Physics 121
Advanced Laboratory

MUON LIFETIME EXPERIMENT

A. Introduction:

The Muon Lifetime Experiment introduces the student to ideas and techniques of modern particle physics. It explores the decay of a muon into an electron

$$\mu^- \rightarrow e^- + \nu_e + \nu_\mu \qquad (1)$$

(or the comparable decay of the antimuon μ^+) and directly measures an effect of the weak interaction. (Most experiments in Advanced Lab measure effects of the electromagnetic interaction.) The proper lifetime for this decay is determined by starting a clock when a muon stops in a plastic scintillator slab, and then stopping it when an electron (the product of the decay) is observed to be emitted in the slab. The observed time intervals for many such decays obey an exponential distribution

$$N(t) = N_0 \exp(-t/\tau_\mu) \qquad (2)$$

where $\tau_\mu \cong 2.2$ μsec is the mean muon lifetime.

B. Background References:

This experiment requires familiarity with each of the following: (Most of the references cited are collected either in this manual, the Muon Lifetime Experiment Manual (MLEM), or in the Advanced Lab Particle Counting Equipment Manual (PCEM).)

1) Basic knowledge of the physics of the weak decay, for background and motivation. (E.g. the Physics 5D Lecture Notes, "Fundamental Particles", in MLEM; or Weisskopf, *Knowledge and Wonder*)

2) Production of muons in the atmosphere from cosmic rays, and in particular, the muon spectrum at sea level. This will help you make estimates of expected count rates during various phases of the experiment. (See the chapter "Cosmic Rays in the Atmosphere and at Sea Level"; the brief report "Cosmic Radiation (CR)"; or the chapter "Cosmic Rays at Sea Level", all in MLEM.)

3) The loss of energy of fast charged particles when interacting with matter, due to collisions with atomic electrons (the Bethe-Bloch equation). This is needed to understand the electronic signals which are output from the scintillator slabs following detection of a muon. (See the chapter "Passage of Radiation through Matter" in MLEM; other good sources are Chapter 5 in *Experiments in Modern Physics*, by AC Melissinos; Fermi's Nuclear Physics notes; or Segre's *Nuclei and Particles*) Some understanding of other mechanisms of energy loss, such as Bremsstrahlung and Cerenkov radiation for electrons, and the photoelectric effect, Compton scattering and pair production for photons, would also be useful.

4) Nuclear Counting Instrumentation and Electronics
(General Reference: R.C. Fenrow, *Introduction to Experimental Particle Physics*)

a) Properties of Scintillation Detectors (See the tutorial "Experimental Nuclear Physics" in MLEM; the chapter "Scintillation Phosphors" in PCEM; and section 5.4 of Melissinos)

b) Response of Photomultiplier Tubes (PMT's) (See the article "Photomultiplier Tubes for Use in High Energy Physics" in PCEM; section 5.3 of Melissinos gives useful background)

c) Time delay and reflections in coaxial cables. (See section 6.6 "Signal Cables" in the Chapter "Fast Electronics" in MLEM; an excellect source is Experiment 1 "Coaxial Transmission Line" in *The Art of Experimental Physics* by DW Preston and ER Dietz)

d) Use of the oscilloscope for fast pulses. (Use the oscilloscope manual if you have questions on the functioning of the laboratory scope.)

e) Nuclear Counting Electronics: Analogue vs. logic pulses; discriminators; logic units; counters; pulsers; delay generators; time analyzers. (See the tutorial "Experimental Nuclear Physics" and the chapter "Fast Electronics" in MLEM; the Particle Counting Tutorials in PCEM; Melissinos, Chaps. 5 and pp 403-412 will also be useful. Data sheets for the actual electronics modules used in the lab are provided in PCEM.)

