Muon Decay

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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).

Note: This experiment requires long data collection times so start early. Also, this manual is not intended to be all inclusive. You are expected to reference the equipment manuals and technical resources provided in the lab, on the lab wiki, etc. You may not consult with students who have done this lab before or refer to their write-ups.

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 and *do* obey the Pauli exclusion principle. 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.

Theory

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

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

The first reaction is antimuon (μ^+) decay, which generates a positron (e^+), muon antineutrino ($\bar{\nu}_\mu$) and electron neutrino (ν_e). The second reaction, of our interest, is muon (μ^-) decay, which generates an electron (e^-), muon neutrino (ν_μ) and electron antineutrino ($\bar{\nu}_e$).

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 $\lambda t/n$, so the probability that the muon will not decay in this subinterval is $(1 - \lambda\, t/n)$. 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

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

we obtain

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

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

$$\int_0^\infty P(t)dt = 1 \qquad (9)$$

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

- Oscilloscope - Tektronix DPO 2012
- High Voltage Power Supply - Canberra 3102D
- Constant Fraction Discriminator – Canberra 2126
- 4-Fold Logic Unit - LeCroy 364AL or 365AL
- Dual Gate Generator - LeCroy 222
- TAC/SCA – Canberra 2145
- Computer w/ MCA card - Dell Computer w/ Ortec TRUMP-PCI card

The Experiment

You are to setup and take data for the Basic setup and the Alternative setup. If configured correctly the Basic setup should yield at least 5000 counts in 24 hrs. and the Alternate setup should yield at least 2000 counts in 24 hrs. Allow 3 days for data collection with the Basic setup and 7 days for the Alternative setup. Compare the results from these two setups in your write-up.

Note: We do occasionally have power outages and computers do crash so, to avoid losing data and time, save your data 2 or 3 times a day. Also, after collecting data for the first 12-24 hrs, inspect it and make sure it looks reasonable.

Equipment and Experiment Details

Impedance Matching

Since this experiment measures time on the order of μsecs, impedance matching is very important. Since most of this equipment has an input & output impedance of 50Ω, it may be necessary to use an impedance matcher on the inputs of the scope. However, this will not always be true. Also, using a "T" in the cables impacts the impedance and must be considered when determining the proper matching. Failure to properly match impendences will result in signal distortion.

NIM Bins & Modules

Most of the equipment in this lab is NIM electronics. NIM stands for Nuclear Instrumentation Module and is a mechanical and electrical standard used by experimentalists in particle and nuclear physics. In the equipment rack are two NIM bins, these are standardized power supplies that can power a wide assortment of NIM modules. The modules are inserted in the bin. Each bin has a power switch on its right side. This switch controls the power to the modules in the bin. The upper bin contains pulse shaping, timing and data collecting modules. The lower bin contains 4 HV Power supplies.

High Voltage Power Supply

To power on the HV power supplies, always power the bin on first then turn on the individual power supplies. When powering them down, do the opposite; turn the power supplies off first, then turn off the power to the bin.

When HV is applied to a PMT it must be increased slowly to prevent damaging the PMT or making it unnecessarily noisy. 30 yrs ago this was done by hand but modern NIM HV power supplies are "smart" and ramp the voltage up at the appropriate rate. Due to this feature, the output of the supply responds slowly to rotations of the control knob. This maks it possible to overshoot the desired output voltage. So, when setting the HV near the maximum recommended voltage of 1KV, turn the control knob small amounts and wait for the output voltage to stabilize before proceeding. The good news is, once the desired voltage has been selected it does not need to be readjusted; the power supplies may simply be switched off and on (only by their individual switches) as desired because the automatic feature takes care of the rest.

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). If a PMT signal exceeds the threshold voltage, the discriminator outputs a square pulse.

