Phys 471 – MODERN EXPERIMENTAL PHYSICS II

Lab 4 – Muon Mean Lifetime

I. INTRODUCTION

The purpose of this experiment is to measure the lifetime of one of the elementary particles of matter, the muon.

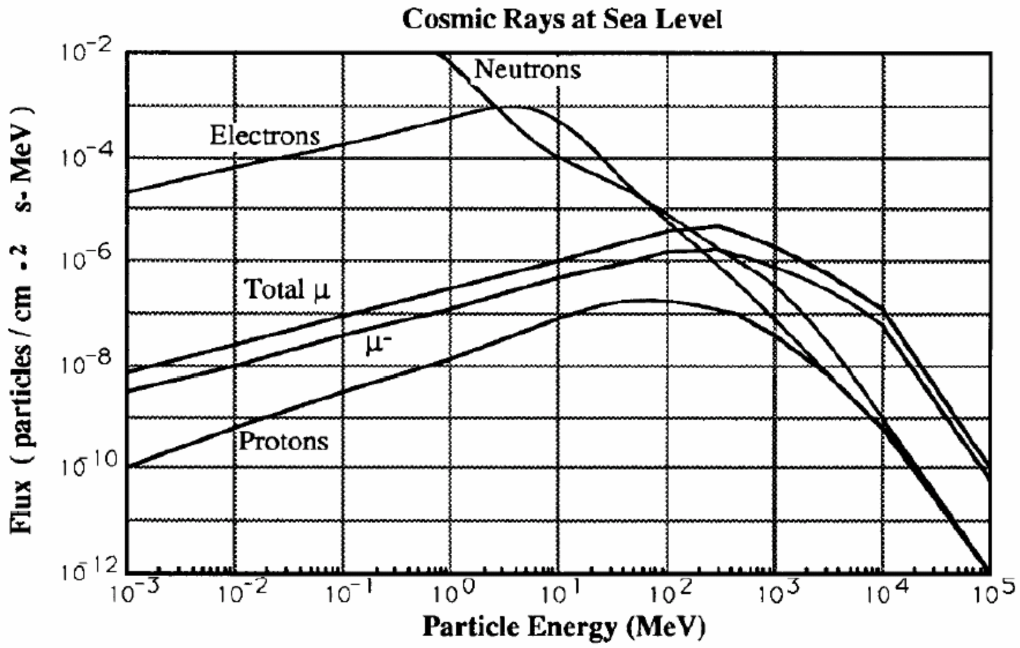
There are six so-called leptons: the electron (e), the muon (μ), the tau (τ) lepton and their associated neutrinos (ν_e , ν_μ , ν_τ). The muon and the tau leptons have identical properties to those of the electron, except that they are heavier. In this experiment you will measure the muon lifetime, one of its first properties to be experimentally determined.

This manual is organized to guide you through the experiment, though you are not required to strictly follow the procedures suggested herein. In fact, you are encouraged to develop your own ideas and methods.

Before initiating the experiment make sure to read this entire manual first, so you know what you will need. Not all the requirements to complete your report are explicitly noted in this manual, rather it is up to you to fill in the missing blanks. There are suggested questions that you should think about and answer. Some of the questions (and their answers) are quite important and discussion of them should be worked into the laboratory report.

II. PHYSICS OF MUONS

Muons have nearly the exact same properties as electrons with the exception that they are heavier. They can decay due to the mass difference between muons and electrons. Muons and electrons interact with matter only electromagnetically or by the weak nuclear force. The latter causes the radioactive decay of particles and atoms. Cosmic ray muons (this experiment) arise from the decay of pions ($\pi \rightarrow \mu + \nu$) which are produced by high energy collisions of incoming cosmic rays with nuclei in the atmosphere. See below for some estimates of cosmic ray muon flux.



Flux of cosmic ray particles at sea level at 40° N geomagnetic latitude. Data from J. Ziegler, Nucl. Instr. Methods, 191 (1981) 419. Below 3 MeV for electrons and about 10 MeV for protons the fluxes depend on local atmospheric conditions.

