B-4 Muon Lifetime

From Physics 191r

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MEAN LIFETIME OF MUONS IN MATTER

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first experiment: II

Contents

LEARNING GOALS

- Observe muon decay in a plastic scintillator
- Measure the lifetime of the muon
- Learn to use nuclear instrumentation modules such as discriminators, logic gates and gate generators
- Determine the mass of the muon

INTRODUCTION

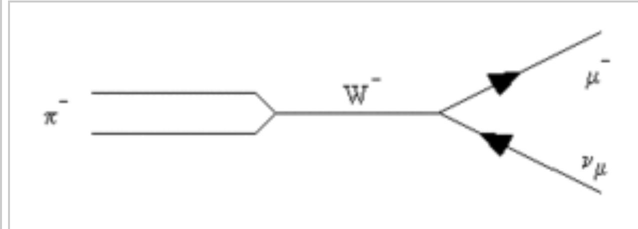

Figure 1. Feynman diagram of pion decay.

Cosmic rays with energies ranging from 10^8 to 10^{20} eV continually bombard the earth. These electrons, nuclear particles and photons are thought to be released in supernova explosions. They interact with particles in the Earth's upper atmosphere producing secondary particles including pions and kaons, which subsequently decay to muons:

$$\pi^{\pm} \longrightarrow \mu^{\pm}\nu_{\mu}$$

and

$$K^{\pm} \longrightarrow \mu^{\pm}\nu_{\mu}$$

The lifetimes of the pion and the kaon are on the order of 10^{-8} sec (The exact values may be found in the Particle Data Booklet (http://pdg.lbl.gov/)). These are weak decays as in the Figure 1.

Figure 2 shows the components of cosmic ray flux. At sea level, about 80% are muons. The rest are electrons and protons. The flux is on the order of $\dfrac{10^{-2}}{cm^2 sec \cdot sr}$.

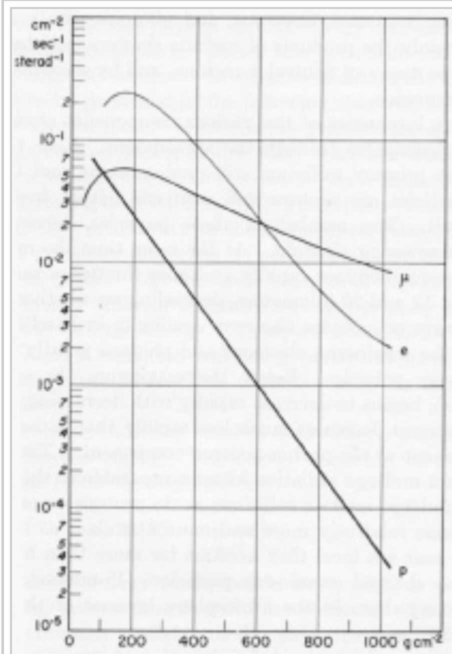

Figure 2. Vertical intensities of various cosmic-ray components at 50° geomagnetic latitude as functions of atmospheric depth. (B. Rossi, *High Energy Particles*, p 8).

Muons are unstable particles with the same charge as electrons but approximately two hundred times the mass. Positively charged muons decay into a positron, muon antineutrino and an electron neutrino:

$$\mu^{+} \longrightarrow e^{+}\overline{\nu}_{\mu}\nu_{e}$$

The corresponding antimatter decay is:

$$\mu^{-} \longrightarrow e^{-}\nu_{\mu}\overline{\nu}_{e}$$

The μ^- can also be captured by the nucleus via:

$$\mu^{-}p^{+} \longrightarrow n\nu_{\mu}$$

The probability of capture depends on the atomic number Z of the absorbing material and goes like Z^4 for small Z. For example, the lifetime due to nuclear capture, $\tau_{capture}$, is 1.93 µsec in carbon and 0.142 µsec in iron (Rossi, p. 170). Figure 3 shows the different lifetimes of positive and negative muons in aluminum.

