MUO - Muon Lifetime

Physics 111B: Advanced Experimentation Laboratory

University of California, Berkeley

Contents

1 Overview of the Muon Lifetime Experiment (MUO)

Revised 2020

The muon is an unstable particle, with a lifetime on the order of microseconds, which decays by means of the weak interaction into an electron and two neutrinos. If we start out with N_o muons, then the number of muons present at a time t later is $N(t) = N_0 e^{-\frac{t}{T}}$ where T is the lifetime.

In this experiment, cosmic-ray muons that enter a large tank of liquid scintillator trigger the emission of a pulse of photons. These photons are detected by a photomultiplier tube. If the muon stops inside the tank, another pulse of light is produced when the muon decays. The time difference between the pulses is a mean for measuring the lifetime. An histogram of these time differences for many decaying muons resembles an exponential distribution from which the mean lifetime can be determined.

This lab will be graded 20% on theory, 20% on experimental procedures, and 60% on analysis. For more information, see the **Advanced Lab Syllabus**.

2   Preparation

Complete the Pre-Lab found in bCourses/Files/MUO, and prepare for your meeting with a faculty or GSI to verify your understanding of the materials. Refer to the suggested readings below, or any other resources as needed.

1. View the **Muon Lifetime Video**. ***Note: In order to view the private Youtube videos hosted by the university, you must sign into your berkeley.edu Google account.*** *Please note that the data acquisition system shown in the video has been replaced with a new one which is described in this write-up. However, the working principles are similar.*

Suggested Reading:

1. B. Rossi, "**Interpretation of Cosmic-Ray Phenomena**", Rev. Mod. Phys. **20**, 537 (1948). *Gives the cosmic ray flux at sea level. Figure 6 on p. 545 is important for your calculations.* **Searchable Page**

2. D. Griffiths, ***Introduction to elementary particles***, 1987. *Read the introduction (pp. 1-10). The result of a tedious calculation of the muon lifetime is given in pp. 307-309.*

3. R.D. Evans, ***The Atomic Nucleus***, McGraw-Hill (1955). *Read about radioactive decay in Chapter 15.*

4. C.S. Sutton et al., "**Undergraduate Cosmic Ray Muon Decay Experiments with Computer Interfacing**", Computers in Physics, Nov/Dec, 76 (1987), #QC52.C658.

5. O.C. Allkofer, ***Introduction to Cosmic Radiation***, Verlag Karl Thiemig, Munchen (1975). Read Sections 4.1, 9.1-9.6, 9.12, and 10.1-10.4.

6. **Exponential Probability Distributions**

7. "**RCA-4522 Photomultiplier Tube Specifications**", RCA Electronic Components, June, 1 (1968).

8. **National Instruments Digitizer VI**

9. **Stanford Research Systems DG645**

The above references and other information can be found at the **Physics 111 Library Site**

You should keep a log of your observations while watching video of the experiment. This log will serve as a detailed record of everything that was done and how/why it was done, as well as all of the data and analysis, also with plenty of how/why entries. This will aid you when you write your report.

3   Objectives

- Measure the lifetime of a muon

- Demonstrate relativistic time dilation

- Measure local cosmic-ray muon flux

- Learn how to use random numbers in simulation

- Create a simulation of muon decays and measure the lifetime

- Study signal processing

4   Introduction

Muons are particles that have a mass over 200 times that of the electron. Muon decay is of great importance in the study of weak interactions, one of the fundamental forces in nature. The value of the muon lifetime is one of the most precisely known constants, and is currently measured with a precision of a few parts per million. The reason why it is measured so well is because it can allow us to determine the fundamental parameter, Fermi's constant, of the weak interaction or the weak coupling constant which is equivalent to the fine structure constant of the electromagnetic interaction. Alternatively, if we know the value of the weak coupling constant, the lifetime of the muon can be used to estimate the mass of the charged intermediate vector boson $W^{\pm}$.

When high-energy cosmic-rays collide with molecules in the earth's atmosphere, they produce particles that decay into low-energy muons. We will be studying such muons in this experiment. Eighty percent of the cosmic rays at sea level are muons, positively or negatively charged. They have a mean lifetime of a few microseconds.

They decay by the following processes:

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \tag{1}$$

and

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \tag{2}$$

By the CPT theorem, the lifetimes of the negative and positive muons in *vacuum* (i.e. due to reactions (1) and (2)) are equal. However, in matter, negative muons, when brought to rest in the close neighborhood of some nucleus (Z,A) a muonic atom is formed with the muon orbiting in the K-shell. The negative muon in the muonic atom can either decay as shown in reaction (2), or it can disappear through the competing reaction:

$$\mu^- + p \rightarrow \nu_\mu + n \tag{3}$$

where p and n are the proton and neutron respectively. The rate of the muon-capture process (3) depends strongly on the charge Z of the nucleus which captures the muon. In muonic carbon atoms, the rate of the muon capture (3) is about 10% the decay rate in (2).