When observing nuclear beta decay, one finds experimentally that the decay $\pi \rightarrow p + e^-$ seems to violate the conservation of energy. Pauli was first to propose the existence of a massless particle now called the neutrino to explain this discrepancy. Then the decay becomes

$$n \rightarrow p + e^- + \overline{\nu}_e.$$

Fermi (1932) developed a theory of nuclear decay in analogy with the electromagnetic interaction. The lifetime of the neutron would be given by

$$\tau = \hbar / \Gamma$$

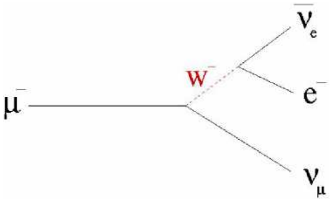
with

$$\Gamma = \frac{G^2 E_0^5}{30\pi^3}$$

where G is a constant, and E_0 is the nuclear energy difference (*1.81* MeV). Using the measured half-life of the neutron, we determine G to be 1.136×10^{5}. GeV.

The muon lifetime can be determined by direct analogy to this decay. Muons are spin-1/2 particles (just like electrons, protons and neutrons) so the decay is given by:

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



The mean lifetime of the muon is given by

$$\tau = \hbar / \Gamma$$

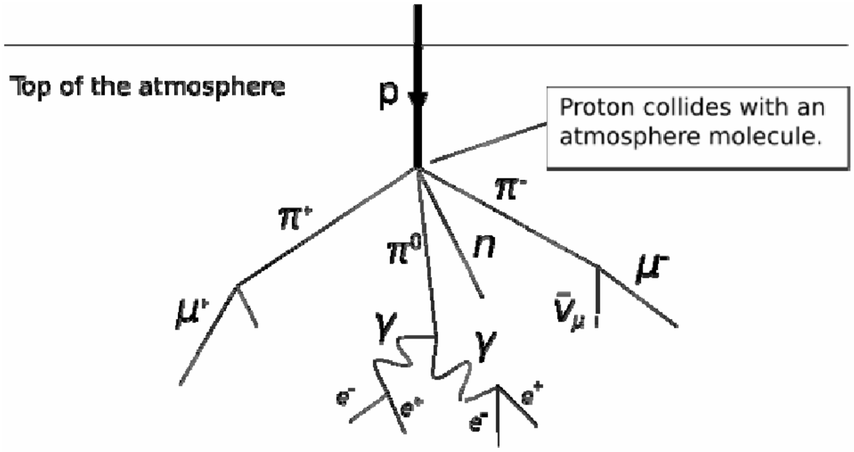
where

$$\Gamma = \frac{G^2 m_\mu^5}{192\pi^3}$$

m_μ is the mass of the muon. We get a constant of 192 instead of 30 because we cannot neglect the recoil of the final electron as we could for the proton in the proton - neutron system in nuclear beta decay. Note that the mass of the muon is much greater than that of the muon neutrino or the mass of the electron so m_μ is analogous to E_0 in nuclear beta decay.

A full theory of the weak interaction was developed between the mid 1950s and the late 1960s by a variety of people, most prominent of which are Glashow, Weinberg and Salam. See the references for further information about the theory of the weak interaction.

The muons are produced by high energy collisions between incoming cosmic ray nuclei and nuclei in the atmosphere:



III. MUON DECAY EXPERIMENT

When a muon is stopped in a material, it is usually captured by an atom of the material. Then, two possible processes contribute to our observed signal. One is that the captured muon decays weakly and gives rise to an energetic electron which can excite the atoms or molecules in the medium. If the medium is a scintillator, light is emitted in the de-excitation of the atoms. The other process is that the muon is eventually captured by the nucleus. It is likely that the product nucleus will give rise to nuclear decay products which will excite the medium and produce light if the medium scintillates. The resulting light will produce a signal in the photomultiplier tube (PMT.) Here we use blocks of plastic scintillator as the stopping media.

The density of the plastic scintillator ("stopper") is ~1g/cm^3. Its composition is close to that of CH. The rate of energy loss is *dE/dx* such that the total energy deposited is

