MUON EXPERIMENT

Phys 2010 – Brown University – March 13, 2009

Purpose

The purpose of this experiment is to determine the mean lifetime of the muon. A muon is a weakly interacting particle similar to an electron but differing in lepton number and mass (roughly 207 times as massive).

Introduction

There are three fundamental forces in particle physics: the strong force, which holds nuclei together; the electromagnetic force, which holds atoms together; and the weak force, which is responsible for two seemingly unrelated phenomena, beta decay and supernovas. The fourth force, gravity, is so weak that it can be neglected for particles with small rest energies.

Before quarks were understood to be the fundamental units of matter, particles were classified into four groups based on how they interact and on their spin. These four groupings are photon, lepton, meson and baryon. Quarks, leptons, and force mediating particles such as gluons and photons are now understood to be more fundamental, yet the four group classification remains an important way of grouping subatomic particles.

The photon forms a class of its own. It is a boson, that is, it has integral spin and does not obey the Pauli exclusion principle. It interacts electromagnetically, strongly, and weakly.

Massive particles that interact strongly, weakly, and electromagnetically (when charged) are called hadrons. Hadrons with integral spin are called mesons and are composed of two quarks; those with half-integral spin are baryons and are composed of three quarks. The proton and neutron are two famous baryons, the pion is a meson. Four and five quark combinations have been predicted, but experimental evidence remains inconclusive.

The final group of particles, leptons, contains such particles as the electron, muon, and neutrinos. All leptons are fermions, that is, they have half-integral spin. They interact weakly, electromagnetically when charged, but do not interact strongly. Evidence of the muon's existence was discovered in 1934 by Anderson and Neddermeyer while studying cosmic rays. For historical reasons, muons were called "μ-mesons" until the 1960's when the definition of the word "meson" was made more specific.

Muon decay

In this experiment we will investigate muon decay that takes place according to the following reactions:

$$\mu^+ \to e^+ + \overline{\nu}_\mu + \nu_e$$
$$\mu^- \to e^- + \nu_\mu + \overline{\nu}_e \qquad (1)$$

All subatomic particles are characterized by a constant probability of decay per unit time. This probability is an intrinsic property of a particle and, like the particle's mass or spin, helps identify the particle. It is standard to denote the decay per unit time as λ. Now we consider some of the statistical aspects of particle decay.

First consider a sample of N(t) muons at time t. The infinitesimal change in the number of muons in a time dt is given by:

$$dN = N(t+dt) - N(t) = -N(t)\lambda dt \qquad (2)$$

The last equality follows from considering the definition of λ while the minus sign comes from the fact that dN must be negative if muons are decaying. From this differential relation we have

$$\frac{dN(t)}{dt} = -N(t)\lambda \qquad (3)$$

$$N(t) = N_0 e^{-\lambda t} \qquad (4)$$

N_0 is a constant, which we interpret as the initial number of muons by requiring as a boundary condition to our differential equation $N(t=0) = N_0$.

Another important statistical concept for this experiment is the probability density function P(t). P(t) has the following property: P(t)dt is the probability that a muon <u>will not</u> decay for a time t after its creation or capture in the scintillator, but <u>will</u> decay within the interval dt after t. That is P(t)dt = (probability of non-decay from 0 to t) × (probability of decay from t to t + dt).

To find an expression for P(t), first we divide the time interval t into n discrete subintervals. The probability that a muon will decay in one subinterval is approximately λt/n, so the probability that the muon will not decay in this subinterval is (1 - λ t/n). Thus the probability that a muon will not decay within n subintervals is $(1 - \lambda\, t/n)^n$ and the probably that the muon will decay from t to t+dt is λdt . Thus

$$P(t)dt = \lambda(1 - \frac{\lambda t}{n})^n dt \qquad (5)$$

In this calculation, the muon only "considers" decaying n times before time t. In reality, it could decay at any time. Thus we should take the continuous limit

$$P(t)dt = \lim_{n\to\infty} \lambda(1 - \frac{\lambda t}{n})^n dt \qquad (6)$$

Noting that

$$\lim_{n\to\infty}(1+\frac{1}{n})^n = e \tag{7}$$

we obtain

$$P(t)dt = \lambda e^{-\lambda t}dt \tag{8}$$

Since the muon must decay, P(t) satisfies the normalization condition below, which can be checked.

$$\int_0^\infty P(t)dt = 1 \tag{9}$$

Muon lifetime, τ_0, is defined as $\tau_0 = 1/\lambda$. The current world average puts the muon lifetime at $\tau_0 = 2.19$ us.