The goal of this lab is to measure the lifetime of the muon. In order to obtain a correct result, calibrating the acquisition electronics properly is important, however most of the adjustments are made in the analysis using software. Don't rush through the adjustments, but ensure you understand what you are doing and how your changes affect the measurement. Once you have the calibrated data plotted, you still need to figure out the amount of background, how to subtract it from the data, and decide what range of the time interval should be used before making a proper analytical fit to extract a correct value for the lifetime.

5   Apparatus

Although you will not perform this experiment, it is important for you to familiarize yourself with the basic principles of the apparatus and the experimental procedure, for you will need to have a good understanding of how the theory relates to the experiment and identify sources of error.

5.1   Overview

Figure 1 is a diagram showing the appartus used in this lab. Muons are derived from the process of cosmic-ray particles striking the nuclei of atoms and molecules in the atmosphere. They are detected with a large liquid scintillation counter located in a shaft which can be accessed from room 275 LeConte (Figure 2). It is filled with 125 gallons, 500 kg (1/2 cubic meter) of mineral oil in which a scintillating substance is dissolved. The passage of fast charged particles, in this case the muons, through the liquid gives rise to short pulses

of light a couple tens of nanoseconds in duration. This phenomenon is called scintillation, as illustrated in Figure 3.

The light pulses are converted into electrical pulses by a photomultiplier tube through successive multiplying stages as depicted in Figure 4. There are two photomultiplier tubes located at the top and bottom of the detector. The housing enclosing the electronics components, called the base, of the top photomultiplier tube is shown in Figure 5. Referring to Figure 6, the high voltage on the PMTs are set to -1900 V (top tube) and -2300 V (bottom tube). Each photomultiplier views half of the tank, which is divided by an opaque baffle in the horizontal mid plane. Most of the muons that are incident on the detector pass straight through it. Only the lowest energy muons come to rest within the scintillating liquid. A muon that enters, stops, and subsequently decays in the liquid scintillator gives rise to two pulses separated by a few microseconds, one when it enters the liquid, and a second one when it decays.
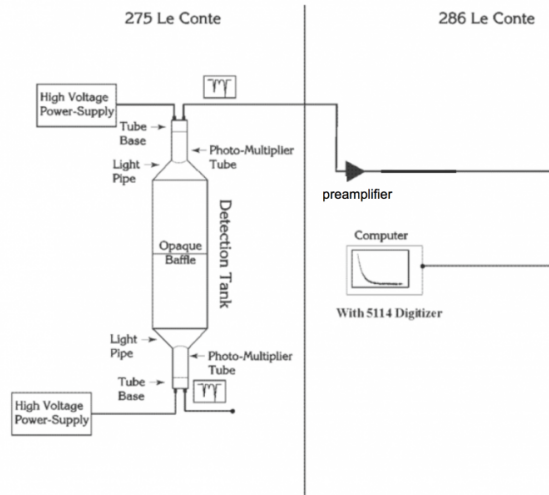

Figure 1: Block Diagram of the Muon Lifetime Experiment

Figure 2: Vertical shaft in LeConte 275, where the large liquid scintillation tank sits. See larger image **here**

Figure 3: Scintillation of excited liquid scintillators.

The electrical signal is sent through an RG-58 coaxial cable to data acquisition system in LeConte 286 (Figure 7). The pulses are amplified with a SR445A preamplifier feeding into a digitizer installed in a computer which works together with a LabVIEW program as: (1) an oscilloscope, (2) a differential detector logic system.
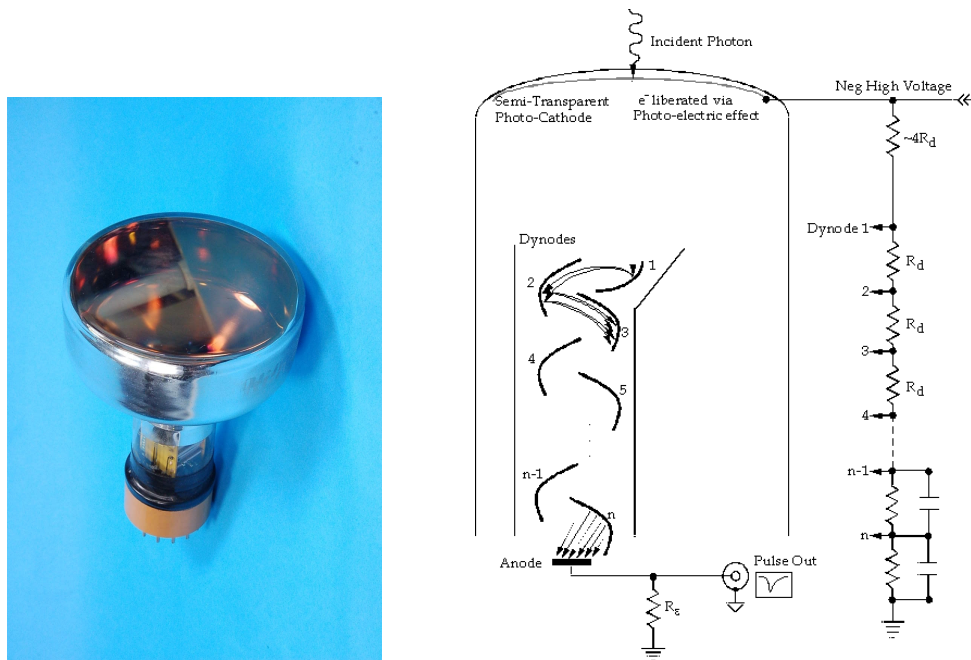
Figure 4: Image (left) and drawing of the internal structure (right) of a photomultiplier tube.