$$\Delta E = < dE / dx > \Delta x .$$

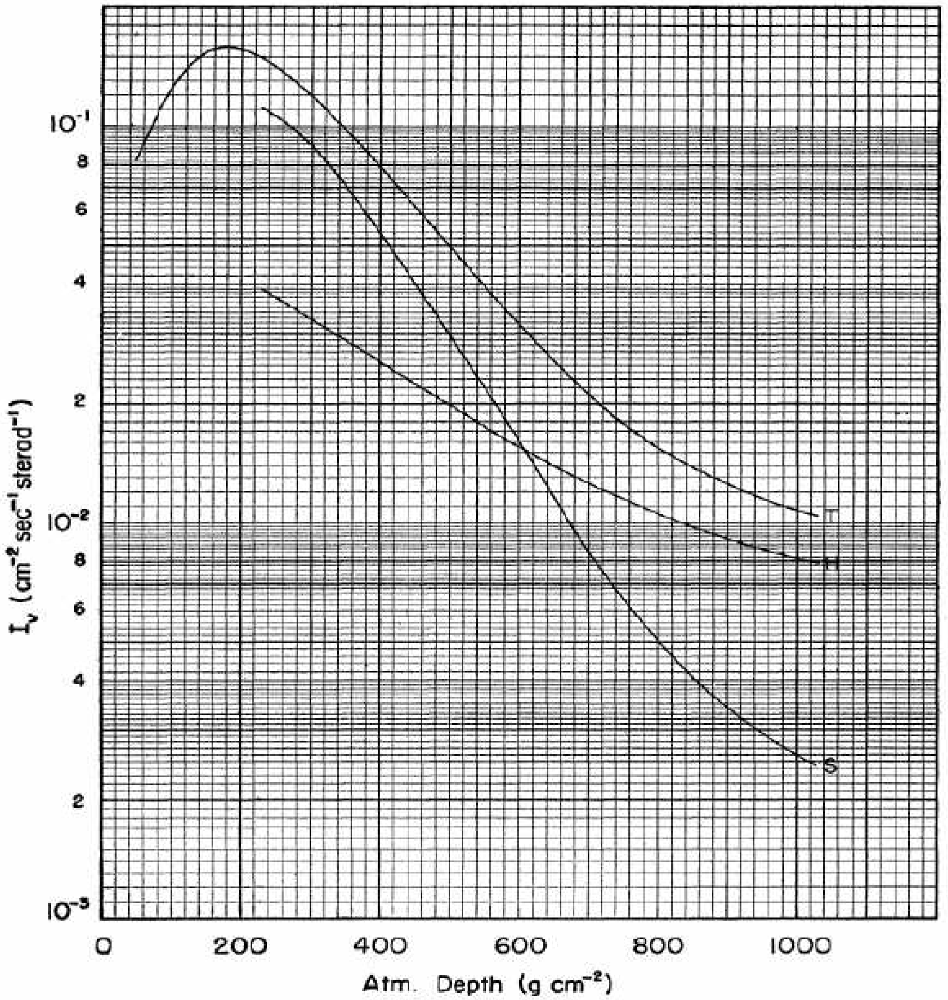
The scintillator is covered with reflecting foil so that most of the photons multiply reflect and escape through the top. A high gain 14 stage PMT (**max voltage 2500V**) is connected to the plastic scintillator block with an optical grease to enhance light collection. About 20% of the photons entering the PMT are converted to electrons in the semi-transparent photocathode. Each one of these electrons is accelerated by a high electric field in the tube, ejecting a few more electrons upon collision with an internal dynode. This tube has 14 dynodes and an overall electron gain of about 10^8. Each muon traversing the scintillator will produce a pulse of light.

To estimate the arrival rates of single pulses, measure the size of the scintillator and estimate the total rate of muon events R. You can use the following empirical formula that gives a good approximation to the number at sea level as a function of zenith angle:

$$I(\phi) = I_v \cos^2(\phi)$$

where I_v = 0.0083 cm^{-1} s^{-1} sr^{-1} (see figure below, Rossi 1948.) (sr = unit of solid angle), and $I(\Phi) d\Omega dA dt$ is the number of muons incident on differential area *dA* during the time *dt* within the solid angle $d\Omega$ from the direction normal to *dA*. Integrating this function over the appropriate solid angle, you can estimate the total flux from all directions.

Below is a plot of the vertical intensity dN(dAdtdΩ) of the soft, hard, and total cosmic ray flux as a function of the atmospheric depth near the geomagnetic equator [B. Rossi, Rev. Mod. Phys. 20, 537 (1948).] Sea level is ~900 g/cm^2



• **Question 1 -** Estimate the number R of muons passing through the detector each second. (First estimate the size of the detector.)

Muons lose about 2 MeV of energy per gram per square cm of material that they traverse. Thus muons with less than certain critical energy will stop in the scintillator. These stopped muons will decay within several microseconds, emitting an energetic electron which excites atoms in the scintillator producing another pulse of light. Just as the radioactive decay experiments, the distribution of these times can be related to the muon lifetime.

