Muon Detection and Lifetime Measurement

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Purpose

Introduce the student to some of the basic techniques and approaches used in nuclear and particle physics.

Preface

In this experiment, you will measure the mean-life of the muon using typical particle detection and discrimination techniques. The mean life of the muon is directly related to the fundamental strength of the Weak Nuclear Force, one of the four fundamental forces in nature.

Important Concepts

- pion and muon decay
- Fermi coupling constant
- photomultiplier tubes
- identification/reconstruction of particle physics events
- coincidence counting

Related Experiments

- Detections of particle decay products
- Exploration of Muon and Weak Force physics
- Confirmation of time dilation (i.e. Rossi and Hall)

Introduction

The muon is an elementary particle indistinguishable from the electron except that its mass is ~ 200 times greater. Muons are produced primarily from the decays of charged pions, $\pi^{\pm}$, which are themselves produced (copiously) in extensive air showers caused by cosmic rays. Primary cosmic rays cover the spectrum from protons to intermediate mass nuclei (i.e. with atomic weights less than or equal to iron). The primary cosmic rays interact with nuclei in the atmosphere creating large numbers of charged and neutral π mesons. These subsequently interact or decay. Depending on the energy of the initial cosmic ray, millions or billions of secondary particles can be produced. This is called an extensive air shower.

Generally, the neutral mesons, π^o, decay before interacting. Depending on their energy, the charged pions may interact with nuclei in the atmosphere or may decay, $\pi^\pm \rightarrow \mu^\pm + \nu$, to charged muons and neutrinos. To understand this behavior, look up the lifetimes, τ_π, and masses, m_π, of charged and neutral pions. The average distance they travel (before decaying) depends on their energy, E_π, and is given by:

$$Distance \sim (E_\pi / m_\pi c^2)\, c\, \tau_\pi$$

where c is the speed of light. What are typical distances if $E_\pi = 10^9$ eV or if $E_\pi = 10^{10}$ eV? If this distance is large then it is likely the π interacts before it decays.

Unlike pions, muons do not interact strongly. Thus to first order they will decay before they interact. The distance a *typical* $E_\mu = 10^9 - 10^{10}$ eV muon travels is thus:

$$Distance = (10^9 \sim 10^{10}\ [eV])/(105.7\ [MeV])(3 \times 10^8\ [m/s])(2.197 \times 10^{-6}\ [s]) =$$

$$6.24 \sim 62.4\ [km],$$

where the muon mass $m_\mu = 105.7$ MeV. This distance is sufficiently great that many muons reach the earth surface. In fact, at the earth's surface muons are the dominant component of secondary particles from cosmic ray showers. Most of the muons are of modest energy by the time they reach ground level. Thus some will range out (i.e. stop) in a tank of liquid scintillator. The study of the subsequent decay of these stopped muons is the basis of this experiment.

Muons decay via the weak interaction similar to the β-decay of free neutrons and nucleons in nuclei:

$$\mu^\pm \rightarrow \nu_\mu + e^\pm + \nu_e$$

Because neutrinos only interact via the weak nuclear force, muon decay is one of very few natural processes that only involves the weak interaction. The decay rate is actually a measure of the strength of the weak interaction, much like the electronic charge is a measure of the strength of the electromagnetic interaction.

As with nuclear β-decay the energy (E_e) spectrum of the resultant $e^\pm$ is that for a typical three body weak decay:

$$d\Gamma(E_e)/dE_e = (G_F^2/12\pi^3)\, m_\mu^2\, E_e^{\,2}\, (3 - 4\, E_e / m_\mu).$$

where $d\Gamma$ is the muon decay rate. If this is integrated over possible electron energies:

$$\Gamma = 1/\tau_\mu = G_F^2\, m_\mu^5 / 192\pi^3$$

where τ_μ is the muon lifetime and G_F is the Fermi coupling constant. The Fermi coupling constant is the fundamental coupling constant of the charge changing weak interaction. Thus a measurement of the muon lifetime provides a measurement of G_F once the muon mass is known!

A fraction of the muons that reach the earth's surface have just the correct energy to stop in a block or tank of scintillator. As the muons stop they deposit ~ 2 MeV/(gm/cm^2) in the scintillator. Because the density of scintillator is ~1 (gm/cm^3), muons deposit ~ 2 MeV/cm of path length. This is much greater than the ~ 1 MeV/cm of typical γ-rays in Part 1 of this lab. Thus these stopping muons result in a pulse of light (in the scintillator) which is easily detected.