Figure 5: Close up of the base of the top photomultiplier tube. See larger image **here**
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Figure 6: High-voltage power supplies for top & bottom photomultiplier tubes with the black base of the top photomultiplier tube shown. See larger image **here**

Figure 7: Front view of the data acquisition system for the muon lifetime experiment in LeConte 286. See larger image **here**

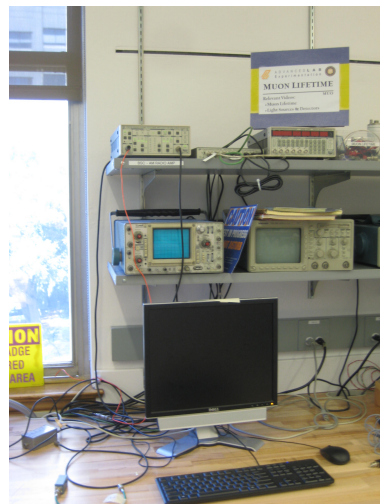**Questions for the students to consider while going through the experiment**
Q1: Why do we use a coaxial cable to carry the signal?

The LabVIEW program **Muon Detection Program** coupled to the digitizer card detects pulses from two photomultiplier tubes, measures their arrival times, amplitudes, and widths, and, for a subset of pulses that satisfy a preset criteria, writes the data to disk.

The pulses can be viewed with an oscilloscope or digitized and stored on the computer. You are going to measure the time difference between these correlated pulses, as well as the amplitude and width of each pulse. After many such observations, you will obtain a distribution of the number of counts vs. time difference. Ideally, when these data are plotted, they will form an exponential decay curve, whose decay constant is the lifetime of the the muon. You will read the data offline, filter it to reject noise, plot the time difference between two pulses in the same photomultiplier tube, and use the distribution to measure the muon lifetime.

5.2   Explanation of the LabVIEW Programs

Screenshot of the Muon Detection Program

This experiment uses two different LabVIEW programs: **View Signals** and **Muon Detection Program**. The purpose of **View Signals** is to choose the best input parameters by inspecting the signals and seeing how changes in the input parameters affect the signals and counting rates. (This reads the input signals like an oscilloscope). The optimal input parameters will then be used in the program **Muon Detection Program**, whose purpose is to save pulses to data files, from which you calculate the muon lifetime.
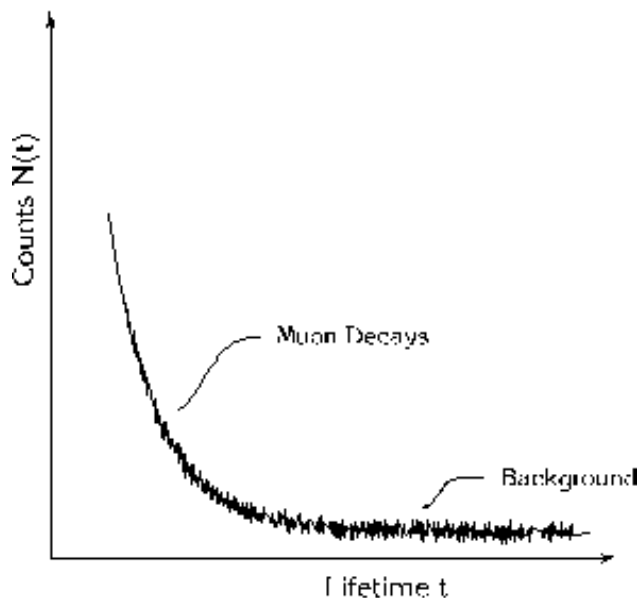

Figure 8: Distribution of the temporal separation between two signals. Note that the X axis sometimes is called the channel number for the digitizer. The Y axis is also called the amplitude counts.

A high-speed digitizer installed in the back of the computer receives two signals. The digitizer represents the incoming analog signal by generating a series of numbers that describes the discrete samples. The top PMT is connected to Channel 0 of the digitizer, and the bottom PMT is read out by Channel 1. The digitizer is configured and initialized when we click **Start Acquisition** in either of the Muon LabVIEW programs and essentially a programmed way to interpret the incoming signal. However since the purpose of the digitizer is to represent the incoming signal and process the data you can change its configuration throughout the program. We can set the input range for each channel separately; 2 V is about right for both channels (the offset is set to 20% of the range, so 2V corresponds to the range $[-0.4V , +1.6V]$). The input impedance is set to 50 ohms and the digitizer uses full bandwidth.

