6.120 μs apart. What you want to do is collect all the coincidences together. You can do this by importing the data into EXCEL and sorting the first column from smallest to largest. It will look like the left column below the first group. I’ve only shown the first few coincidences, there are about 2200 total and 20 coincidences at 100ns. Note that the “bins” are 20ns wide and that it starts with 60 ns for the first coincidences. Apparently the electronics has problems if the coincidences are less than 100ns. As a result I recommend that you start with those at 100ns and “start your clock there.” You want to count the number of coincidences in 400 or 500ns intervals. If you do it for 400ns intervals, the first would be from 100ns through 480ns. (Actually 100ns through 499ns but they only are recorded to the nearest 20ns.) The second bin would be from 500ns through 880ns and so on. For 500ns wide bins you would do 100ns through 580ns etc. When I grouped them into 500ns bins I got the result at the right. The first column is bin number and the second is the number of coincidences in that interval. This is the data you will fit to an exponential decay plus a background term. You can estimate the background by averaging the counts in the last bins, say 24 through 39. In this case it is 11.4 with a standard deviation of 5.4. (Note the large fluctuation in number of counts in these last bins.) You would subtract this from the count in bins 1 through about 18 and then fit the resulting data to an exponential decay. You probably

40017	1546890914
40017	1546890915
40013	1546890916
40010	1546890917
40011	1546890918
40010	1546890919
6120	1546890920
40016	1546890920
40015	1546890921
40015	1546890922
40016	1546890923

time
60
60
80
80
80
80
80
80
80
80
80
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100

bin	events
1	421
2	321
3	260
4	198
5	143
6	127
7	102
8	84
9	61
10	57
11	31
12	41
13	26
14	28
15	24
16	33
17	23
18	25
19	17
20	14
21	8
22	12
23	13
24	9
25	16
26	14
27	25

would not use the regions where the background approached the original count in the bins.

When I went through a process like this I got a lifetime of 2.28μs ± 0.13μs. Since there was a large uncertainty in the background I also did this for backgrounds of the calculated background +1 and – 1. The background – 1 fit a little better i.e. a larger F statistic, so I did it a third time for the background – 2, but the fit was not as good. The "best" fit lifetime was the one with the background – 1. That gave $\tau = 2.21\mu s \pm 0.12\mu s$. However the data was only collected for about 24 hours. It is much better to go for at least 48 hours and set the tube voltage lower so the background is smaller. The background rate for this data set was too large.

A major part of this lab is the analysis of the data. I want to see what you did and I want you to justify what you did. It is important to give a standard deviation for your results.

100
100
100
100
120
120
120
120
120
120
120

28	12
29	8
30	5
31	9
32	11
33	12
34	4
35	15
36	16
37	6
38	9
39	9