

The Muon Lifetime

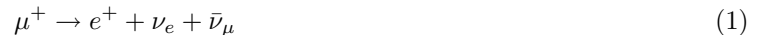
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Goals

The main goal of this experiment is to measure the lifetime of the muon. Positively charged muons incident as cosmic rays are detected and stopped in a slab of aluminum. The positrons that result from the decay of these muons are also detected. The lifetime of the muon is determined from the distribution of delay times between muon and positron detection.

Background

Positively charged muons (μ^+) are created in the upper atmosphere of Earth from the decay of π mesons. Although the lifetime of the μ^+ particle is only around 2 μsec , due to relativistic time dilation many are present near sea level. (The muon flux at sea level is roughly $10^{-2}/\text{cm}^2/\text{ster}/\text{sec}$.) The μ^+ decays according to



with an exponential decay rate given by

$$N(t) = N_0 e^{-t/\tau}, \quad (2)$$

where N_0 is the initial number of particles, $N(t)$ is the number of particles at time t , and τ is the μ^+ lifetime. In this experiment, you will determine the value of τ by measuring a distribution of decay events $N(t)$, using coincidence techniques to measure the time delay between the detection of μ^+ and e^+ particles. The μ^+ particles will be stopped in a slab of aluminum, where they will decay according to equation (1). Scintillation detectors will be used to detect both the muons and the positrons; coincidence detection will filter out only the μ^+ decay events. A Time-to-Amplitude Converter (TAC) will then be used to convert the time delay between μ^+ and e^+ detections into a voltage that can be recorded by a computer, using a simple A/D circuit. From a distribution of such events, collected over a period of hours, you will deduce the muon lifetime.

Apparatus

A schematic diagram of the experimental apparatus is shown in Figure 1. A charged particle passing through a scintillation detector is detected by the small flash of light produced in the plastic sheet; this light flash is converted to a pulse of electrons by the photomultiplier tube. The output from the photomultiplier is fed to the input of an amplifier/discriminator, which is used to filter out the noise inherent in the detector as well as to amplify the incoming charge pulse. The output from the amplifier/discriminator is then fed into the coincidence circuit. In order to measure only the muons and positrons associated with the muon decay, coincidence detection - a combination of logic modules and delay lines - is used as follows. We wish to keep track of the timing between two events: (a) the detection of an incoming muon that will subsequently decay in the aluminum slab, and (b) the detection of the positron that results from the decay of the muon we detected in (a). We'll use these two events to 'start' and 'stop' a 'clock'; it is the distribution of delay times between the 'start' and 'stop' events that we want to use to determine the muon lifetime. The muons in (a) are the particles that are detected by both the A and B detectors (see Figure 1), but not the C detector. The positrons in (b) are the particles that are detected by either the A or the C detectors, but not by both. In other words:

$$\text{'start' signal:} \quad (\mathbf{A} + \mathbf{B}) + \bar{\mathbf{C}} \quad (3)$$

$$\text{'stop' signal:} \quad \mathbf{A} \text{ XOR } \mathbf{C} \quad (4)$$

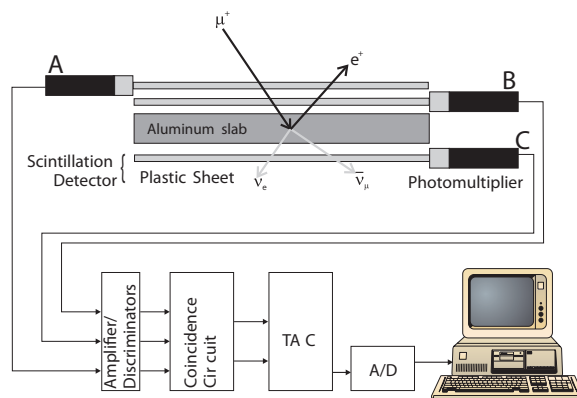


Figure 1: Schematic diagram of the apparatus.

One coincidence circuit that can be used to satisfy equations (3) and(4) is shown in Figure 2. In addition

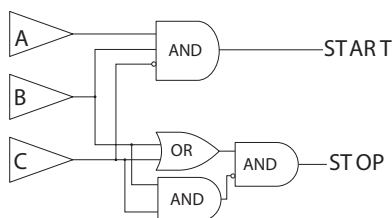


Figure 2: Coincidence circuit used.

to the logic modules shown, delay lines (i.e., calibrated lengths of cable) must be used between the various elements in the circuit to ensure that each of the three detectors are in coincidence with each other - so that a (hypothetical) particle detected 'simultaneously' by all three detectors produces pulses that are all synchronized - as well as to ensure that the start and stop signals are timed for proper operation of the Time-to-Amplitude Converter (TAC). The TAC is used to convert the time between the 'start' and 'stop' signals into a voltage that can be recorded by the computer, with the aid of the A-to-D board.