Roughly 5% of the μ^- will be captured into low Bohr orbits and then interact with the nucleus of the scintillator atoms before decaying. Thus the majority of μ^- and virtually all the stopped μ^+ decay before interacting with electrons or nuclei in the scintillator. Each muon decay results in an electron with a energy up to $m_\mu/2$ ~ 53 MeV (i.e. neutrinos are essentially massless). These electrons also can result in a pulse of light (in the scintillator) which is also easily detected.

If one starts a clock each time a muon stops, i.e. this defines $t = 0$, then for a total number of stopped muons, N_{stop}, the number of muons remaining at a time t later is:

$$N(t) = N_{stop}\, exp\, (-t\,/\tau_\mu\,).$$

Note: Clearly this assumes that muons are not lost due to interactions with the scintillator (see comments above). Process other than weak decays that remove muons will result in a low value for τ_μ. *Random accidentals will be flat in time and will result in a high value for* τ_μ, *unless you analyze your data properly.*

The number of muon decays in the time interval from t_1 and t_2 is:

$$\Delta N(t)\ \Big/_{t=<t>} = \Delta N(<t>) = N_{stop}\,(-\Delta t\,/\tau_\mu\,)\,exp\,(-t\,/\tau_\mu\,)\Big/_{t=<t>} = N_{stop}\,(-\Delta t\,/\tau_\mu\,)\,exp\,(-<t>/\tau_\mu\,)$$

where $\Delta t = t_2 - t_1$ and $<t> = (t_2 + t_1)/2$. Thus a histogram of the number of the observed decays, $\Delta N(<t>)$, binned in time bins of width Δt, is predicted to be a simple exponential in $<t>/\tau_\mu$. A semi-log plot of $\Delta N(<t>)$ versus $<t>$ will have a slope -1/τ_μ.

Procedure

The muon decay experiment starts with a large tank of liquid scintillator viewed by two phototubes (PMTs). If one PMT is sufficient to trigger on cosmic ray muons and on the electrons from muon decay, why use two PMTs? The basic setup is shown schematically in Figure 1. As depicted in Figure 1, the difference between a through going muon and a stopped muon followed by a β-decay, is one pulse versus two pulses.

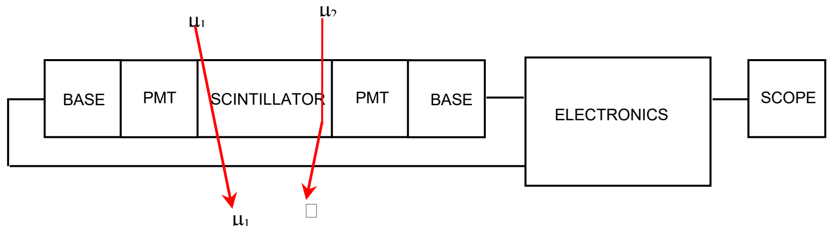


Fig. 1. Schematic setup for muon lifetime experiment. μ_1 passes through the scintillator losing some energy: A single voltage pulse appears on the scope. μ_2 stops in the scintillator and decays after time t to an electron: Two voltage pulses appear on the scope.

You will measure the lifetime of the muon using a dedicated circuit board from QuarkNet as the 'electronics' package shown in Figure 1.

1. PMT Calibration

Photomultiplier tubes (PMTs) require high voltage supplies, and scientists working with them need to take care that the high voltage (HV) lines are properly attached and not showing any signs of damage before the power supply is turned on. The PMTs in this experiment require ***negative*** **HV, and NO MORE NEGATIVE THAN ~ -1500 V** should provide adequate output signals. In practice, you need to adjust the HV for each PMT to get approximately the same output signals. Use an oscilloscope for initial PMT calibration. Typically, the PMT output signals are discriminated with $V_{threshold} > 30$ mV.

PMTs employ multiple stages in order to achieve the gains necessary for the signal to be visible by other instruments. In the first stage, a photoelectron produced at the photocathode strikes the first dynode, which produces some number, d, of secondary electrons. These electrons then strike the second dynode, which in turn produces d^2 electrons. This is repeated at each of the PMT's N dynodes so the final electron signal leaving the PMT is d^N. In general, d increases as some power (>1) of the PMT voltage. Given that, for this experiment, the number of photons hitting a PMT in a single muon event may be variable, show that the PMT voltage per event scales as expected with the supply voltage. How long in duration is an event, and does this make sense based on what you know about the speed of light?