Q2: Why do we have to set the input impedance to 50 ohms? If not, what will happen to the signal?

6   Procedure

We will walk you through the procedure of setting up the experiment and collecting data, as you will see in the demonstration.

6.1   Determine optimal settings using the LabVIEW program View Signals

Program operation and description National Instruments Digitizer VI

1. Using the LabView Program **View Signals** on the desktop

   - If the pulses coming into the digitzer card are negative, such as the one shown in Figure 9, we will enable **Flip Polarity**.
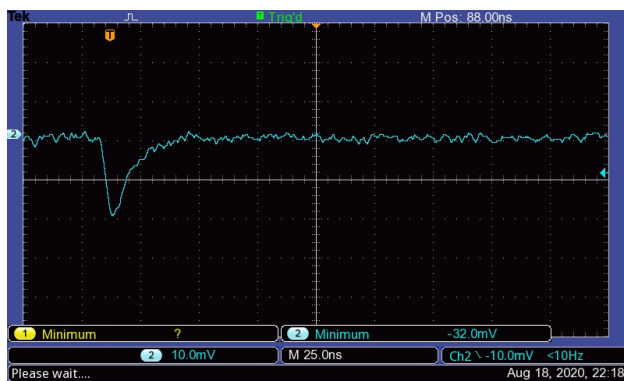

Figure 9: Screenshot of a signal seen with an oscilloscope. The yellow horizontal line shows the set threshold for the count.

   - We will estimate the average height of the primary and delayed pulses.

2. We will inspect the amplified pulses with ViewSignals VI. Varying the frequency cutoff, we will observe how the signal and noise change. Then we will pick the frequency cutoff that optimizes signal/noise ratio and set the thresholds so that the counting rates (both input and output) make sense. Both should be safely above the noise level.

   Q3: For the standard data taking (i.e. when we will be collecting data for measuring the muon lifetime), we will require 2 pulses in the top PMT (Channel 0) and 0 pulses in the bottom PMT (Channel 1). What does this setting mean? (Refer to Appendix A, LabVIEW Program Controls as necessary)

3. We will use the pulse generator (SRS DG645) to simulate a sequence of two pulses of approximately the size and width as the output of the detector later for calibration. The first thing we take note of is the front panel of the SRS DG645 for producing the pulses. The "edge" section is located on the left side of the display. The "edge" refers to the 5 different output channels, each with a 50 ohm impedance, located in the bottom of the front panel under the display. We notice that the outputs have two letters associated with them, each located on a different edge of the signal. The first edge refers to the offset above ground and the second edge to the step size, this will effectively determine the peak-to-peak voltage of your signal above ground (an example would be A and B, where A is the offset and B is the step size). Under the display there is a section labeled "display" where we can navigate the different

edges and move the cursor on the display (indicated by the character that is flashing). The two signals are connected to ports AB and CD. We adjust the voltage for the expected peak heights. Next we want to set the delay of the second pulse relative to the first. This can be accomplished by pushing the "delay" button located in the display section. It will prompt us to input a time delay in seconds. The width of the pulse can also be determined by the delay function, however now the delay is not between different outputs, but rather it is between different edges of the same output. We will use the oscilloscope to examine the generated pulses to make sure they are consistent with our settings. Feel free to examine the manual found here: **SRS DG645 Manual**.

Q4: With the Program & apparatus counting muons, make note of the *Trigger* rate and the *Output* rate that are displayed on the program Front Panel. Do these rates agree with your calculations for the muon incidence and stopping rates (from the Pre-lab)? How might changing the threshold settings affect the *accuracy* of your data?

6.2 Data Collection and Calibration of Electronics

We set up the Main program & apparatus and start taking data. We transferred our settings from the View_Signals VI to the main VI, Muon_Detection_Program.

In experimental physics it is important to understand the electronics you work with and the limitations they place on your data. The equipment can reveal a lot about the scope of the experiment. To better understand the setup for this lab we will need to run three types of calibrations:

1. **Time resolution of the digitizer**. Our digitizer works in discrete steps and therefore there is a limit on its time resolution that is based on how quickly it can process and convert the incoming signal. We want to determine this time resolution, and consider what timescale it should be on to ensure that our experimental procedure works and the data we receive is accurate. The time recorded by the two PMTs for *through-going muons*, (i.e. muons that go through both halves of the scintillator tank) will give us an understanding of the timescales that the experiment operates on.

    In order to extract this information from the **Muon Detection Program** the correct number of expected pulses in each channel should be input. The first PMT is located above the scintillating material while the other is located below. We will use the **View Signals** program to make sure that the trigger level and pulse thresholds counting rate is reasonable, the trigger level should be roughly near 0.1V (we may need to apply additional cuts on pulse amplitude if we set the thresholds too low). After we have collected a sufficient amount of data you are ready to examine the response rate between the two channels. This time difference data belongs to a certain distribution. Fit it to a function you think is suitable (Hint: Here you have a large number of data points whose values are independent to one another all with small variations about an expected value, in our case we would expect it to be zero. There is a common theorem used in statistical distributions such as this and will help dictate which function will fit the distribution.)