Equipment

The following equipment is used in the muon decay experiment:

- High Voltage Supply Northeastern RE2003
- Discriminators, LeCroy Model 821
- Logic Circuits, Coincidence and Anti coincidence, LeCroy 364AL or 365AL
- TAC (or TPHC) Time to Amplitude Converter Ortec Model 467
- Computer controlled MCA, Ortec Model ACE4-BI, Version 4.06
- Amplifier - Ortec 485
- Scaler - Ortec 484
- Gate Generator, LeCroy Model 222
- Function Generator, Hewlett Packard Model 3310A (For calibration purposes.)

Note: All unused yellow outputs of TAC and MCA should be terminated in 50Ω (crimp style BNC connectors with yellow tips are 50Ω terminators). Also inputs to MCA and/or oscilloscope should be matched to 50Ω. This technique is called impedance matching, and is necessary for proper signal transmission.

Experiment

Important note: Parts of this experiment requires long running times so start early. In order to avoid wasting time, the data taking must be monitored. Looking at the MCA display is not sufficient for this: At least once every 24 hours you should save and print out the data. Make a semilogarithmic plot of at least a sampling of the data to be sure you are observing an exponential distribution with a reasonable slope. This monitoring is part of your experimental record and each partner should carry it out.

Scintillator, Photomultiplier Tube, and Discriminator

The setup for the basic experiment is shown in Fig. 1. Many cosmic ray muons pass through the main scintillator per minute, and a fraction of them, having lost sufficient energy, will come to rest in the scintillator and will soon decay. Both the muon arrival and the electron produced in the decay of the muon will give rise to the emission of photons in the plastic material of the scintillator. Because of the low intensity of the emitted photons, a photomultiplier tube (PMT) is used to amplify the signal and convert it to a detectable electric pulse. Naturally, the scintillator-PMT combination must be free from any light leaks. (See Melissinos for a discussion of a scintillation counter). A PMT signal will cause square pulse from the LeCroy Quad Discriminator if the PMT signal passes the discriminator threshold voltage you have set.

Determining Discriminator Thresholds

One can view the PMT signals by connecting the coaxial output from the PMT to an oscilloscope (remember to impedance match). You will notice some pulses have large amplitudes, indicating what is most likely a muon event. However, others will have much smaller amplitudes and could either be a real muon event or noise. One of your tasks will be to set a reasonable value on the discriminator threshold, which must be chosen to distinguish between noise and muon events. The trigger setting on the scope can be used to simulate the effect of setting a threshold. Be careful, setting this value too high will make it impossible to collect enough data in a reasonable amount of time. Note that good threshold values will depend on the applied PMT voltage. Best results are found with a PMT voltage of about 1 kV. DO NOT APPLY MORE THAN 1.1 KV TO THE PMT'S. To assure this, remember to turn the power supply voltage knob slowly when approaching this value.

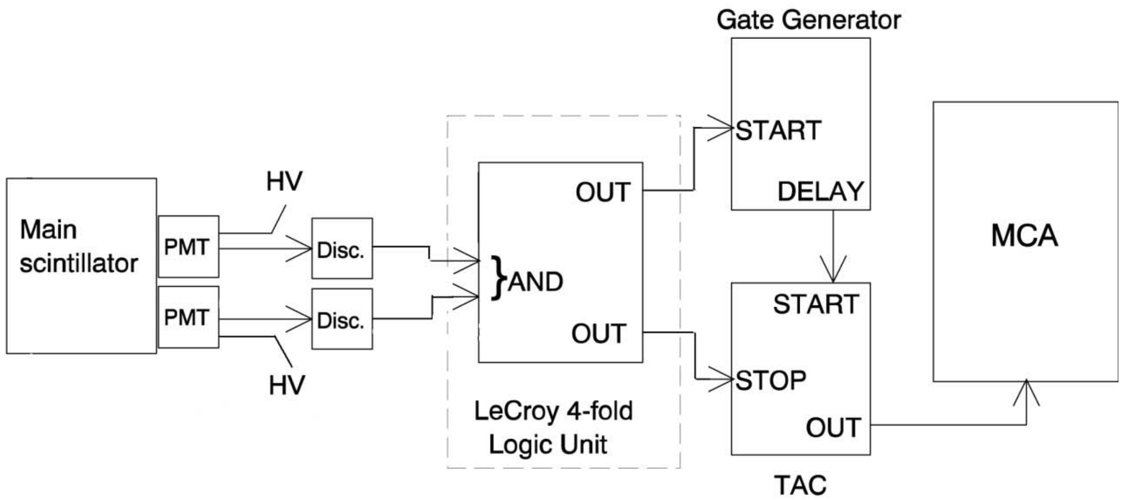

Figure 1. Experimental setup.