C. Experimental Configuration:

At the heart of the experiment is the logic circuit of Fig. 1. Three plastic scintillator slabs are stacked along the vertical direction. When a fast charged particle traverses any slab, the light generated is collected and amplified by a PMT and output to a discriminator, and then to a logic unit. The logic unit output drives a clock, or time analyzer (also called a TAC, or time-to-amplitude converter). The clock is started when a muon stops in slab 2; the logic for this event is $S1 \wedge S2 \wedge S3$, where the signal S3 causes a "veto" Following this, the clock is stopped when an electron is detected in *any* of the three slabs; the logic is $S1 \vee S2 \vee S3$. ($\wedge$ = and; $\vee$ = or) The output of the time analyzer is a pulse whose amplitude is proportional to the time interval between the start and the stop signals; this output is collected by the pulse height analyzer (PHA) which creates a histogram of the number of counts collected within a fixed small interval about any given delay time. The distribution is related to that of Eq. 2.

D. Procedure:

1) The first step is to familiarize yourself with the output of the photomultipliers by observing them directly on the scope. (Indeed, you will need to use the scope frequently throughout the setup procedure, to establish the nature of the signal at various stages of the experiment and/or circuit. Hence, you need to be familiar with the workings of the scope early on.) Obtain an understanding of the signal arising from a typical muon traversing the scintillator, i.e. determine the typical amplitude, rise time and decay time; and obtain some idea of the signals arising from noise (i.e. electrons produced in the PMT that do not arise from incident photons). Vary the trigger level to obtain some sense of the distribution of magnitudes of the pulses, and the relative magnitudes of true signals and noise. [Q: What is the appropriate input impedance to the scope, 50Ω or $1M\Omega$? What happens if you choose the wrong input impedance, and why?] [Note: Learn how to use the connectors on the coaxial cables. Do not remove the Lemo cables by yanking; but rather, release the catch by pulling back on the sleeve before removing the cable.] You can gain a sense of the leaks due to room lights by triggering the scope on line voltage, i.e. at the same 60cps as the room lights.

2) To perform step 1) you will need to explore the role of the high voltage HV applied to the PMT. How does the gain, or number of pulses triggered, increase as HV increases? How is the noise affected? [Note: Most PMT's are designed to operate in the range 1000-2000V. Don't use higher voltages as this can decrease the lifetime of the PMT, and even destroy it. Use of an amplifier between the PMT's and the discriminators can reduce the HV required for optimal counting of muons.]

3) The next step is to find the right combination of discriminator threshold V_T and PMT voltage HV. Note that the two are coupled: increasing V_T at fixed HV is equivalent to decreasing HV at fixed V_T. Given the 2000V restriction on HV, it makes sense to set V_T initially as low as possible, and vary only HV. (The value $10V_T$ can be read at the front panel of each discriminator.) Later you may wish to set different values for V_T. At this stage, explore the response of each tube i (i=1,2,3) to HVi. Use the Counter/Timer (Scaler) to measure the counts Si. A plateau in Si vs HVi (Fig. 2) indicates high efficiency for counting incoming muons; counts above the plateau at higher HV are due to PMT noise. [Q: Given that the the scintillator has an area 2'x4', how many counts per second do you observe at the plateau? How many do you expect, given the known sea level spectrum of muons? Note also for future reference the magnitude of fluctuations in Si for a given count period; do these obey Poisson

statistics?] [Note: The PMT's have a finite warmup time and the gain is not necessarily reproducible after turning them off and then on again. After you have established the settings HVi, leave the PMT's on for the duration of the experiment.]

4) Timing: Prior to studying the coincidences you need to consider several aspects of the timing of pulses.

a) The output pulse of a discriminator has a fixed amplitude, however the width is adjustable. Given the input pulse width determined in part 1, what is an appropriate output width? What would happen to the coincidence rate Si∧Sj if you made the pulses too short? Too long?

b) You will also want to adjust the width of S3 differently than S1 and S2 so that the veto occurs independently of the jitter between S1 and S2. Determine this jitter on the scope. What is an appropriate value to choose for the width of S3? What is the origin of this jitter?

c) Finally, it is possible that the counting electronics introduces different time delays for S1, S2 and S3. Examine these delays on the scope. You can account for them by measuring a delay curve (Fig. 3) adding together different lengths of cable to achieve different delays. (Do this after learning to count coincidences. What delay results from one foot of cable?)