    Q5: You should see that the mean is not centered on zero, why is this? What does the standard deviation of the function tell you? The standard deviation corresponds to the margin of error within your distribution. What are we measuring and what does the error tell us? Do you need to apply any correction to the lifetime data ?

2. **Efficiency of the digitizer**. Since the goal is to determine the muon lifetime from a histogram of *counts vs time*, we will make sure that each time interval is counted by the apparatus equally. To check this, we will to provide the apparatus with *a-priori* uniform distribution of time differences. This is done by combining signals from two *uncorrelated* sources: a through-going muon, and an external pulse generator (DG645). As long as the counting rates from the two sources are similar, it's likely that the two trigger pulses will come from different sources.

- First, we will set up the apparatus according to the procedure: **Calibration setup Procedure for Muon Lifetime Calibration**.

- Then, we will use a ZSCJ-2-1 Power Splitter to add the Delay Generator signal to the Muon pulse, and run it to Channel 0 of the digitizer. The Power Splitter just takes signals from input 1 and input 2, and outputs their sum on output S.

- We will use the Scope Soft Front Panel to check the signal, to see generator peaks and the Muon signal peaks. The polarity of both should be the same (be sure to remember if the polarity is positive or negative).

- We will run the Muon Detection Program. Setting the trigger level to be above the amplitude of the Delay Generator peaks (0.6V works well) and setting the Pulse Detection Threshold to about 0.2V, we will make sure that the Exact Number of Pulses are 2 on Channel 0 and 0 on Channel 1.

- We will collect and save the data.

- Data analysis: look at the distribution of time differences dt in each channel. Apply selection on pulse heights if the thresholds are set too low (e.g. the second pulse in each channel should be from DG645, and therefore very constant in amplitude). Select the interval where the counting rate is most uniform. Determine if the data are consistent with constant counting rate, or if you need to make a correction to the real muon decay data.

  (a) Plot the histogram of counting rate vs dt for each channel. Remove bins that obviously over-count, if any.

  (b) If there is an obvious slope to the distribution, you may not have set the thresholds correctly, and the VI is triggering on two muon pulses, instead of one muon and one generated pulse. Try adjusting thresholds in the VI, after carefully inspecting the amplitudes of the muon and generator pulses. You may also be able to select the correct pairs of pulses in the RAW file. The generator pulse has a very stable amplitude, typically between 0.1-0.2 V after the digital filter. Select events in the RAW file in which one of the pulses has this specific amplitude, and the other is larger.

  (c) Once you have a reasonable distribution of counting rate vs dt, convert it to log scale, and fit to a straight line. Is the slope significant ? If it is, how does it affect your muon data ?

3. **Calibration of the digitizer clock**. Even though the VI reports the time interval dt in seconds, you need to check that the time scale is accurate. To do this, we will to send pairs of pulses from DG645 generator to the digitizer, vary the time interval between the pulses, and reconstruct this time interval with the VI.

This is a procedure for the lab staff to go through while doing the demonstration:

- First, reconfigure the internal trigger of the Delay Generator to 12.5 kHz (this should be half the value used in the previous part). If the value is kept at 25 kHz, a third pulse may be detected (Think about why this is?).

- Configure the CD output of the Delay Generator to send out a 100 ns pulse some time after the AB pulse. Remember that we set the AB pulse to be sent 1 μs after the internal trigger, so setting the CD pulse to begin at 3 μs will correspond to a time difference of 2 μs between the pulses. We will pick the amplitude and polarity to match that of pulse AB.

- Plug output AB into input 1 of the Power Splitter, and plug output CD into input 2 of the power splitter. Plug output S into the digitizer channel to be tested.

- Run the Soft Scope Front Panel and make sure that the signal is what you expect. Note the time difference between the pulses.

- Run the Muon Detection program to collect data. Be sure to set the trigger at a low enough value for the pulses to be picked up (0.2 V works well).

- We should see just one of the histograms bins being filled. We will collect data for enough time differences to be sure that the digitizer reads all time differences correctly, from 1 μs to 40 μs.

- Repeat this procedure for the other digitizer channel.

4. **Linearity of the pulse height measurement**. With the setup above, we will set the time difference between **AB** and **CD** to some fixed value (e.g. 5 μs), and vary the amplitude of **AB** and **CD**. We will collect data for each setting, plot the reconstructed pulse heights versus the amplitude set by the DG645 generator.

7 Analysis

1. We will collect data with the default setting (low thresholds, require 2 pulses in Channel 0 and 0 pulses in Channel 1).

2. Inspect the distribution of pulse heights and pulse widths for both the first and second pulses. Can you explain the features ? Apply a cut to remove low-amplitude noise pulses. See how the distribution of time separation dt changes when you cut on pulse height.