Signal Path from Discriminator to MCA

Consider a muon which stops in the Scintillator. Output from the discriminator initiates both a START and STOP pulse. STOP goes directly to the Time to Amplitude Converter (TAC), the START is delayed before going to the START input of the TAC. The STOP has no effect as it arrives before START (delaying the START input assures this). The TAC, which is something of a fancy stopwatch, begins counting on the START command. A muon decay will produce a second signal within a time interval of a few mean lives. Again, both a STOP and START pulse will be generated. The STOP pulse tells the TAC to stop counting. A time interval between the START (muon arrival) and STOP (muon decay) commands is computed by the TAC, which outputs a signal to the Multi-Channel Analyzer (MCA) located in back of the computer. The amplitude of the TAC signal is proportional to the time difference. The width of the TAC output is variable but should be kept near a minimum to obtain a clean signal to the MCA.

Creating Delays with the Gate Generator

To generate a time delayed START pulse, one could use a sufficiently long cable (for rg58/u cable the delay is approximately 5 nsec/meter), or “delay boxes” provided for in the lab. Good results are produced when the LeCroy 222 Dual Gate Generator is used as shown in Fig. 2. Here the Gate Generator is used simply to introduce a delay.

To determine the length of the delay the oscilloscope must be used since the gate generator is not calibrated. The delay is measured on the scope trace simply by triggering the scope on the prompt STOP pulse from the discriminator while observing the delayed START pulse.

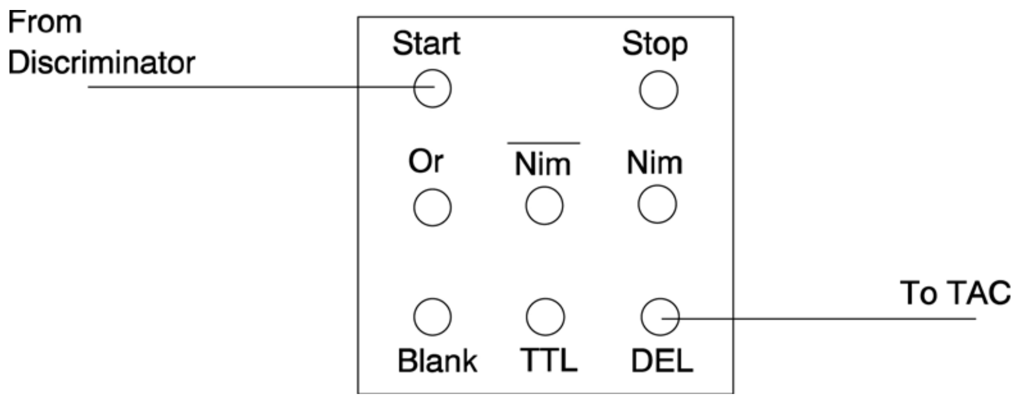

Figure 2. LeCroy Gate Generator used to delay START pulse.

Using Maestro

Maestro has been installed on the lab's computers. This program can be used to process and analyze data from the TAC. If there is old data being displayed, you can clear the buffer by right clicking on the canvas and selecting clear. Connect the TAC output to the MCA card located in the back of the computer. Pulses from the TAC are now counted by Maestro. Each pulse will increase the appropriate bin count by one. Correspondence between bin location and pulse amplitude (muon lifetime) is achieved through calibration.

Bin Calibration in Maestro

For calibration one must use the Gate Generator. However, for this purpose the STOP pulse is delayed relative to the START pulse. The rest of the setup remains the same as for the basic experiment. Thus each pulse in the main scintillator will result in output of the TAC, which is fed into the MCA. The height of this pulse, hence the MCA channel in which the pulse appears, is proportional to the time delay between the START and STOP pulse. The delay must be measured using the oscilloscope since the Gate Generator is uncalibrated.

