LIFETIME OF THE MUON

Introduction

Muons are unstable particles; otherwise, they are rather like electrons but with much higher masses, approximately 105 MeV. Radioactive nuclear decays do not release enough energy to produce them; however, they are readily available in the laboratory as the dominant component of the cosmic ray flux at the earth's surface. There are two types of muons, with opposite charge, and they decay into electrons or positrons and two neutrinos according to the rules

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

$$\mu^- \rightarrow e^- \; \bar{\nu}_e \; \nu_\mu \, .$$

The muon decay is a radioactive process which follows the usual exponential law for the probability of survival for a given time t. Be sure that you understand the basis for this law.

The goal of the experiment is to measure the muon lifetime which is roughly 2 μs. With care you can make the measurement with an accuracy of a few percent or better. In order to achieve this goal in a conceptually simple way, we look only at those muons that happen to come to rest inside our detector. That is, we first capture a muon and then measure the elapsed time until it decays. Muons are rather penetrating particles, they can easily go through meters of concrete. Nevertheless, a small fraction of the muons will be slowed down and stopped in the detector.

As shown in Figure 1, the apparatus consists of two types of detectors. There is a tank filled with liquid scintillator (a big metal box) viewed by two photomultiplier tubes (Left and Right) and two plastic scintillation counters (flat panels wrapped in black tape), each viewed by a photomultiplier tube (Top and Bottom). Charged particles (muons and electrons) emit light when they pass through scintillation material. This light is detected with photo-multiplier tubes. For more discussion of scintillation and photo-multiplier tubes please read the write-up on detection of high-energy particles. The experiment relies on co-incidence techniques. When a cosmic ray passes through all detectors it should generate signals in all photomultiplier tubes at nearly the same time (how long does it take the muon to travel from the top to the bottom of the detector?) Similarly, when the muon decays in the tank of liquid scintillator, the resulting high energy electron or positron will generate light in the left and right photomultiplier tubes.

General Experimental Approach

There are two approaches to measuring the lifetime of the muons stopped in the liquid scintillator. In the first approach we try to make sure that the muon has in fact stopped in the liquid scintillator box. For example, if the muon triggers the Top plastic scintillator and Left and Right detectors, but not the Bottom plastic scintillator located under the liquid scintillator box (see Figure 1), then there is a good chance it has stopped inside the box. However, one also has to consider the possibility that the muon travels at an angle through the apparatus or that the bottom detector has a detection efficiency less than 1. If we are sure the muon has stopped inside the liquid scintillator box, one just has to wait a few micro-second and a second pulse of light in Left and Right detectors will indicate the decay of the muon.

In the second approach, we look at all events that trigger the Left and Right detectors of the liquid scintillator. The majority of them would be penetrating muons, but a small fraction will

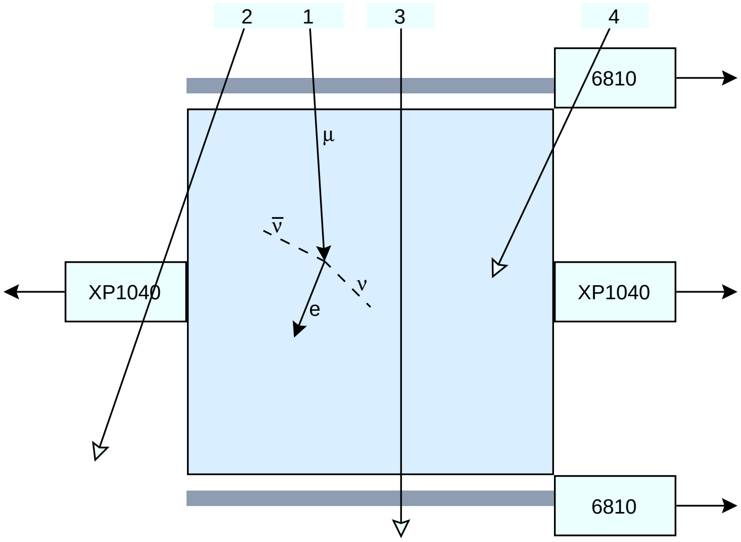


Figure 1: Schematic of the liquid scintillator tank (light hatched area) and fixed plastic scintillators (dark hatched areas). Track 1: A muon that stops is recognized by $\mathrm{T} \cdot \mathrm{L} \cdot \mathrm{R} \cdot \overline{\mathrm{B}}$. The bar over B detector indicates absence of the signal in the bottom detector at that instant. When it decays later it is recognized by $\mathrm{L} \cdot \mathrm{R} \cdot \overline{\mathrm{T}} \cdot \overline{\mathrm{B}}$. Track 2: A misidentified stopping muon $\mathrm{T} \cdot \mathrm{L} \cdot \mathrm{R} \cdot \overline{\mathrm{B}}$. Track 3: A through-going muon (or other particle) $\mathrm{T} \cdot \mathrm{L} \cdot \mathrm{R} \cdot \mathrm{B}$. Track 4: An accidental muon decay signal $\mathrm{L} \cdot \mathrm{R} \cdot \overline{\mathrm{T}} \cdot \overline{\mathrm{B}}$.