3. Correct the dt plot for any non-uniformity measured in **Step 2** of the **Calibration** section

4. Make note of the time calibration done during the demonstration from **Step 3** of the **Calibration** section

5. *Make a semi-log plot of counting rate D vs. time separation dt.* On this plot, fit the background (from about 10 to 20 μs) to a straight line (with the slope not necessarily zero). Extrapolate the line under the muon decay region and subtract the background in each channel from D, yielding D_2. **THINK:** How does the choice of the background fit influence your results? Is the fit to the background a constant throughout time, a linear decay, or an exponential decay?

   Q6: Once you have determined the fit and keeping in mind that we are interested in the counting rate, think about how you can properly remove this background noise from the muon decay region i.e. what mathematical operation relates the noise to the muon decay?. Discuss what could be determining the fit of the background and its correlation to the data you are interested in.

6. *Make a semi-log plot of D_2 vs dt.* Make sure errors are correctly computed for $\log D_2$. Make a least-squares fit to a straight line (over a time interval where such a fit makes sense). The slope of this line is inversely proportional to the "effective" muon lifetime. Also show lines corresponding to "effective" lifetimes that are one standard deviation higher and lower than the mean lifetime. All lines should be normalized to the same total number of counts. After you make a fit, also check and see how the calculated exponential curve fits the measured curve. Change the limits of the fit by adding or deleting data points and the beginning and end of the data interval; observe how the lifetime values and the χ^2 of the fit change. In other words, cut and trim your data to observe the effects on the lifetime measurement. Justify any omission of data when you quote your final answer.

7. Be sure to read Evans Chapter 15 at this point. As indicated in the lab write-up, some negatively charged muons (μ^-) undergo nuclear capture in the muonic carbon nuclei of the mineral oil in the scintillation tank. These muons generate a start pulse when they enter the detector but do not generate a stop pulse when they are nuclear captured. Therefore their decay times are not detected. Although the reprints show that the entire population of $\lambda_{\text{combined}} = \lambda_{\text{decay}} + \lambda_{\text{captured}}$, it may not be obvious that the *free-decaying* μ^-'s will also decay with this combined rate. This is a subtle point that you should be sure to ask about if you need to.

   - Note that $\lambda_{\text{decay}} \cong \frac{1}{2.2\mu s}$ for both positive and negative free muons, and that $\lambda_{\text{captured}} \cong \frac{1}{26\mu s}$ is the rate of negative muon capture in the material (carbon) of the detector.

   - As discussed above, there are *two* different populations of muons that you measure, μ^- and μ^+, and they decay with the different decay rates, $\lambda^{\mu^-}_{\text{combined}}$ and $\lambda^{\mu^+}_{\text{decay}}$ respectively. The histogram of decay-times that you will get from the equipment (barring background and noise) is the sum

of *two* exponentials: $\text{Histogram}(t) = A \exp(-t\lambda^{\mu^-}_{\text{combined}}) + B \exp(-t\lambda^{\mu^+}_{\text{decay}})$, where A and B are constants. To analyze these data properly requires a non-linear curve fitting program. But because $\lambda^{\mu^-}_{\text{combined}}$ and $\lambda^{\mu^+}_{\text{decay}}$ are very close to each other, it is difficult to get good results. Instead, it is recommended that you fit your data to a *single* exponential: $\text{Histogram}(t) = A e^{-t\lambda_{\text{effective}}}$. This gives you an "effective" life-time. The use of the word "effective" is only to signify the answer the computer gave you. It is possible to fit any curve to a single exponential and get an answer; the computer just does the best it can. So when you are asked to estimate the true lifetime, expect to make some approximations and don't expect to come up with an exact answer.

- Assuming that half of the observed decays come from μ^-, with apparent decay rate $\lambda^{\mu^-}_{\text{combined}}$, estimate the magnitude and sign of the difference between the true muon lifetime and the "effective" lifetime (for μ^+ and μ^- together) measured in this experiment.

8. What is your value of the muon lifetime and its uncertainty, and how does this value compare with the published lifetime? **IMPORTANT:** estimate *systematic* uncertainties, i.e. think how the procedure, calibration, analysis method etc. may bias your results.

9. What is the value and uncertainty of the Fermi coupling constant determined in this experiment? How does this measurement compare with the published value?

7.1 Note on Analysis Tools

This analysis can be done with a variety of tools, but we would recommend one of the more common packages designed for high-volume datasets. Thus, while it's possible to do a rudimentary version of the analysis in Excel, we do not recommend it, and we do not provide pre-packaged histograms of dt for that reason. You could use MATLAB with the convenient Curve Fitting and Statistics add-on packages, as well as additional home-made fitting tools. Comprehensive tutorials for MATLAB are available at **Intro to Matlab** and elsewhere on the web (some useful functions are `hist()` and `histfit()` and it would be very wise to review the error analysis lab). If you want to use MATLAB outside the 111 lab, it is available for students at a discount at the University Store. There is also a GPL (free) clone **Octave**, which is compatible with MATLAB at about 90% level (that is, about 90% of the commands are implemented, but the Curve Fitting package, regrettably, is not available). Octave can be downloaded for Windows, MacOS, and Linux.