• **Question 2 -** Roughly how much energy will a 100 MeV muon deposit in 1 cm of scintillator?

Start by doing an initial experiment to find the operating point for the PMT high voltage and for the discriminator. Turn up the high voltage (HV) gradually (about 5 sec per coarse division) and do **not exceed 2500 volts** for the PMT. Look at the analog PMT output pulses (negative, so be sure to use negative scope threshold) as a function of HV. You may want to follow the instructions on how to "plateau" the PMT HV, or use your own method. Note that there is a threshold-plateau effect in the response versus HV. You should also look carefully at the noise pulses: PMTs become exponentially noisier at higher voltages. Thus there is an optimum voltage for any PMT which maximizes the signal-to-noise ratio. Look at the changes in pulse shape out of the PMT as the HV is raised. Make sure you avoid operating the PMT over voltages where the pulse becomes "nervous".

Use the oscilloscope to look at your signals. Be sure you check and understand the waveforms and pulses at each step. Begin by looking at the background noise level in the electronics with the PMT HV off. While the inputs and outputs of the logic electronics generally are terminated in 50 ohms, the oscilloscope has high impedance inputs, so be sure to terminate the scope inputs with 50 ohm terminations. Un-terminated lines will cause reflections of pulses due to the impedance mismatch with the 50 ohm cable. Be aware of timing effects of cables: A pulse in RG-58 coax travels at ~2/3 c, giving a delay of 1.5ns per foot. Read the instruction manuals for the instrumentation.

Setting the discriminators. (The procedure proposed here might be relevant or not to your experiment. It depends on the logic you use to perform your measurements, regardless whether it is appropriate or not for your developments, you should answer the following questions.) You may want to set the discriminators such that you count mainly muon stopping and decay events. (Stop and consider what processes produce the light signals that are converted into electric signals by the PMT). We can start understanding how this is done by considering the idea of the experiment. Cosmic ray muons enter the detector, and some collide and stop. (The higher energy muons pass through). Of those that stop, some decay and some are captured by nuclei. We want to measure the time interval to decay (its distribution). Think about the range of pulse heights produced by stopping muons. Use the scope and observe the largest pulse height (largest energy deposited) by these muons (you have to set up some logic to be able to measure stopping muons).

Question 3: Compare this with the pulse height produced when a muon passes through the detector (again, you have to build a logic circuit to measure these muons).

Question 4: For the stopping case, show the range of energies expected. [Consider how much energy a 2 GeV (the mean at sea level) muon will lose if it traverses the total thickness of your detector. Compare this with the energy lost (signal) of a muon which stops just few centimeters, say 1 cm or 2 cm, inside the detector) in 30 cm.]

Questions 5: How much scintillator does it take to stop the decay electron? A good estimate is that a relativistic electron loses about 2 MeV per cm (per gm/cm in CH). Assume that the scintillator is CH.

Question 6: Compare range of signals from stopping muons and decay electrons in the scintillator. The max electron energy is ≈ 53 MeV when electron's momentum is opposite to the two neutrinos. (See Melissinos textbook)

One can adjust the PMT voltage and measure the counts above a fixed discriminator threshold (see notes on how to "plateau" a PMT); or one can fix the PMT voltage and vary the threshold.

In the first case one graphs the count rate over a small (say -25 mV) discriminator threshold versus the applied voltage for the photomultiplier tube (use the counter module installed in the NIM crate). Beware that if your discriminator level is too low, you will count mostly electronic noise, and if it is too high, you will see nothing at all. Investigate this experimentally with the scope. There is a not a nice plateau because one has a wide range of pulse heights. However the operating point is not that critical. Look for a change in the slope of a graph of counts vs. threshold, or log(counts) vs. threshold. This allows you to check that your PMT voltage-discriminator setting is reasonable, so that you are seeing muon decay signals. Use an oscilloscope to look at signals out of the PMT and determine the signal size for the electronic noise, a muon passing through the scintillator and an electron decaying after a muon has been stopped in the detector. The last will be the hardest to find. The signal of the decay product electron will occur on average about 2 μsec after the muon stops. Once you have the basic idea of what the signal looks like, use the output of the discriminator to trigger the oscilloscope. Lower the discriminator level until the scope triggers all of the time (you should be triggering on the electronic noise). Increase the discriminator level until you no longer see the electronic noise and you see both muons and the occasional electron from muon decay on the scope. Compare the scope discriminator setting which gave decay events with what you set in the electronics to check that they are similar. Note that the Philips discriminator has a test point on the front panel (use a DVM to test) giving 10 times the discriminator level (250 mV = 25 mV discriminator level); the level adjustment can be made from the front panel.