Having chosen a time delay setting, each event in the main scintillator will generate the same delay between START and STOP pulses and thus. In Maestro this corresponds to some bin “filling-up.” Using the mouse and left and right arrows, select this bin. From the menu go to Calculate and select calibrate. If there is already a calibration select destroy calibration. Assign a time to this channel based on your reading from the oscilloscope. By using several settings of the time delay, the relation between MCA channel number and time is determined.

Note that you are using all the muons passing through the main scintillator, whether they decay or not. The rate is sufficient to calibrate the MCA. Since the rate of decaying muons is very small compared to the total number of muons passing through, it is a good idea to check out the detector using the total flux before connecting the circuit for the decay time measurement.

Coincidence/Anti-coincidence (allow ~2 weeks for data)

If two muons, both passing through the main scintillator, arrive close enough in time they will be counted as a muon decay. To lower the coincidental background rate the following coincidence/anti-coincidence setup is used (see Fig. 3). We wish to consider a setup which efficiently discriminates between coincidence and anti-coincidence muons without reducing the counting rate excessively.

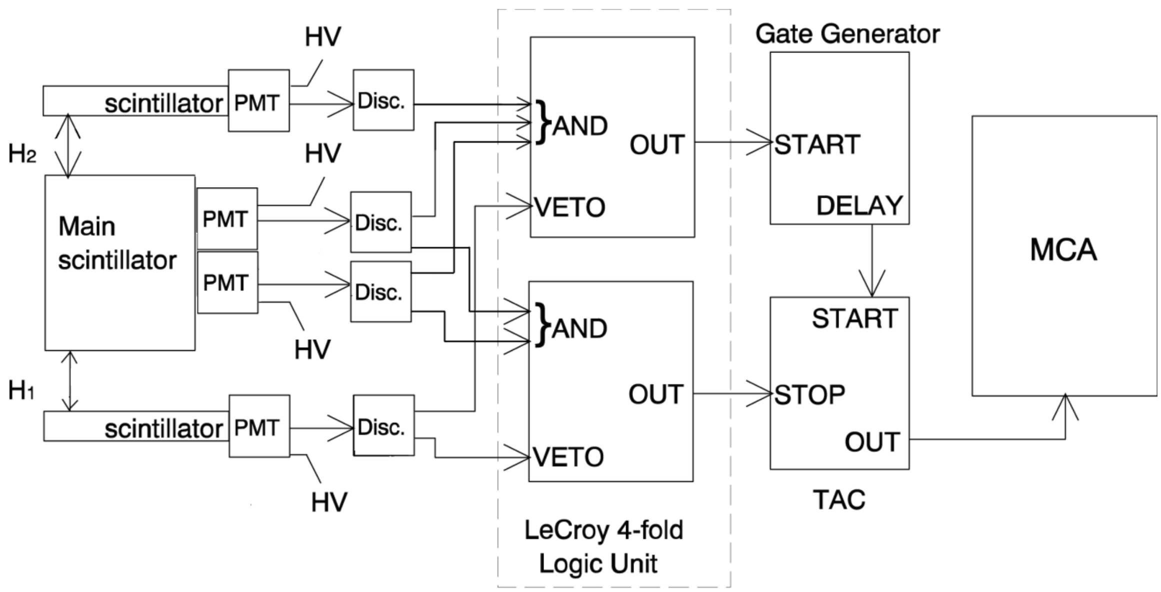

Figure 3. Alternative setup with coincidence and anticoincidence requirements.

A second power supply is used so that the count rates of the top and bottom scintillators are approximately the same (with the same discriminator threshold voltage). Again, the delay is done with the Gate Generator.

With this setup a START pulse is generated when a coincidence signal is seen in the top and main scintillator, and is not vetoed by the bottom scintillator. This signifies that a particle has traversed the top and main scintillators, and has not continued into the bottom scintillator. Most of these particles have stopped in the main scintillator. A STOP pulse is produced when a "decay" signal comes from the main scintillator alone and is not vetoed by the bottom scintillator.

The width of the pulse from the small counter discriminators should be longer than the pulse from the main discriminator and should overlap insure proper coincidence and vetoing (figure 4). Note that the listed times are not necessarily optimal.

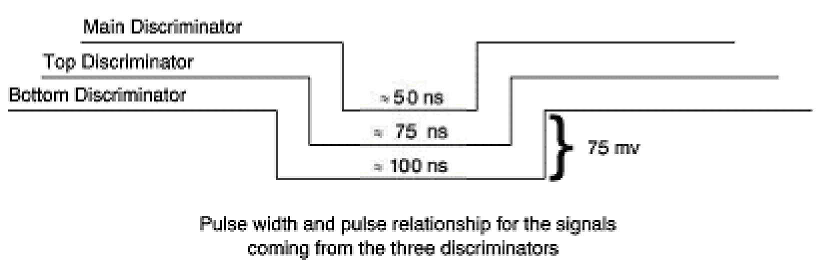

Figure 4. Timing information for the coincidence/anti-coincidence setup.