We measure the lifetime of positive and negative muons in a scintillator. The muon decay is characterized by an exponential. If we have $N(t)$ muons at time t, then $dN = -N\Gamma_{\mu}dt$, where Γ_{μ} is the decay rate. The solution of this differential equation is $N(t) = N_0 \exp\left(-\Gamma_{\mu}t\right)$, and thus the number of muons decaying at time t is $-\frac{dN}{dt} = N_0 \Gamma_\mu \exp\left(-\Gamma_\mu t\right)$. One can measure the lifetime $\tau_\mu = \frac{1}{\Gamma_\mu}$ by fitting the observed decay rate.

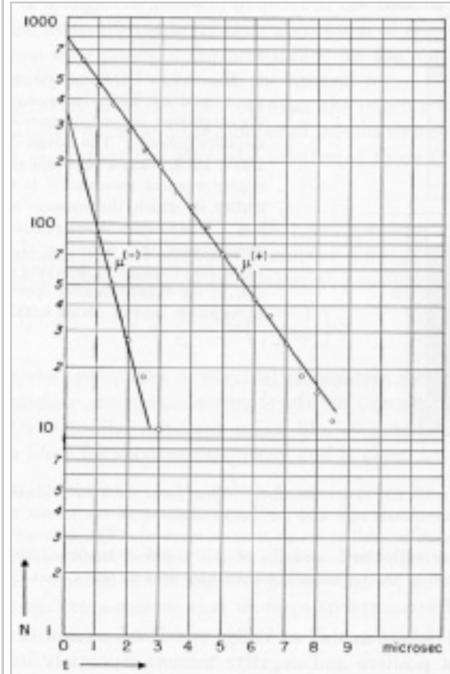

Figure 3. Disintegration curves of positive and negative muons in aluminum. (Rossi, p 168).

The negative muon decays weakly as shown in Figure 4.

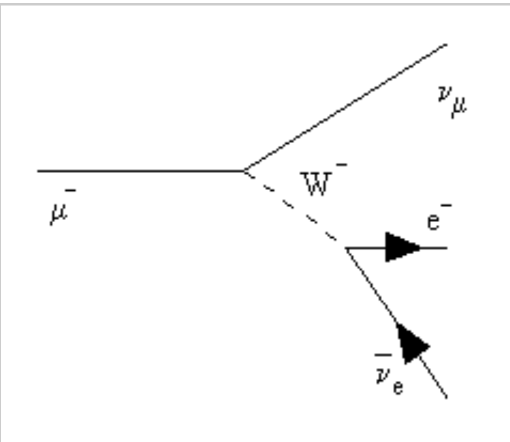

Figure 4. Feynman diagram of muon decay.

The neutrinos are not detected in our apparatus. The probability that this decay occurs depends on the couplings shown in Figure 5.

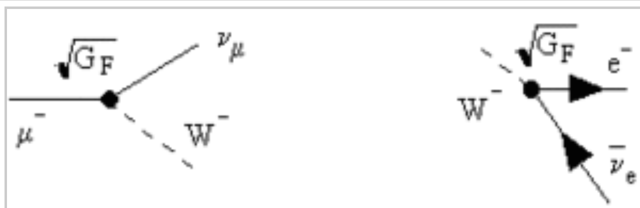

Figure 5. Feynman diagram of muon decay.

where the Fermi constant G_F is the strength of the coupling of the weak force. Since the decay rate Γ_μ is proportional to the square of the amplitude of the above diagram, one expects $\Gamma_\mu = 1/\tau_\mu \propto G_F^2$. In fact, the lifetime of the muon is:

$$\tau_\mu = \frac{192\pi^3\hbar^7}{G_F^2 m_\mu^5 c^4}$$

where m_μ is the mass of the muon. If we measure τ_μ and m_μ, we have found G_F!

APPARATUS AND INSTRUMENTATION

A set of three plastic scintillation detectors stacked vertically detects muon events. See the diagram below. The scintillator material (polystyrene plus a phosphor, p-terphenyl) emits a light pulse when an ionizing particle deposits energy in it. The light pulses are converted into electrical pulses by the photomultiplier tubes (PMTs). The signals from the three PMTs are processed by discriminators, which generate logic pulses when they receive pulses larger than a predetermined threshold. Coincidence units and a gate generator form the trigger logic that defines when the events should be captured by the digital storage oscilloscope. A computer and LabVIEW data acquisition programs transfer information from the scope, record and plot the data. A “home-made” scaler counts the number of triggers.