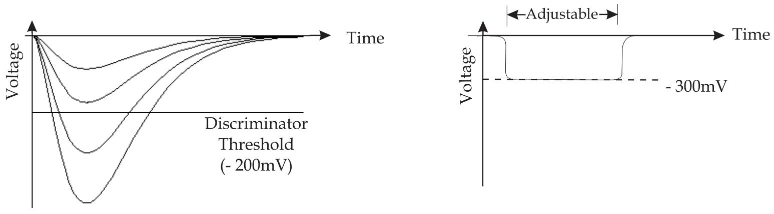
come from stopped muons. Suppose we make a histogram of the time difference between two consecutive events in the liquid scintillator. Since the arrival of the penetrating muons is a random process, the histogram of the pair-wise time difference from these events will have a constant time distribution. On the other hand, decays of stopped muons will generate two events with an exponentially-decaying probability as a function of time. Hence, one expects to see an exponential decaying signal on top of a flat background.

There are some tradeoffs in each of the approaches. In the first approach we restrict ourselves to vertically-going muons, but there should be almost no background from penetrating events. In the second approach the number of muon decay events will be larger since muon from all directions will contribute, but the background events will also generate counts and tend to increase the statistical uncertainty. Which approach is better depends on the concrete numbers relevant to the apparatus.

Equipment

High voltage power supplies are needed for photomultiplier tubes (PMT). The maximum high voltage for Left and Right supplies is 2800 V and for Top and Bottom supplies is 2400 V. Never switch the polarity of the HV supplies. Some of them have ”Stand-by” setting. One should leave the supply on that setting for about 10 seconds before switching to the ”On” position. The outputs of the photomultiplier tubes are connected to the panel on the top of the equipment rack.

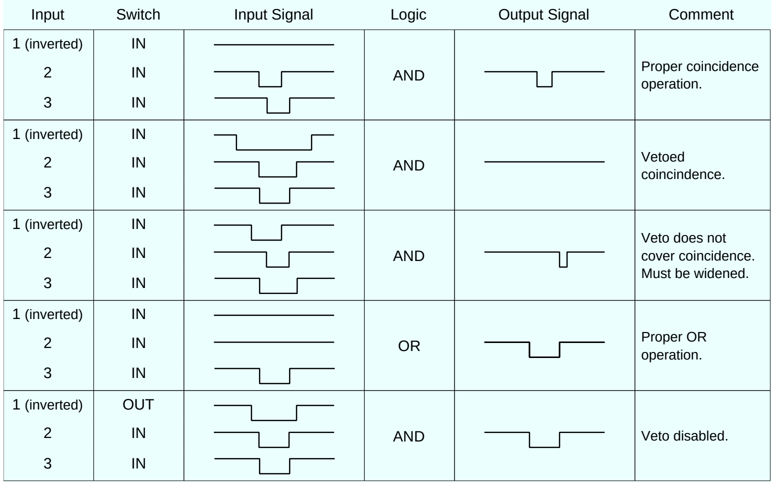
Discriminators are devices that convert a photomultiplier pulse into a square pulse of well-defined shape, as illustrated in Figure 2. The threshold adjustment on the discriminator determines the minimum pulse size that is required to trigger it. One can also adjust the width of the output



Phototube Output Pulses

Discriminator Output Pulse

Figure 2: Plots of the photomultiplier tube and discriminator outputs. The discriminator output starts about 10 ns after the phototube pulse put into it drops below the -200 mV threshold. This delay is a fixed characteristic of the electronic circuit.



Input	Switch	Input Signal	Logic	Output Signal	Comment
1 (inverted)	IN		AND		Proper coincidence operation.
2	IN				
3	IN				
1 (inverted)	IN		AND		Vetoed coincindence.
2	IN				
3	IN				
1 (inverted)	IN		AND		Veto does not cover coincidence. Must be widened.
2	IN				
3	IN				
1 (inverted)	IN		OR		Proper OR operation.
2	IN				
3	IN				
1 (inverted)	OUT		AND		Veto disabled.
2	IN				
3	IN				

Figure 3: Example of the operation of the coincidence circuit.

pulse. Most of the electronic circuits expect negative-going square pulses.