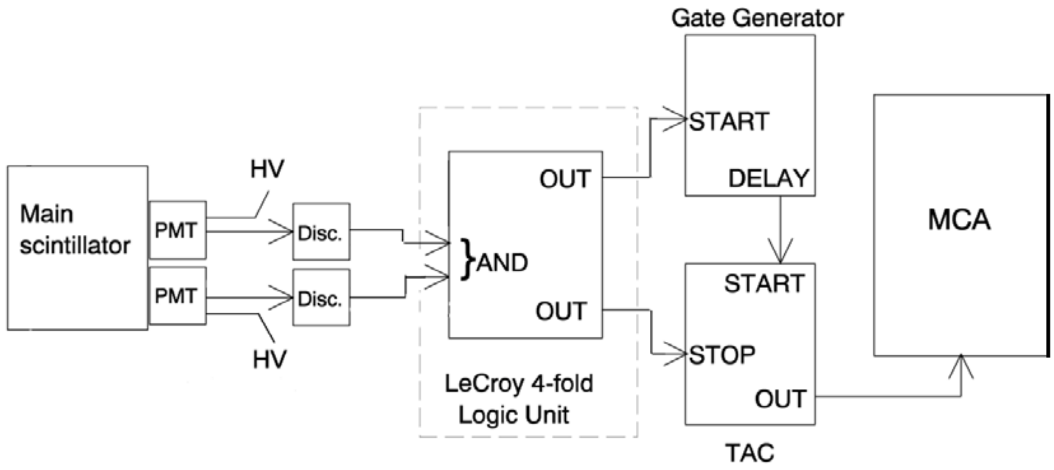

Fig 1) Basic Experimental Setup

Determining Discriminator Thresholds

View the PMT signals by connecting the output from the PMT to an oscilloscope (remember to impedance match). Notice some pulses have large amplitudes - likely muon events, however, others have much smaller amplitudes and could be a muon event but could also be noise. To reduce the noise component you need to set the input signal threshold on the discriminator. This value is to distinguish between noise and muon events. The trigger setting on the scope can be used to simulate the effect of setting the threshold. Note, setting this value too high will significantly lengthen the data collection time while setting it too low will distort your data with noise. The threshold value depends on the HV applied to the PMT. DO NOT APPLY MORE THAN 1.1 kV TO THE PMT'S. Turn the HV control knob slowly when approaching 1kV.

Setting Up Coincidence

Though PMTs are generally quiet devices, they do generate some electrical noise. To keep this and noise from other sources from being recorded as signal, we put two PMTs on the main scintillator. We compare the coincidence of their outputs and if they occur within a small tolerance of time, the Logic Unit outputs a square wave. You will determine and set this tolerance (time).

Starting and Stopping the TAC

From the Logic Unit the signal goes to the TAC. But the TAC needs a Start pulse and a Stop pulse but we only have one pulse at a time and we do not know which pulse is which? Notice in Fig 1) that a pulse from the Logic Unit goes straight into the Stop input of the TAC. A different but identical and simultaneous pulse from the Logic Unit goes into the Gate Generator where it is delayed. From there this delayed pulse goes to the Start input of the TAC. So, for every pulse that comes from the Logic Unit a direct pulse goes into the Stop port of the TAC and a delayed pulse goes into the Start port. Here is the cleverness of this arrangement, when a muon enters the scintillator a pulse stops the TAC and resets it making it to take a new measurement. A short time later, determined by the delay setting, a pulse starts the TAC - which is just a fancy stopwatch. If the muon decays a second pulse stops the TAC and if all is set correctly the TAC sends a pulse - with a time depended height - to the MCA where it is recorded. Of course there is another Start pulse sent to the TAC but since it is unlikely there will be a stop pulse within the set time window, nothing of merit happens.

Creating Delays with the Gate Generator

To generate a time delayed Start pulse, one could use a sufficiently long cable (rg58/u has a delay of ~5 nsec/meter) however, we will use the LeCroy 222 Dual Gate Generator see Fig 2). To set the delay time an oscilloscope will be used. Set the scope to trigger on a direct pulse out of the Logic Unit. Connect the Delay output of the Gate to the other channel of the scope. There should be two similar signals on the scope with a small time shift between them. Use the "Full Scale Width" knob and the small adjustment screw under the knob to set the desired delay time. Remember to consider impedance matching.

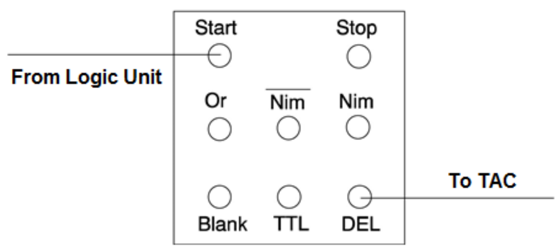

Fig 2) LeCroy Gate Generator Used to Delay the Start pulse.

Using the MCA (Maestro& the TRUMP-PCI Card)

The MCA is composed of the Maestro program and the TRUMP-PCI card. Cables are plugged into the card at the back of the computer and the software interfaces with the card to collect data and do data analysis. The user's manual is on the lab wiki: https://wiki.brown.edu/confluence/download/attachments/29406/MAESTRO+V6+User+Manual.pdf?version=1&modificationDate=1380592747664 Before the data from the MCA can be trusted, it must be calibrated.