In the lifetime measurement, the particles of interest are the muons that stop in the middle detector. Only a small fraction of the incident muons stop. A typical muon incident upon the apparatus has energy of 20 GeV and only loses a few MeV in the plastic scintillators. The signature of a muon, which does stop in the middle detector, is a pulse in the top (T) detector, in coincidence with a pulse in the middle (M) detector as well as no pulse in the bottom (B) detector. We call this triple coincidence our "start" signal: i.e., $start = T \wedge M \wedge \overline{B}$. We determine the lifetime by measuring the delay between this signal and a subsequent signal that has an electron signature. The simplest electron signature is any pulse from the middle detector, i.e., $stop = M$. One could also stop on an electron that goes back up $(T \wedge M \wedge \overline{B})$ or one that goes down $(\overline{T} \wedge M \wedge B)$.

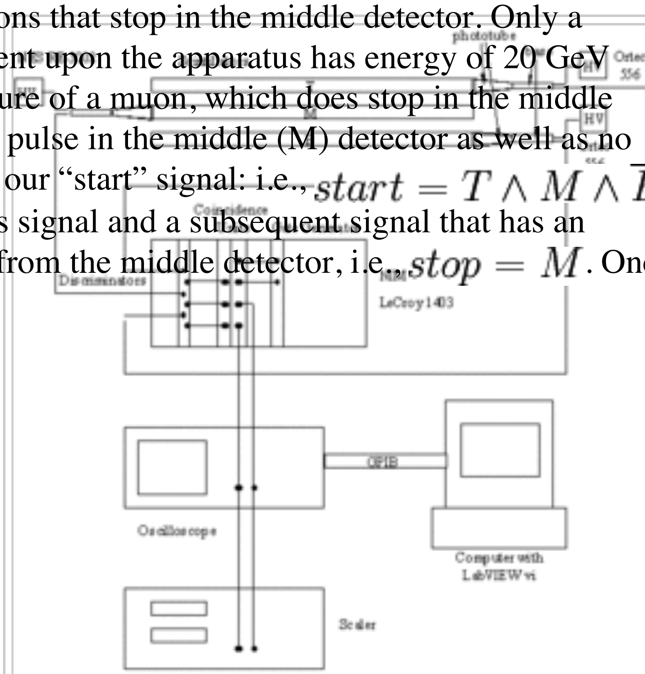

Figure 6. Muon lifetime block diagram

We are only interested in stop pulses that follow a start pulse within an appropriate time window. One can define a "gate" pulse, using a delay gate generator that starts shortly after the "start" pulse and has a width of, e.g., 10 times the expected muon lifetime. The scope is then triggered on (stop ^ gate).

The delay measurement is repeated for a large number of muon decays. A histogram of the results should show a negative exponential distribution.

Figure 7. Homemade scaler and coaxial delay box

Scintillation Detectors

The scintillators are made of clear plastic of density 1.08 g/cc. A small amount of phosphorescent material added to the plastic emits light in response to stimulation by ionizing radiation. The light is blue to soft UV (distribution centered around 450 nm). The plastic is wrapped in a reflecting layer and then covered with black plastic to keep out ambient light. The body of the detector is long, flat and thin. It is coupled to a photomultiplier tube by a trapezoidal light pipe made of the same plastic, without the phosphorescent material. When the cathode of the photomultiplier is struck by a photon of sufficient energy, an electron is liberated through the photoelectric effect. The cathode is operated at a large negative voltage. The photoelectron is accelerated toward the next electrode, called a dynode, which is held at a potential closer to ground. The energy gained by the electron is sufficient to liberate several electrons from the first dynode. A series of dynodes creates an avalanche effect, multiplying the original electron by a factor on the order of 10^6 to 10^8. The electrons are collected at the anode (the last electrode) and generate a fast, negative current pulse. A BNC coaxial connector on the base of the PMT is connected to the anode.