5) Coincidence Efficiency: To obtain maximum efficiency for counting coincidences, e.g. $S1\wedge S2$, use the circuit of Fig. 4. Hold one high voltage, e.g. HV2, fixed at a reasonable value, and vary the other, e.g. HV1. The scalar allows you to simultaneously measure $S1\wedge S2$ and one other count rate, either S1 or S2. This allows you to normalize coincidences in one of the two ways shown in Fig. 5. Why does the curve $(S1\wedge S2)/S1$ vs. HV1 decrease at the same voltage that the curve $(S1\wedge S2)/S2$ vs. HV1 shows a plateau? Find the optimal settings of HV1, HV2 and HV3 for counting coincidences. Be prepared to defend your choice of settings.

6) Valid starts: Having performed steps 3 and 4, and step 5 for various combinations ($S1\wedge S2$ vs. HV1 and HV2; $S1\wedge S3$ ...) you should have a good idea of which combination of high voltages, thresholds and delays gives maximum efficiency for counting true events of incoming muons. As a final step, you might explore the effect of these settings on the start signals $S1\wedge S2\wedge S3$. How many true starts do you observe per second? Given the expected energy spectrum of incoming muons and the specific energy loss (dE/dx) in the plastic, what value do you expect? Can you think of ways to maximize valid (and minimize inavalid) starts and stops through appropriate discriminator settings?

7) Delay of starts relative stops: Why must a delay cable be inserted, as in Fig. 1, in the start circuit between the logic unit and the time analyzer? What will happen if the start signal is not delayed somewhat relative the stop signal? What is the appropriate magnitude to choose for this delay?

8) Calibrating the time base: The PHA gives counts per channel number. The channels can be calibrated in microseconds using the circuit of Fig. 6 and the procedure described in the software manual for the PCA-II card. As a first step, familiarize yourself with the interactive software. (See the Nucleus Personal Computer Analyzer (PCA-II) manual.) Measure the true time delays obtained from the circuit of Fig. 6 on the scope, as there are additional delays due to instrumentation. (Be sure to include the delay τ_D inserted in step 7.) Then perform the calibration, and be sure to save the calibration file as you will need it again when you transfer data to a second computer for data analysis. [Note: Turn off the pulser; do not leave it on overnight!]

9) Data Collection: You are now ready to begin data collection. As data collects, compare it to your estimation of the number of counts you should be receiving in each channel as a function of collection time. How long will you have to collect data to obtain a given level of accuracy (e.g. ±10% for the channels at small times)? (Q: Do you see a spike, or large peak, at short times? If so, what is this due to, and how might it be eliminated?)

10) Analysis: Transfer your data to a computer with software for performing least square fits. (At present the Physics Department Computer Lab has the program SigmaPlot which contains statistical analysis software.) You can make initial estimates of the fit parameters by plotting the log of the count rate vs. time. How is the mean muon lifetime related to the average number of counts? Note that there can be additional background counts, over and above those predicted by Eq. 2; how do these arise? Include these as a parameter in the fit. Think carefully about how to determine the error in τ_μ. Determine χ^2 and the significance of the fit.

11) Final Comments:

a) A certain fraction of muons that stop in the slab do not decay, as in Eq. 1, but are captured by nuclei. Learn about the reaction which occurs, and determine its signature (or lack thereof) in your detector. Use the literature to estimate the rate for these events. How does it affect your estimate of the muon decay lifetime? (This latter point requires careful thought.)

b) You can use the same apparatus, with a different circuit than that of Fig. 1, to measure the vertical cosmic ray flux of muons inside the laboratory. To do this you will have to account for the effective solid angle subtended by the slabs. How does the value compare to the standard value; if it differs can you understand why, and estimate the expected difference? What are the relative roles of hard and soft cosmic rays in this measurement?

c) How would the experiment have to be altered to measure the energy spectrum of incoming muons? To measure the energy spectrum of the outgoing electrons in muon decay?