MCA Bin Calibration

To calibrate the MCA we will use the Gate Generator and the TAC however, in this cases we will reverse the configuration of the direct and delayed pulses. The direct pulse will go to the Start input and the delayed pulse will go to the Stop input. This way, every pulse entering the scintillator will generate an output pulse from the TAC and all of the pulses will have the same width; the delay between the pulses as measured on the scope and set with the Gate Generator. This will generate a column on the MCA that identifies the bin associated with that time interval. Before calibrating you need to determine the longest time interval you want to record on the MCA and set the "Time Range" on the TAC accordingly. The "Time Range" sets the maximum time the TAC will measure before timing out and also sets the voltage per time scaling of the TAC.

Once a column appears on the MCA, enter the delay measured on the scope and enter this time difference in Maestro's calibration routine – see the Maestro manual. Do a minimum of 3 different pulse widths, one near the shortest time, one in the middle and one near the longest time. Doing but more calibration points is better. It is good practice to record your time vs bin information in case something happens and the calibration in Maestro fails. This way you can calibrate the raw data after the fact if needed.

Note: In this configuration, all muons passing through the main scintillator are being recorded. Since the rate of decaying muons is very small compared to the total number of muons passing through the scintillator, this is a good opportunity to check out the detectors etc. buy measuring the total muon flux.

Reducing Coincidental Background

In the Basic configuration, it is possible for two muons to enter the main scintillator close enough in time that they would be counted as a decayed muon. The Alternative setup shown in Fig 3) uses two additional scintillators and a combination of coincidence/anti-coincidence configurations to significantly reduce this coincidental background rate without excessively reducing the overall counting rate.

In this setup a Start pulse is generated when the pulses from the top and two main PMTs are coincidence and a pulse from the bottom PMT is not coincidence. This signifies that a particle has passed through the top scintillator, entered the main but not passed through to the bottom scintillator. Most of these particles have stopped in the main scintillator.

A Stop pulse is produced when a second pulse (the "decay" signal) comes from both of the main scintillator PMTs but not from the bottom.

The count rates of the top and bottom PMTs should be set approximately the same and they should have the same discriminator threshold.

The pulse width of the top and bottom discriminators should be longer than the pulse width of the main discriminator and should overlap to insure proper coincidence and vetoing – see Fig 4). Note that the listed times are not necessarily optimal.

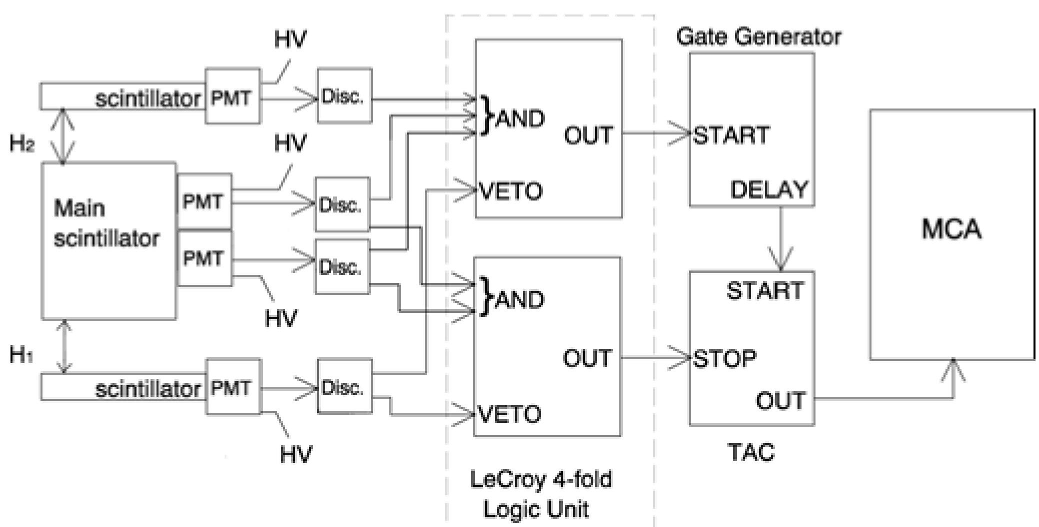

Fig 3) Alternative setup with coincidence and anticoincidence configurations.