Figure 8. Coaxial delay box

PMT Afterpulsing

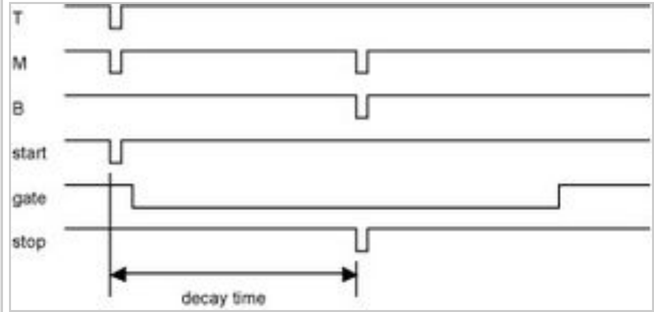

Figure 9. Muon lifetime timing diagram

Photomultipliers have a property that may interfere with the muon lifetime measurement. With some probability, on the order of a few percent or tenths of a percent, any given electron pulse in the PMT will be followed by a correlated pulse called the afterpulse. There are two types of afterpulses. The first type is caused by secondary electron emission from the dynodes or the supporting structure of the dynodes. These occur within tens of nanoseconds of the pulse, and are thus not a concern for the muon lifetime measurement. Second, ions formed in the PMT from residual helium can travel up the dynode chain and again liberate secondary electrons, which in turn cause afterpulses. Since ions are much heavier than electrons, these afterpulses occur on a longer time scale. These ion afterpulses have to be rejected by the discriminator. If necessary, one can do data runs for different thresholds to verify that the muon lifetime result does not depend on disciminator threshold.

NIM Modules

Discriminator (LeCroy 821) The purpose of the discriminator is to reject pulses smaller than a threshold. Input to the discriminators comes directly from the phototubes. The input pulse polarity is negative. If the amplitude of an input pulse is greater than the threshold, the discriminator gives an output pulse. If the amplitude of an input pulse is less than the threshold, the discriminator does nothing. A small recessed potentiometer is used to adjust the threshold. *Use caution when adjusting the threshold and width; it is possible to damage the circuit board by putting a screwdriver in the wrong place*. The threshold voltage times ten is present at a front-panel analog dc output. The output pulse is a negative current pulse of 16 mA, which corresponds to a –0.8 V pulse into 50 Ω. This is referred to as a NIM pulse. The width of the output pulse is adjustable by another recessed potentiometer. The LeCroy 821 is a quad discriminator.

Coincidence Units (LeCroy 622) Each unit has two inputs and a switch to choose between AND and OR. There are two pairs of NIM outputs, one fast negative output and one complimentary output. The width of the NIM output pulse can be adjusted with a front-panel recessed potentiometer. The output pulse must be wide enough to be adequately sampled by the scope. The LeCroy 622 is a quad unit.

Note on "vetoing": When you try to form A and $\overline{B}$, it is important to make sure that the $\overline{B}$ pulse fully overlaps the A pulse. In other words, the $\overline{B}$ pulse must arrive earlier and stay longer than the A pulse. One can achieve this by delaying the A pulse using the coaxial line delay box (located underneath the scaler) and widening the $\overline{B}$ pulse.

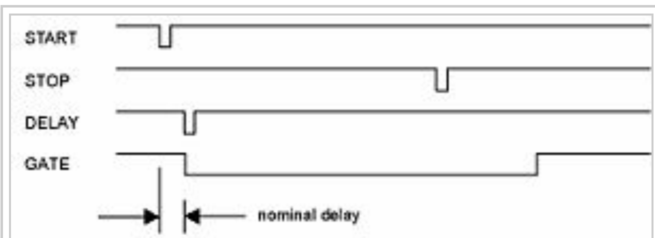

Figure 10. Delayed gate pulse.

Gate Generator (LeCroy 222) The LeCroy 222 is a dual gate generator. Each channel has a START and a STOP inputs. Two outputs are used in this experiment: DELAY and NIM. NIM produces a pulse that starts immediately after a START pulse and has a width determined by the rotary switch and recessed potentiometer. However if the GATE and START pulse overlap, the coincidence GATE $\wedge$ START will be true by definition for popular START signals. To avoid this problem, trigger the GATE in one section of the 222 using the DELAY output from the other. The STOP input can be used to terminate the GATE before it times out.