The QuarkNet Board that we will use to count events measures duration of the event, rather than voltage (see "Time over Threshold" explanation below). In reality, voltage is the more physically meaningful quantities, as seen above. The assumption the board makes is that pulse duration (measured as "time over threshold") is linear in voltage (i.e. number of electrons generate, roughly equivalent to energy of event). Do you see that this is a valid assumption? (Some numbers that might help: muons deposit ~ 2 MeV per cm of path length. The end-point energy of the electrons or positrons resulting from the beta decay of the muon is ~ 53 MeV.)

Finally, you will observe some variation in pulse timing from the 2 PMTs, even for a "coincidence event" (i.e. photons collected from the same muon event by both PMTs). Do you observe a fixed relative delay between the detectors? How will this affect your final measurements, and can you compensate?

2. *QuarkNet Board*

The QuarkNet card was designed and built by engineers at Fermilab in Batavia, Illinois to replace Nuclear Instrumentation Module (NIM) rack-mounted equipment (traditionally used and still found in many national labs). A single circuit board amplifies PMT signals by 10x and uses voltage comparators for discrimination with adjustable threshold. On-board timing is implemented with CPLD (Complex Programmable Logic Device) via software installed at Fermilab. Photon events are time-resolved with an accuracy of 1.25 ns using a time-digital-converter. A micro-controller interfaces with the control PC using a custom LabVIEW program.

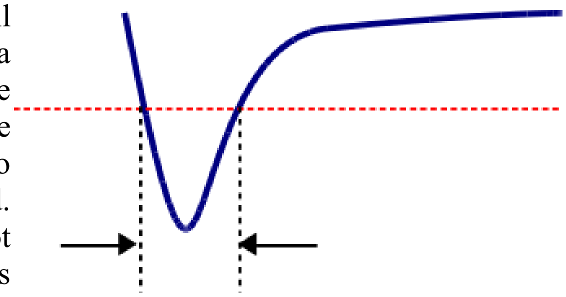
Connect the PMT outputs to two detector input channels on the QuarkNet card. (Note: each channel preamplifier has 50 Ω input impedance; you need to keep this in mind if you use a parallel oscilloscope to monitor.) Apply 5 VDC power to the QuarkNet card by plugging the AC adapter into a wall socket. A blinking LED associated with each channel indicates the occurrence of a local trigger. The LEDs can give a rough visual guide to assist in configuration (Note: the digital counter is of little value). Open the LabVIEW program Setup.vi.

Card Timing: Triggering can be initiated by either: 1) one pulse from a single PMT or 2) coincident pulses from 2, 3, or 4 PMTs. Coincident triggering is more reliable because it is less susceptible to false signals produced by random background noise. This experiment has two PMTs available to monitor photons in the scintillator tank.

If coincident triggering is used, the time overlap window (coincidence time) must be set. The default value is 40 ns. At the default setting, two PMTs must produce individual pulses that exceed their specified threshold voltage AND occur within 40 ns of each other to create a trigger. If the coincidence time is too short, relatively few card triggers will occur. If it is too long, there is increased probability of false triggers. The oscilloscope display of the pulses can guide this setting. The coincidence time has no meaning in the single trigger configuration.

Once the card triggers, all the detector input channels will record above-threshold photon signals during a specified time (gate width). The proper gate width will depend on the type of experiment being performed. If only the triggering pulse or pulses are to be recorded, the gate width can be relatively short. If muon decay events are of interest, the gate width must exceed the expected muon lifetime by 4 to 5x. Longer than this will introduce noise; a significantly shorter gate will make determination of the decay time difficult.

Threshold: Each channel of the QuarkNet card will locally trigger when the amplified PMT pulse exceeds a specified threshold voltage. This is illustrated by the dotted red line in the adjacent figure. Recall that the threshold voltage must be adjusted by 10x compared to the PMT output to account for amplification on the card. Also note that individual channel triggers do not guarantee the gate will open if coincidence triggering has been selected. Simultaneous PMT events as defined by the coincidence time window are required.



T: time over threshold

The time-over-threshold of an individual pulse can be recorded with a precision of 1.25 ns. This time gives an approximate measure of the integrated power and hence the relative energy in the PMT pulses.