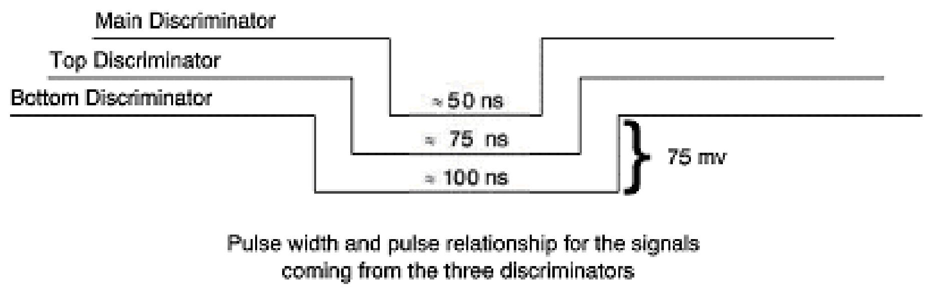

Fig 4) Timing Information for the Coincidence/Anti-coincidence Setup.

Data Analysis

Your MCA output should look something like Fig 5). Calculate the mean lifetime of the muon using a semi-log plot of decays versus channel number. 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.

Use least squares to determine the slope of both the time calibration and the semi-log plots, as described in Bevington. Also, fit known functions to the data to determine the lifetime. For the determination of τ_0, statistically weighted figures should be used.

Printing from Maestro

Do not print directly from Maestro, you will get pages and pages of numbers in a column. To print out a data plot, save your data and close the window. Then open WinPlot and recall the spectrum. From here you can print the plot.

Printing to a file in Maestro may provide you with a useful data format.

Questions

1. Give a brief summary of how a scintillator and a photomultiplier work.
2. What factors go into choosing the delay time? How does this delay time affect your data?
3. If the Start pulse generated by the arrival of a muon is delayed by 1 μsec and the Stop pulse from the associated decay is not delayed, why isn't the mean lifetime of the muon measured to be 1.2 μsecs in this setup?
4. Calculate the error in your determination of the mean lifetime of the muon. (Use the method in Bevington.)
5. What is the flux of cosmic muons at sea level?
6. Measure the average rate of pulses from the main scintillator. Assuming a random time distribution, calculate the expected number of muon pairs that will enter the scintillator close enough time to be falsely measured as a decay.
7. Make the required measurements and estimate the fraction of the background that was eliminated by using the coincidence/anti-coincidence setup. Discuss why the coincidence/anti-coincidence setup reduces background counts.

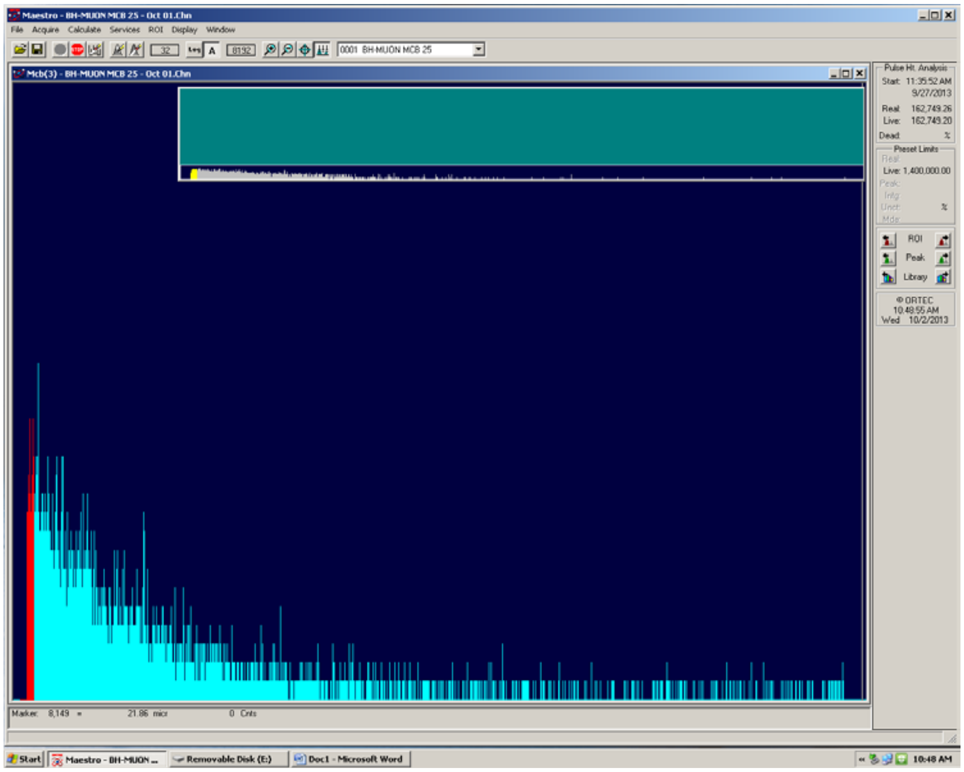

Fig 5) Typical MCA Output.

References

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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.