Data Acquisition

The Tektronix DPO3014 digital storage scope is used to capture the electronic signature of muon and electron decays. The scope must be configured in such a way that:

- It triggers on “stop ^ gate”.
- The trigger mode is normal (not auto).
- The horizontal range is adequate to capture both the “start” and the “stop” pulses for the longest decay time of interest (= gate width).
- The position of the “stop” pulse is close to the right edge of the screen.

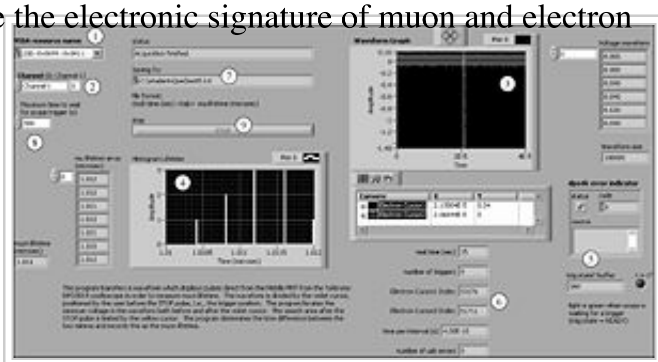

Figure 11. LabVIEW program for muon lifetime measurement.

A LabVIEW virtual instrument (vi) called "mu_life_apr11.vi" communicates with the oscilloscope and records lifetime data. For the mass measurement, use "mu_pha_apr11.vi." This vi collects data for mass and lifetime simultaneously. The numbers of the following bullet points correspond to labels in the figure of the lifetime vi.

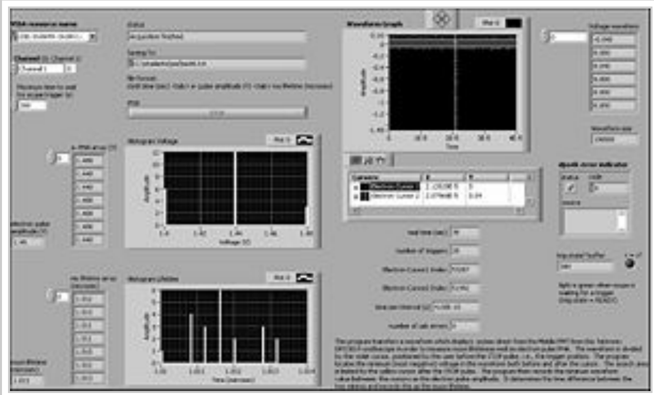

Figure 12. LabVIEW program for muon mass measurement.

- (Figure 11-1). "mu_life_apr11.vi" establishes communication with the scope at the USB address in control # 1. It places the scope in SINGLE mode. When an event triggers the scope it goes to STOP mode. At fixed intervals the program queries the scope to see whether it is still waiting for a trigger.
- (Figure 11-2). When a trigger is detected, the program requests the scope to transfer the waveform in the channel selected by control # 2. Select whichever channel is displaying the output from MIDDLE discriminator. MIDDLE is a subset of both START and STOP, so both muon and electron will be detected in this channel.
- (Figure 11-3). The waveform is displayed at indicator # 3. It may not appear identical to the oscilloscope view due to sampling speed limitations. Be sure to use at least 100,000 points in the waveform to ensure adequate sampling of the pulses. The waveform array and array size are displayed to the right of the waveform graph. After the first event is detected, the user has to set one cursor before and the other cursor after the STOP pulse. Use the horizontal zoom tool to get a close look.
- (Figure 11-4). Indicator # 4 is a histogram of lifetime data. An array indicator lists all the lifetime values, and the most recent value is displayed to the left of the array.
- (Figure 11-5). The error indicator and trigger state indicator, # 5 inform the user whether an error occurs in USB communication. If an error occurs, the vi resets the interface and places the scope back in SINGLE mode.
- (Figure 11-6). Indicators # 6 display the real time (clock time) elapsed since mu_life.vi started running, the number of triggers, the index of both cursors, the interval between time points of the waveform, and the number of USB errors.
- (Figure 11-7). Data is recorded in a text file. Every data point is appended immediately after it is acquired to protect against computer crashes. The most common cause of interruption is Windows Update; make

sure that it is turned off. The data file should look like the table at right. The user is queried for a file name and the path to the file is displayed in indicator # 7.