Setup: The LabVIEW program Setup.vi helps configure the QuarkNet card. The goal is to set the PMT bias voltage along with the channel thresholds to acquire reliable data counts. The negative-going voltage of the PMT output pulses must be sufficiently above the background noise and at a level where they can be readily discriminated.

Initial setup should be performed with single detection, a gate width of 100 ns, and 100 mV threshold. Negative voltage for all PMT signals is assumed, so the threshold is entered as a positive number. These settings are not critical, but should be a good starting point. The sampling period should be long enough that the count does not vary widely between display updates. Start the program, wait three seconds for the card to initialize, and press the RUN button. Detector counts will be displayed. To change an operating parameter, press PAUSE, make the desired change, then press RUN. The PAUSE button allows parameters to be modified without a complete card reset. As the threshold voltage increases, the count rate should drop. When higher thresholds do not noticeably reduce the count rate, a good operating threshold voltage is identified. Keep the PMT voltage constant and configure the second channel using the same criteria. If adequate thresholds can't be established on both channels, the PMT voltage must be changed.

Select the coincidence tab to enable single counting from both PMTs and display their coincidence counts. Both detectors should be counting at a higher rate than the coincidence events; you can also determine which of the two detectors is limiting the coincidence trigger rate. Proper behavior verifies the threshold settings and the width of the coincidence time window. Record the working parameters and do not adjust the PMT voltage.

Open the LabVIEW program Muon.vi. With appropriate timing settings and threshold parameters determined above, this program records photon events collected by the PMTs. Two measurements can be performed: photon energy distribution and muon decay lifetime.

Pulse duration detection and calibration: Select the measurement 'Energy' and open the Coincidence tab. The experiment can be done with a single PMT, but more reliable data is obtained with simultaneous signals from two PMTs to verify the presence of a valid photon in the scintillator. The goal of this measurement is to determine the approximate "energy" of each photon event by recording its time above threshold, shown as T in the above figure. (See "PMT calibration" section—how valid did you find this measurement?) The gate width can be set with the aid of the oscilloscope. It should be long enough to capture the photon signal; too long will introduce unnecessary noise. Since the width of the triggering photon is of interest, the gate minimum should be set to zero. Only data from one of the PMTs (decay detector) will be recorded.

Start the program and wait 3 seconds for the card to initialize. When the card is ready, press the RUN button. You will be prompted to specify the name and location of a data file where the collected values of T (in ns) will be written. Since data can be collected for an arbitrarily long time, this file will auto-save at a user-specified interval. Real-time data is displayed on an updating histogram. The distribution should approach an ideal Gaussian depending on the number of data points and histogram bins.

When sufficient data has been collected, stop the program. Repeat the measurement but stop it when the number of data points is about half of the first run. Change the decay detector to the other PMT and do the same pair of measurements (4 total). For the analysis, produce a histogram with a Gaussian fit for all the data sets to determine the mean pulse width and variance; express the latter as a percentage of the mean. How does the analysis depend on the number of histogram bins? Comment on the differences and calculate the experimental uncertainty for each data set.

Muon decay: Select the measurement 'Decay' and open the Coincidence tab. In this experiment, the decay detector waits for a second photon that follows the coincidence trigger, which should correspond to a muon decay. The program must be configured to ignore trigger events, which will radically skew the data toward time zero. The gate minimum setting must be set longer than duration of any possible trigger pulse, accounting for fluctuations introduced by the coincidence time window. (Tip: The gate minimum should be longer than the gate width used in the pulse duration/energy experiment.) To observe the expected exponential decay, the gate should remain open for multiple muon decay lifetimes. At long gate widths, data accumulated will represent the noise background; the background data introduces a constant offset on the statistics. The desired decay events are statistically rare, so you will need to observe the experiment for some time to verify that it is working as expected, and then you will need to let it run at least overnight. When sufficient data is collected, stop the program. The time events are all written to the specified data file.

Repeat using the other detector as the decay detector. What differences do you expect and observe?

For the analysis, bin your event times into a histogram, choosing an appropriate bin size. Do you expect any non-decay events to be included in this data? If they are, is there a way for you to account for them in the analysis? Fit the data to an exponential decay (or an appropriately altered equation) to find lifetime. If you plot the histogram on a semi-log plot, the slope of the linear fit is the measured muon decay lifetime. Calculate the experimental uncertainty and compare the lifetime to the accepted value for in literature. (You should be looking for values from

“CODATA”, and you should explain how muon lifetime related to fundamental constants in your report).