You could also use Python and run your analysis on a Jupyter notebook. You might want to look over functions in NumPy and SciPy for your data analysis.

The tool of choice for High Energy and Nuclear physics is **ROOT**. It is a sophisticated data statistical analysis package, specifically designed for analyzing large data sets, curve fitting, etc. While MATLAB is best at linear algebra and signal processing, ROOT is most natural for reading a large data set, applying cuts, and performing non-linear fits. ROOT is available for free download from **CERN**, and there is good documentation and tutorials on the **Root's main site**. We also provide a sample (bare bones) analysis examples below: **Muon Analysis in ROOT**

8 Computer simulation of experiment and analysis

Write a program in Matlab (or other software of your choice) to simulate muon decays and accumulate their lifetime distribution. Fit the generated data using whatever means you used above to determine the muon lifetime. Software routines that simulate data are called Monte Carlo programs (see ref. 10 or 11). By fitting this computer-generated data you can directly verify that the fitting procedure reproduces the input parameters (i. e., number of events and lifetime). These Monte Carlo simulations are common in complex experiments to model the experimental system and check the analysis methods.

Computers usually generate random numbers r_i uniformly distributed over the interval (0,1), that is, the

successive values, called iterates, of r_i are described by the probability distribution

$$P(x)dx = 1 \tag{4}$$

You wish to simulate a series of muons whose lifetimes t_i follow an exponential probability distribution

$$P(x)dx = \tau \exp(-\tau x) \tag{5}$$

where τ = mean muon lifetime. Prove that

$$t_i = -\tau \ln r_i \tag{6}$$

will convert iterates from the uniform distribution to the exponential distribution.

Write a program to

- generate a number of exponential iterates, t_i, and

- sort them into time channels N_k, which roughly correspond to the width and range of the experiment channels. (Increment N_k by 1, if t_i falls into the range of channel k).

- and store the data on the disk drive.

Fit these data with your fitting program. Investigate the dependency of the fitting program output on the number of events simulated. How many exponential iterates are needed to get good results from the fit?

A more detailed Monte Carlo analysis of your experiment is possible. For instance, generate the accidental background and study the influence of accidentals, statistics and fit -range on the results of your analysis.

- Last day of the experiment please fill out the **Experiment Evaluation**

Program operation and description [1]

9   References

1. Particle Data Group reference page: **http://pdg.lbl.gov**

2. National Instruments **Waveform 5124 Digitizer Manual.**

3. **RCA Photo Multiplier Tube Manual**.

4. B. Rossi, **Cosmic Rays**, McGraw Hill (1964). *History and background.*

A   LabVIEW Program Controls

Here is a brief description of the different program controls (a more detailed explanation is given in the following section):

The user control **Range (microseconds)** determines the minimum length of the record (counting from the trigger), i.e. the maximum difference between the trigger and the second pulse. The triggering event is set to be at 12% of the way through each record, so that the digitizer can see pulses just before the trigger. The user control **Min sample rate** specifies the minimum sample rate (leave it at 250 MHz). The type of triggering is set to analog edge triggering. The user can select to trigger on Channel 0, Channel 1, or External (which we do not use). The trigger slope is set by the user control **Pulse polarity**, and the user control **Trigger level** sets the trigger level. For signals with negative polarity the user should make sure that the green light is on and the signal is flipped, you can determine the polarity of the signals by hooking them up to the oscilloscope.

Both programs initiate a record acquisition by the digitizer and, once the voltage exceeds the trigger threshold, retrieve voltage waveform data for both channels, incrementing the **Trigger Count** by one. The programs remove the voltage offset by averaging the voltages of the first 200 samples of the record, all of which should occur before the triggering event, and subtracting that voltage from all the voltage waveform data. The programs then search for up to two pulses below (for negative **Pulse polarity**) or above (for positive **Pulse polarity**) the **Channel 0(1) threshold,** which the user will set. This threshold is relative to the offset, not ground. The first pulse will correspond to the Muon entering the scintillating material within the tank and the second to its decay. The time difference between the first and second pulses has to be less than the **Range**, which the user set, and greater than the **Pulse 2 delay,** which the user set. The range is simply a measure of how long the program will wait between pulses before moving on to the next signal. The pulse 2 delay is there in order to ignore any noise generated after the first signal that may pass the trigger level. Typically 1 microsecond is enough breathing time. The user can specify how many pulses in each channel is required for the data to be written to disk, for our case we are looking for two events (i.e. the incident and the decay). The **Output Count** is incremented if exactly that number is found in each channel. Whether or not the output condition is satisfied, the process repeats with the next data record.

It is important to note that in the program **View Signals**, after clicking **Start Acquisition**, the program continues to acquire records from the amplifier and searches them for the specified pulses until the user clicks **Stop Acquisition**. This program graphs the **Raw signals** acquired by the digitizer, the **Signal with offset removed** and the **Filtered signal** – for each channel (Channel 0 in white, Channel 1 in red).

