Muon Lifetime

Background

The muon is a particle very much like an electron, but with 207 times the mass. It is also unstable, decaying very quickly into an electron and a pair of neutrinos. Muons are created by (among other things) the interactions of high-energy γ rays with matter. During these interactions, a shower of other particles is created, including photons.

In this experiment, we will measure the mean lifetime of the muon by measuring the time between the showers of photons marking the beginnings and ends of individual muons.[1, 404–409]

Equipment

Our muon detector consists of a large plastic waveguide with a photomultiplier tube (PMT) at one end. Any photon-generating event that occurs within this plastic has some chance of being detected by the photomultiplier. The signal from this photon event is sent to a Time-to-Amplitude Converter (TAC), which converts the time between two signals to a voltage pulse proportional to the time. That voltage pulse is then sent to a Multi-Channel Analyzer (MCA) which generates a plot of number of pulses vs. pulse voltage. Since the pulse voltage is proportional to time, the resulting plot should show an exponential decay curve such as one would expect for any radioactive decay:

$$N = N_o e^{-\frac{t}{\tau}}$$

As you may imagine, there are some inefficiencies is this setup.

- The muon must enter the detector, or be created by a cosmic ray within the detector.
- The muon must decay within the detector.
- Photons from both creation and decay must reach the PMT, which must detect them.
- The signals from the PMT must reach the TAC while it's ready to start/stop timing.

Amazingly enough, it actually works despite all this!

In order to count a muon and send the time-proportional signal to the MCA, the TAC must receive both a 'start' and a 'stop' signal, in that order.

Since ‘start’ and ‘stop’ are indistinguishable (they’re both just pulses from the PMT) we send the signal to both inputs. The signal goes to the ‘stop’ input of the TAC first, then connects to the ‘start’ input through a delay cable. If the TAC is not timing when a signal comes from the PMT, it ignores the ‘stop’ signal. After a couple nanoseconds, the signal gets through the delay cable and hits the ‘start’ input, which starts the TAC. If the TAC is already timing when a pulse arrives from the PMT, it stops when it gets the signal, and sends an appropriate pulse to the MCA.

Most of the time, only one of the photon events marking the beginning and end of a muon life is observed. The TAC will start timing in response to this event, but won’t receive a ‘stop’ signal. If it does not observe a ‘stop’ signal before the end of its measurement range (set at 10 μs), then it will stop timing and begin waiting for another ‘start’ signal without sending anything to the MCA.

In order to convert the voltage pulses received by the MCA (recorded as “channel number”) back into time so that we can determine the lifetime of the muon, we have to calibrate the TAC. To do this, we use a pulse-pair generator with a variable delay to create pairs of events with known time separation. These pulses are sent through an amplifier to enlarge and shape them, then (optionally) through a single-channel amplifier (SCA) to further shape them into sharp spikes for better time resolution. These spikes are sent to the TAC, which sends a voltage pulse to the MCA; they are also sent to an oscilloscope which allows us to measure the actual time between pulses. All this allows us to make a graph of time vs. channel number. A linear fit of this graph gives us an equation for time, so that we can convert the channel numbers from the muon data back into time for analysis of muon lifetime.

Procedure

1. Make sure all connections and settings are correct for calibration. (See default settings below.)

2. Set the variable delay and adjust the oscilloscope so that the time between pulses is easily measured. Record the channel number of the resulting peak on the MCA.

3. Adjust the variable delay, and repeat step 2, until you have a good data set for creating a plot of time vs. channel number.

4. Connect the TAC stop input to the “anode” connection of the PMT.

5. Double-check to make sure that all connections are correct for measurement, then turn on the PMT high voltage supply main switch. After 10–15 seconds, turn on the high voltage switch. (Ignore any terrible noises from the ancient HV supply unless accompanied by smoke.)

6. Make sure the MCA is set to run for longer than its default of 240 seconds, and start it. If you're using the optional 429 Discriminator to count TAC events, reset it now.

7. Wait about a week. While you're waiting, plot a graph of time vs. channel number and do a least-squares fit so that you are ready to convert the MCA data back into a graph of counts vs. time.

8. Export the MCA data to a list of channels and counts, and plot the results. Apply an appropriate curve fit, and report your results with uncertainty.

Due to the relative scarcity of muon-detection events with this equipment, you may turn in this lab report up to one week late without penalty.

Default settings — Calibration

- 1407P Pulse Pair Generator
  - Rate: max, 10 kHz
  - Variable delay — Adjust this for calibration curve.
  - Mode: pulse pair
  - Attenuation: both out
  - Trigger ⟶ oscilloscope trigger in
  - Primary ⟶ 450 normal input
- 450 Research Amplifier
  - Coarse Gain: 100–200
  - Fine Gain: 0
  - Integrate: 0.5
  - Differentiate: 0.1
  - Input Mode: Positive Differential
  - BLR: Lo

  - Fast Bipolar Output ⟶ (oscilloscope *and* 566 TAC) *or* 420A input

- 420A Timing SCA (optional)
  - ΔE: greater than zero
  - E: Adjust so that both pulses show on ‘scope
  - Delay: minimum
  - Switches: Bipolar, Int
  - Negative Output ⟶ oscilloscope *and* TAC stop

- 566 TAC
  - Range: 100
  - Multiplier: 100
  - Delay line (approximately 6 m coax) from stop to start
  - TAC Output ⟶ MCA (BNC to computer)
  - Optional: TAC Valid Conversion Output (on the back of the unit) ⟶ 429 Discriminator Disc Input (This gives you a count of events. Interesting, though not actually all that important.)

Default Settings — Muon measurement

- High Voltage Supply
  - -1000 V to H.V. connection on PMT

- PMT
  - Disconnect amplifier or SCA from TAC.
  - Anode ⟶ TAC stop and oscilloscope (optional now).

References

[1] Adrian C. Melissinos and Jim Napolitano. *Experiments in Modern Physics*. Academic Press, Inc., 2^{nd} edition, 2003.