- (Figure 11-8). If the program does not receive a trigger in 300 seconds, it stops automatically.
- (Figure 11-9). When you are ready to terminate a data run, press this STOP button to close the data file and scope connection properly. The red stop sign in the menu bar aborts the program – use it only if the program locks up.

Real Time (min)	**Lifetime (microsec)**
0.74	1.9600
0.86	1.8200
1.18	0.4900
1.51	2.7800
1.60	3.2400
1.96	0.4200
2.28	0.2300
3.32	0.7500
3.76	1.7000
3.93	2.1300
4.32	1.0100

"mu_pha_apr11.vi" is used for the muon mass measurement. The data flow is the same as described above with the additional feature that the software measures the amplitude of the electron pulse. In order to accumulate information about the electron pulse height distribution, look at the pulses directly from the middle PMT instead of from the middle discriminator. Use the Lecroy 428F linear fan-out to split the signal. Calibrate with muons that go through all three detectors as described below.

Muon Mass

The decay products of a negative muon are an electron and two neutrinos. If the muon decays at rest (a good approximation for muons which stop in a detector), then the total kinetic energy of the electron and neutrinos will be approximately equal to the rest mass of the muon. The reaction must obey conservation of momentum. One possible scenario is shown below.

Convince yourself that in this scenario, the electron carries approximately half of the kinetic energy and that this is the maximum electron energy. As an approximation, neglect the rest mass of all three particles. This is not unreasonable since the electron rest mass is about a factor of two hundred less than the muon rest mass. Thus if we measure the electron energy distribution, and find its cutoff, we will have the mass of the muon.

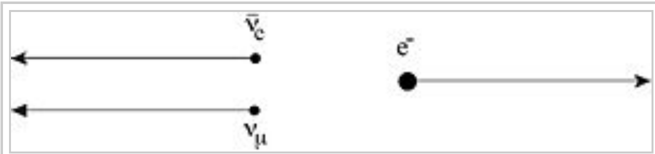

Figure 12. Momentum conservation scenario.

The apparatus for making this measurement is similar to that used for the muon lifetime. A major difference is that the oscilloscope has to be set up to view the electron pulse directly from the middle PMT. The linear fan-out (LeCroy 428F) can split the signal into two channels: one for the discriminator, and one for the oscilloscope.

To calibrate the electron pulse height distribution in terms of energy, measure the pulse height distribution for muons that pass through all three detectors. The peak of this distribution corresponds to the energy deposited by a minimum-ionizing muon. Consult the Particle Physics Booklet for a graph of -dE/dx as a function of muon energy.

EXPERIMENTAL PROCEDURE

First, familiarize yourself with the equipment. Measure the dimensions of the scintillators. Identify cables and find out which power supply is connected to which detector. Set the high voltage to an appropriate value (see step # 1 below) and observe the signals on the oscilloscope. Try to identify the pulses due to through-going muons (which tend to leave nearly constant energy in the detector) by triggering on one detector and observing another. For example, trigger on B and watch signal from T. Some tweaking of the trigger level will be needed to get a clear image. Switch the detectors. You may find larger time jitter in some combinations. Why?

Connect the signals to the discriminator. Adjust the high voltage and the discriminator threshold to optimize efficiency. This is an iterative process:

- 1. Set the high voltage and the threshold to some initial values. The high voltage should be around –2.0 kV to –2.2 kV (-2.4 kV maximum). The discriminator threshold should be set between –50 mV and –200 mV. At this stage you are relying on known properties to set the rough operating parameters of the detectors. *** VERY IMPORTANT: As of December 2009, there are two sets of apparatus for muon lifetime. Set #1 uses Amperex XP2020 PMT's (max HV –2.4 kV). Set #2 uses ADIT B29B02H PMT's (max HV –800 V and typical thresholds 30 to 50 mV). Discuss the pros and cons of each apparatus with the faculty or staff before deciding which to use.**
- 2. Measure the relative efficiency of one detector as a function of its high voltage. To measure the efficiency of the middle (M) detector for example, measure the rate of the coincidences between (T^M^B) and (T^B). The quotient (T^M^B)/(T^B) is the efficiency (ignoring the effects of the geometrical inefficiency and the random noise). If the voltage is set too low, the detector will be inefficient. If too high, noise will predominate. At intermediate voltages, a plateau should be observed. This is the desired operating regime.
- 3. Repeat step # 2 for the other two detectors.
- 4. Now you have optimized the high voltage for the initial threshold setting. Next phase is a confirmation.
- 5. Measure the efficiency of one detector as a function of its discriminator threshold. Use the same technique as in step # 2. Repeat for all detectors.