IV. DIGITAL LOGIC ELECTRONICS

To measure the muon lifetime you need to collect statistics on the distribution of times between the first pulse (arrival of the muon) and the second pulse (decay.) The first pulse may be used to start a timer (actually a time-to-digital converter -- TDC) and the second pulse used to stop it. When feeding the start signal to the START input of a TDC CAMAC module, and the STOP to one of the remaining inputs, the time difference between the START and STOP signals is computed by the TDC, digitalized and readout by a data acquisition program (see next session). If no STOP pulse is received within a preset time (10 μsec for the TDC under use) the TDC is reset and the process starts over. The distribution obtained with the TDC can then analyzed.

Question 7: You are trying to take the difference in time between a stopping muon and its subsequent decay. You need to have a start and a separate stop pulse to carry this out. Draw a diagram showing the logic you plan to employ in this problem. Make sure to provide a detailed diagram showing the timing of each pulse relative to the pulse you will use as start (your reference).

You must calibrate the TDC by correlating different time delays between the START and STOP pulse and the range of time used in your measurements. You can use the time calibrator module installed in the NIM crate.

APPENDIX 1 - Adjusting PMT HV using the plateauing technique for scintillation counters

1. Use your eyes. Look over the counter and fix any obvious openings that light could enter the PMT.

2. Hook up your PMT base to a scope. Note the PMT base anode output circuit is set drive 50 ohms so use proper termination. Make sure the HV supply is set to **NEGATIVE**. Set the HV to -1500V initially. If a large (or intense) pulse is seen a light leak exists that must be located and plugged.

3. After fixing any light leaks, record the dark current pulse. How does this current arise? What is the magnitude of the current?

4. Now bring a gamma sources close to the counter. Record which source you used. Look up the decays for this source. Sketch the source signal seen on the scope.

5. Set the discriminator width to 50 ns. Set the discriminator threshold to an appropriate value. Often this is the lowest setting on the discriminator.

6. Connect the output of the discriminator to a visual scaler. If things are working properly the noise rate (no source) should be 100 Hz or less.

7. Plateau the counter by measuring counts/sec as a function of PMT voltage. You might run from 1100 to 2000V in 500V steps and make any finer measurements as necessary. **DO NOT EXCEED 2200V**.

8. Repeat item #5 for any other different counters.

9. A better way of plateauing counters is to use two or more counters and take appropriate coincidences. Design such a circuit using discriminators, fanouts, and coincidence units and draw it in your notebook. Try to use this method if you have enough time to finish your lab (see the description of the method in the next page).

10. Also, please answer the following questions in your lab notebook.
    a. What is the cosmic ray flux at sea level? What cosmic ray counting rate do you expect with your counter?
    b. What types of particles are cosmic rays at sea level?
    c. What is their mean energy?

APPENDIX II - PMT HV Plateauing using coincidences between 3 counters.

1. Set up a cosmic ray telescope with three scintillation counters.

2. Set the initial HV for the three counters at the plateau voltage you found from last lab or at a value that gives 100 Hz noise rate in the counter.

3. Set up the appropriate NIM logic to make a double and triple coincidence of the three counters. You need to be aware of and/or adjust the discriminator thresholds and discriminator and logic unit widths. You also need to ensure the signals used in the logic units are in time.

4. Plateau the counter by measuring the ratio of triple coincidences to double coincidences as a function of PMT voltage. Take data from 1200 to 2000V in 200V steps and make any finer measurements as necessary.

5. Plateau all three counters. The operating HV should be about 100 V above the knee of the plateau. Mark this value on the counters. Why is this method an improvement over the previous one?

6. Could you use a gamma source as the “beam” for this method? Could you use a beta source as the “beam” for this method?

7. With the PMT HV set at the plateau voltage, measure the cosmic ray rate. Compare this with the number you estimated using the previous method.

8. How can you be sure your counter is really counting cosmic rays (as opposed to any naturally occurring radiation in the room)?