Once the user has determined the optimal settings for the program controls the next portion of the lab deals with the **Muon Detection Program** which measures the pulse height and width in addition to time. To reduce noise, the programs pass the waveforms through a 29-tap low-pass filter. The user will set the cut-off frequency of the filter with the control **Lower-cut off frequency**. **Pulse 1 threshold** and **Pulse 2 threshold** correspond to the unfiltered signal. Unfiltered pulses that meet these thresholds will have their amplitudes reduced upon filtering.

When the user clicks **Start Acquisition**, the program prompts the user to enter two different file paths to save data: a temporary local data file and a network data file. The temporary file is supposed to be on local disk ("C:/") so that network connectivity does not affect performance. The temporary file is copied to the network storage when the program terminates. After the files are open, the program begins acquiring records and searching them for pulses. When an output condition is satisfied (i.e. exactly the specified number of pulses is found in each channel, up to the maximum of 2), the program writes out a record of 12 floating-point numbers to the temporary file: time, amplitude, and width of four pulses: 1st pulse in Channel 0, 2nd pulse in Channel 0, 1st pulse in Channel 1, 2nd pulse in Channel 1. If a given pulse is not found in the record, the time, amplitude, and width are assigned zero values. **IMPORTANT FOR DATA ANALYSIS:** It is the values saved in this text file that the user will be working with in the analysis of this lab. This is the file that the user should be uploading to MatLab or ROOT as it will have all the information about the signals received from the PMT.

As the program runs, it updates a histogram of decay events, where the x-axis specifies the time between the two registered pulses. If everything is working correctly, this should mimic the Muon lifetime decay curve.

The program measures the amplitude and the full-width-half-max of each peak from the signal out of the filter. The filter removes a lot of the noise, so the amplitude and width information are more accurately measured with a filter. Timing information is more accurately measured before the signal is filtered.

A.0.1 Program Controls

Flip polarity

In order for the program to run successfully, a positive signal with respect to ground is expected on both channels. However, the incoming signal from the experiment may be negative, which would crash the program. Enabling **Flip Polarity** negates the incoming signal, so that a negative signal becomes positive. If the incoming signal is already positive, **Flip Polarity** should be disabled.

Select Trigger

This control is identical to selecting a trigger channel on an oscilloscope. When a large enough pulse (see **Trigger Level**) is seen on the selected channel, the program collects data on both channels for a time duration set by **Range**, and then processes those signals for peaks.

Trigger Level (V)

This defines the signal amplitude which is required for the trigger to be activated.

Pulse Detection Threshold (V)

Once the trigger is activated, the program scans the collected signal for pulses. This control defines the minimum amplitude of a signal in order for it to be recognized as a pulse. Any part of the signal which is above this threshold will be recognized as a pulse, and any part which is below this threshold will not be recognized as a pulse.

Pulse 2 Delay (s)

Once the trigger is activated, we wish to ignore any pulses that occur shortly after, since they may simply be noise, as opposed to a muon decay event. This control allows the user to define how long this ignore period should last. This control should be large enough to ignore this noise, but not so large as to ignore a significant portion of the actual muon decay events.

Range (s)

After the trigger is activated, the program must collect the signal which is to be analyzed for some amount of time. This control allows us to set that time duration. After this time has passed, the program analyzes the collected data for pulses, and then returns to listening for the next trigger event. This control should be just large enough to encompass a large majority of decay events.

Exact Number of Pulses

Once the program has identified all of the peaks existing on the most recently received signal, it must determine whether or not these pulses represent a muon decay event. The event is registered as a true muon decay event only if the number of pulses on Channel 0 and on Channel 1 match exactly with the specified **Exact Number of Pulses**. There are three suggested use cases: [CH0 = 2, CH1 = 0]: This signifies a muon which entered the chamber connected to channel 0, and then decayed in that same chamber at a time at least as long as defined by **Pulse 2 delay**, but no longer than **Range**. Since there are only two pulses on this channel and no pulses on the other channel, we are convinced that another muon did not interfere with the measurement. For this setting, the user should set the trigger on Channel 0. [CH0 = 0, CH1 = 2]: Same as above, only for the chamber connected to channel 1. For this case, the user should set the trigger on Channel 1. [CH0 = 1, CH1 = 1]: This represents a muon event in which a muon is first detected in one chamber, but then its decay is detected in another chamber, and no other pulses are recorded. It is suggested that for this case, the trigger Channel is set to the Channel which is connected to the chamber which is on top, since more likely than not, we expect the muon to come from the above the surface of the Earth, and not below.

Vertical Range

This control allows the user to define the vertical range of the digitizer channel. This is analogous to setting the vertical range of a channel on a regular oscilloscope. This value should be just large enough to encompass the amplitude of any received pulse.

Low Pass Filter Cutoff

The program passes a received signal through a Low Pass filter, in order to reduce noise. This sets the cutoff for that filter.

Min Sample Rate

This parameter sets the sample rate of the digitizer.

Other reprints and reference materials can be found on the **Physics 111 Library Site**