You may have to repeat the process more than once if the initial setting was too far from the optimum.

Build the trigger logic with the coincidence and the gate generator modules. Check the relative timing of the pulses at the inputs of all the functional units. Remember: coincidence inputs must have good overlaps; veto input must be wider than the signal to be vetoed.

Once the logic is set up, record the complete schematic in your notebook. The level of completeness must satisfy the criterion that "if your experiment is ripped apart during the weekend, you can rebuild it and it will work the first time." Don't forget to record the pulse widths and the delays. Also measure the count rates for all signals and record them.

Run the lifetime measurement. Try different "stop" signals. They will have different background levels, which you can see as a constant component in your delay time distribution. While you are waiting for measurements, calculate how much data you will need to achieve, e.g., a 1% measurement of the muon lifetime.

Once the data are taken, fit the data. You may use any software packages you prefer. Popular choices are: Excel, KaleidaGraph, CPLOT (available on the Linux box), PAW and Matlab. You need to learn how to use the software to fit the data to an exponential plus a constant background. You also need to be able to extract the error on the fit parameters.

If time permits, measure the pulse height spectra for muons and electrons and extract the muon mass. See the appendix and consult the faculty or staff for details concerning the mass measurement.

NOTES

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Passage of Particle Through Matter" for energy loss rates -- pp 1251-52, i.e., 82-83 of this document. Note this is a large file - be patient!

D. Chitwood, "A Measurement of the mean life of the positive muon to a precision of 11 parts per million (http://www.fas.harvard.edu/~phys191r/References/b4/Chitwood2007.pdf) ," University of Illinois, 2007. See section 9.7 for analysis of PMT afterpulsing.

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BENCH NOTES

- HP 8004 Pulse Generator (http://www.fas.harvard.edu/~phys191r/Bench_Notes/B4/HP8004.pdf)
- Lecroy 821 Quad Discriminator (http://www.fas.harvard.edu/~phys191r/Bench_Notes/B4/Lecroy821.pdf)
- Lecroy 622 Quad Coincidence Unit (http://www.fas.harvard.edu/~phys191r/Bench_Notes/B4/Lecroy622.pdf)
- Lecroy 222 Dual Gate Generator (http://www.fas.harvard.edu/~phys191r/Bench_Notes/B4/Lecroy222.pdf)
- Ortec 556 High Voltage Power Supply (http://www.fas.harvard.edu/~phys191r/Bench_Notes/B4/Ortec556.pdf)
- Canary II Dosimeter (http://www.fas.harvard.edu/~phys191r/Bench_Notes/canary.pdf)
- ADIT B29B02H PMT Specifications (http://www.fas.harvard.edu/~phys191r/Bench_Notes/B4/b29b02h_specs.pdf)
- ADIT B29B02H PMT Data Sheet (http://www.fas.harvard.edu/~phys191r/Bench_Notes/B4/b29b02h_data.pdf)
- PMT Properties (Hamamatsu publication) (http://www.fas.harvard.edu/~phys191r/Bench_Notes/B4/PMT_prop.pdf)
- PMT Handbook (Hamamatsu publication) (http://www.fas.harvard.edu/~phys191r/Bench_Notes/B4/PMT_handbook.pdf)
- Light Levels and Noise (K. J. Kaufmann) (http://www.fas.harvard.edu/~phys191r/Bench_Notes/B4/lightlevelnoise.pdf)

Links

- Particle Data Booklet (http://pdg.lbl.gov/)
- Stopping Range of Ions in Matter (http://www.srim.org/)
- MIT Muon Experiment (http://web.mit.edu/8.13/JLExperiments/JLExp_14.pdf)
- Rice Muon Experiment (http://www.ruf.rice.edu/~dodds/Files332/muon.pdf) --link broken--
- CalTech Muon Experiment (http://www.pma.caltech.edu/~ph77/labs/exp15.html)