Coincidence detectors perform simple logic operations such as AND, OR and NOT. They can be used to generate a pulse when several detectors get hits at the same time or to veto (suppress) a pulse when another detector also gets hit. Some examples of their operation is shown in Figure 3. There are several models with different combination of inputs and switches selecting the logic operation being performed. The width of the output pulse is also adjustable on some models.

Time-to-Amplitude converter (TAC) is a device that linearly converts the time interval between two pulses into a voltage output. It charges a capacitor at a constant rate from the start pulse until the stop pulse and outputs a pulse with height proportional to the resulting voltage on the capacitor. It has Start and Stop inputs and ways to select the range of time intervals that is linearly converted into the height of the output pulse.

Amplifier allows one to linearly amplify a voltage signal by a certain gain as well as invert it if necessary.

Delay line can be used to delay a pulse by a certain amount. It simply contains a long length of coaxial cable where the pulse propagates with a speed of about 20 cm/nsec, 2/3 of the speed of

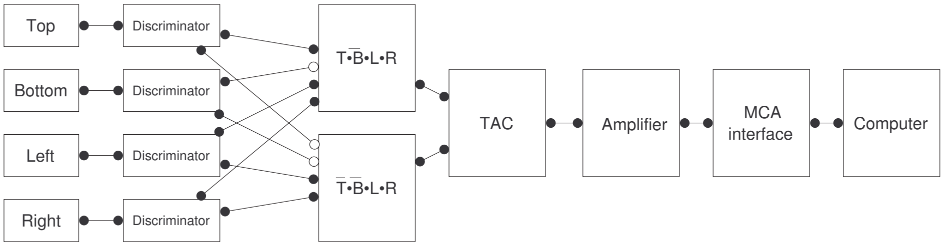


Figure 4: Example of the overall setup using the first measurement approach. Open circles denote the “NOT” operation.

light. A delay line is used if one wants to start and stop the TAC using the same type of coincidence.

Frequency counter can be used to quickly measure the rate of pulses on a particular channel.

Function generator can be used to generate two pulses with a known time interval to calibrate the TAC.

Multi-channel analyzer (MCA) is ultimately used to record the the height of incoming pulses and convert them to a historgram that is stored on the computer. The MCA breaks the input voltage range (0-8V) into 1024 equal bins and adds one count to the bin corresponding to the peak voltage of each arriving pulse. The combination of TAC and MCA allows one to construct a histogram of time intervals between pairs of pulses. Figure 4 shows an example of the overall measurement setup.

Oscilloscope is your friend in learning about the apparatus. Since the events that you want to look at are rather rare, with a few nsec pulse happening every msec or second, you will not see them on the oscilloscope unless it is triggered properly. By deciding how to trigger the scope you can choose to look at a particular kind of pulses. One can choose one of the channels as the trigger or the external trigger input, once you know the proper trigger level. Also since the signals are fast it is important that cables are properly terminated. This means that each output should have a 50 Ohm load (a small BNC plug) attached to it. Commonly used coaxial cables have characteristic impedance of 50 Ohms (that means the capacitance and inductance of the cable per unit length is such that $\sqrt{L/C} = 50$ Ohm) and one can show that a transmission line terminated with a 50 Ohm resistor does not have any reflections. Otherwise the signals will be quite distorted (for fun, look at the signals through the delay line without termination).

Procedure

There are several things to explore before you can collect good data.

a) Photomultiplier voltages and discriminator thresholds.

Looking at the photomultiplier output you will notice that the output pulses vary greatly in size, their size is roughly proportional to the number of photons collected by the PMT and therefore the energy deposited in the scintillation detector. The discriminator threshold should be set so most “real” pulses trigger it but small “noise” pulses are rejected. You can decide which pulses are “real” by using a coincidence between two detectors, that ensures that a muon has passed through the apparatus. You can also connect the PMT output to the MCA through the amplifier and collect a bit of data on the computer to get a sense of the pulse height distribution. Note also that the proper threshold setting depends on the HV setting.