Data Analysis

Your MCA output should look something like figure 5. From a semilogarithmic plot of the number of decays versus channel number the mean lifetime of the muon is calculated. In practice, the number of decays in a group of about 50 channels versus time is plotted, in order to ensure that each point on the plot has a reasonable statistical weight.

One could use the method of least squares to determine the slope of both the time calibration and the semilogarithmic plots, as described in Bevington. One could also fit known functions to the data, thus determining the lifetime. For the determination of τ_0, statistically weighted figures should be used.

Printing From Maestro

You may be tempted to print directly from Maestro. This would be a bad idea! Maestro will print out the raw data (channel number, counts, etc.). To print out a data plot as seen in Maestro follow these steps: Save your Maestro data file. Open WinPlots, which is located on the lab's computers. From the menu go to file and select recall spectrum and open your file. WinPlot will generate a data plot which you can save or printout.

Questions

1. Give a brief summary of how a scintillator counter and a photomultiplier work.
2. How does a delayed START pulse affect your data? What factors go into choosing your delay time? Explain why, if the START pulse due to the arrival of the muon is delayed by 1 microsecond, one does not measure the mean lifetime of the muon to be 1.2 microseconds (since the STOP signal from the decay of the muon is not delayed).
3. Calculate the error in your determination of the mean lifetime of the muon. (Use method in Bevington.)
4. What is the flux of cosmic muons at sea level?
5. Measure the average rate of output pulses from the main scintillator. Assuming random distribution in time, calculate the expected number of coincidences per hour (i.e., the number of apparent decay electrons which are really just additional mesons passing through the scintillator within the accepted interval). Make the necessary measurements to allow you to estimate the fraction of the background, which you have eliminated by using the coincidence/anti-coincidence setup. Discuss why you lose background counts when switching to the coincidence/anti-coincidence setup.

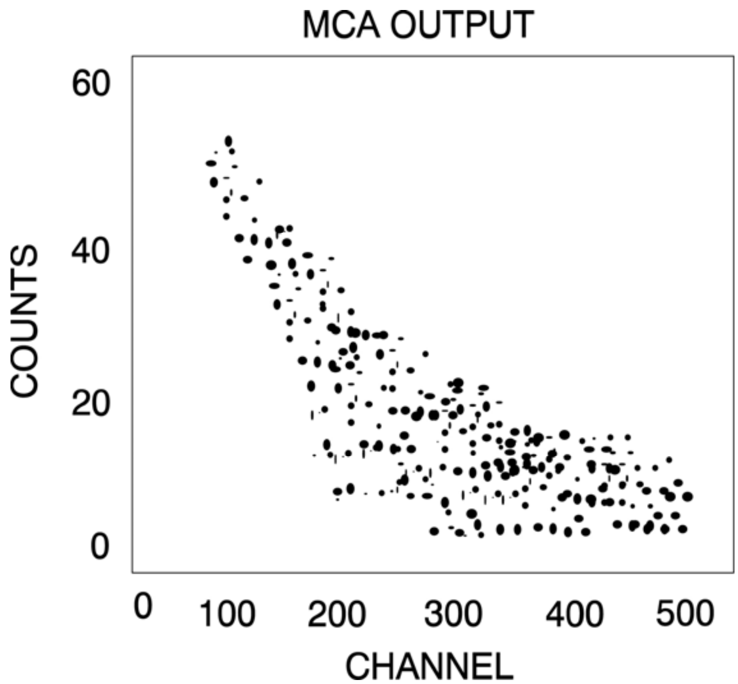

Figure 5. Typical MCA output.

References

1. Arya, *Elementary Modern Physics.*
2. Bevington, *Data Reduction & Error Analysis for the Physical Sciences.*
3. Frisch and Smith, *Measurement of Relativistic Time Dilation Using Mu Mesons,* Am. J. Phys. 31, 342.
4. A. Melissinos, *Experiments in Modern Physics,* Academic Press (1966).
5. A. Das and T. Ferbel, *Introduction to Nuclear and Particle Physics*, World Scientific 2003.