Procedure

1. Adjust the detectors

In order to optimize the signal-to-noise ratio (SNR) of the photomultipliers, you'll need to adjust the high voltage applied to each of these detectors. As shown schematically in Figure 3, the noise level from a photomultiplier will increase monotonically with voltage, while the signal output will reach a maximum value and then plateau. Thus, the highest SNR is achieved when the voltage is set close to the start of the 'plateau region'. A single high voltage (HV) power supply is used for the A and B detectors and a HV distribution box is used to fine tune the voltage applied to each of the detectors separately. The signal

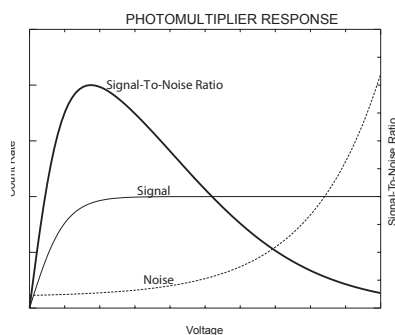


Figure 3: Photomultiplier response versus applied voltage.

generated by each photo multiplier is amplified by a transistor circuit in the base of the photo multiplier tube (see Fig. 4).

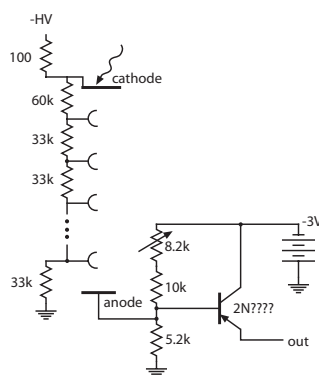


Figure 4: Amplification circuit for photomultiplier tubes

Make sure that the batteries in this circuit are good. Use an electron source to plateau the two detector power supplies used in this experiment. Set the threshold level on the discriminator to the minimum of 25 mV and measure the counting rate as a function of voltage applied. Start at a value of -1500V for both, and increase the voltage in increments of 50V. Take the same data without the electron source. From the signal to noise ratio, you can determine the start of the plateau region, and thus where to set the HV. You should also determine where to set the discriminator threshold level so as to minimize the noise level. **[this should be done in coincidence and without an electron source]**

2. Adjust the coincidence circuit

You'll first need to verify the operation of all the logic units, and insert delay lines as appropriate to ensure that all three detectors are in coincidence. Using the dual-beam oscilloscope, observe the coincident arrival of test pulses in detectors A and B. Measure the A+B coincidence rate using one of the logic units and a scaler/timer. Then 'and' the output of detector C with the A and B signals, and measure the three-fold coincidence rate; you'll need to add delay lines (after the discriminator outputs) in order to maximize this rate. A good rule of thumb is that one foot of RG59 cable delays the pulse by about one nanosecond.

a. Muon detection: To detect muon decay events, wire one of the logic modules as per equation (3). You'll need to connect the output from the C detector threshold circuit to the veto input of the logic module.

For maximum efficiency, adjust the width of the veto input signal (\overline{C}) so that it arrives 10 ns earlier, and lasts 10 ns longer, than the A and B signals.

b. Positron detection circuit: Now connect another logic module according to equation (4). Pay close attention to the lengths of all the cables you use, in order to avoid a systematic error in the lifetime measurement. Remember that each NIM module introduces approximately 10 nanoseconds of delay.

3. Calibrate the TAC and A/D

The output of the Time-to-Amplitude Converter (TAC) is a signal whose voltage is proportional to the length of time between the 'start' and 'stop' input signals. The computer software converts this voltage to a channel output. In order to calibrate the TAC, use the Gate and Delay Generator (GDG) to delay a test pulse from photomultiplier B relative to a test pulse from photomultiplier A. The delay of the pulse can be controlled by the knob on the GDG. Record the peak channel output from the computer for successive delay times. Find the relationship between the channel output and delay time for use on all subsequent data. Note that the 'start' pulse of the TAC must be delayed (using the GDG) relative to the 'stop' pulse so that the TAC is not stopped immediately.

Questions

You will need to acquire data for at least 24 hours in order to accumulate enough counts to determine the muon lifetime with 'reasonable' precision. In your report, be sure to include an estimate of the experimental uncertainty in the determination of the value for τ , as well as a discussion of the source of errors, and how these errors might be minimized or eliminated. In your first attempt you will fit the data to an exponential in order to measure τ . You will note that the fit is not especially good. The primary reason for this is that the cosmic ray muon flux consists of both positive and negative muons. Whereas the positive muons can only decay, the negative muons can disappear via decay and via capture on a proton. The latter process depends on the proton number to the fourth power. For aluminum the capture rate is about 1.5 times the decay rate. Therefore, you should try to fit the data with two exponentials. See the book by Rossi, "Cosmic Ray Particles" for data on positive and negative muon fluxes at sea level. Compare your measured total flux rate per square cm with Rossi's. To what do you attribute any discrepancies?

References

- [1] A. Melissinos, *Experiments In Modern Physics*, Academic Press, 1966
- [2] B. Rossi, *Cosmic Ray Particles*