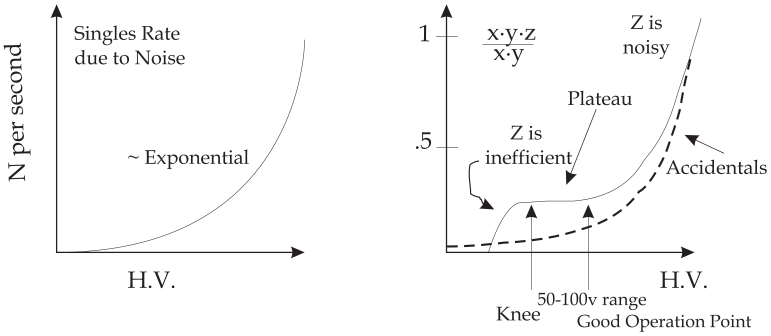


Figure 5: Typical plateau curves.

If the high voltage value on the PMT is too small, it will have low quantum efficiency (that means that it might miss some events entirely) and low gain (that means that all pulses will be smaller). If the HV value is too high, it will cause a lot of spurious “noise” pulses due to sparking and individual stray photons that might make it through the cracks in light shields. Check if there is a significant light leak by comparing the event rate in a given detector with the room lights on and off. If the difference is dramatic, one should try to find the location of the leak (by shining a flashlight, for example) and seal it with black tape.

A fool-proof way of making sure the HV voltage and theshold settings are correct is to use a triple coincidence $x \cdot y \cdot z$, for example, the top plastic scintillator and two detectors looking at the liquid scintillator tank. A double coincidence $x \cdot y$ selects a muon, which should be seen by the third detector. By adjusting the HV and the discriminator threshold you should find a plateau, as shown in Figure 6, where the detected rate is independent on the settings. This is called “plateauing the detector”.

One should also note that a fast cosmic ray muon penetrating through the liquid scintillator tank deposits about 2 MeV per cm of scintillator, or a total of ≈ 120 MeV in the 2 ft tank. On the other hand the electron resulting from muon decay has an energy ranging between 0 and 53 MeV (why is it not the rest mass of the muon, 106 MeV?) so it can’t possibly deposit as much energy as a penetrating cosmic rays do. So, it is possible to adjust the thresholds so that you will trigger only on the penetrating muons and will reject all muon decay signals!

b) Coincidence timing.

To generate accurate coincidences you need to adjust the width of the discriminator output pulses. Generally, you want the pulses to be as short as possible (why?). Watch the pulses from two detectors on the oscilloscope to get a sense of relative delay between them and the fluctuations of the relative arrival times. You can adjust for constant relative delay of the pulses with appropriate length of BNC cable, but fluctuations of the arrival time is the intrinsic limitation of the detectors called time resolution. To get a quantitative measure of the time resolution you can use the TAC and collect a short run on the computer. Set the discriminator output widths to the smallest reasonable values, and put in the appropriate cable lengths. Remember that a veto must arrive a few nanoseconds earlier than the other signals and must last until they are gone (Figure 3).

c) The range of time intervals to be recorded

The range of time intervals converted to the histogram depends on several settings, such as the time range of the TAC and the gain of the amplifier used before connection to MCA. The time scale should be selected so that the range of times you expect for muon decay is well sampled. One also needs to record data for times much longer than expected muon lifetime to ensure that you have a good estimate of the background. There are also various limitations of the apparatus to consider, such as the minimum time interval that can be measured by the TAC. You can calibrate the whole system by generating two pulses with a given time interval using the function generator and seeing which channel it corresponds to in the histogram recorded by the computer.

Data Collection

When everything is setup you can leave the computer to collect data. It should take about a day to get sufficient statistics. Make sure that your event rate is reasonable. What is the flux of cosmic ray muons? Estimate what fraction of them you can expect to stop in the liquid scintillator. Once you feel that you have a handle on relevant numbers, you can compare theoretically or experimentally the two approaches described in the introduction and decide which one should give the best measurement of muon lifetime. Then you can leave the apparatus integrating for a few days to get as accurate measurement of the muon lifetime as possible.

Questions to ponder

Theory

- How are muons formed in the earth's atmosphere? What other particles are produced and why muons are the dominant cosmic rays component? Given the short muon decay time, why do so many make it to the earth's surface?
- Is it necessary to know when a muon was produced to measure its lifetime? Why?
- How does the presence of accidental signals distort the time histogram of muon decay?

Experiment

- What is the rate of triggering for each individual detector in your experiment? What is the trigger rate of 2-detector coincidences? Can you estimate what fraction of these coincidences is accidental? (i.e. with no actual muon present at that time). What is the rate of accidental coincidences for 3 detectors?
- Why did we need 3 detectors for plateauing one of them? When plateauing a detector z using coincidence with x and y, what is the effect of any inefficiency in x and y on your plateau curve? What about spurious noise pulses in x and y?
- Can you account for the background in your muon lifetime data based on imperfections of the detector system?

J. H. Taylor
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