PHY64 Experiment 6: The Muon Lifetime Experiment

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I. INTRODUCTION

Muons are unstable particles produced in the collisions between cosmic rays and the oxygen and nitrogen nuclei in the upper atmosphere. These particles were first discovered by Carl Anderson and Seth Neddermeyer in 1938. While observing the trails of ions produced by high energy particles in a cloud chamber, Anderson and Neddermeyer observed a particle come to a stop. From the curvature and range of the track, they calculated that the particle must have a mass of approximately 10% of the proton mass. Since there was no known particle with this mass, Anderson and Neddermeyer concluded that they had discovered a new particle. In later years a complete identification of the muon was completed.

In this experiment we measure the mean lifetime of the muon using a stack of three plastic scintillators. We stop incoming muons in the 12-cm-thick central block that is viewed by photomultiplier tubes A and B. To ensure that the signal in the two photomultipliers comes from an incoming muon, we require a coincident signal in a third photomultiplier T attached to the top scintillator. To ensure that the signal corresponds to a stopping muon, we impose a final requirement that the coincident flashes observed by phototubes A, B, and T are not accompanied by a coincident flash in the scintillator V located directly below the main slab. These signals are implemented by means of electronic circuits. The light flashes in the photomultiplier tubes are transformed into electrical pulses. A coincidence circuit generates an output pulse if there is an overlap in time of all of the three requirement signals A, B, and T. The signals A, B, and T are sent to a second coincidence circuit that generates an output pulse if there an an overlap in time of the A, B, and T pulses with no accompanying V pulse.

The outputs of the two coincidence circuits are transmitted to an ORTEC time-to-amplitude converter (TAC). The $A \cdot B \cdot T \cdot \overline{V}$ signal indicates the entrance of a muon into the central block and is used to start the TAC. The $A \cdot B$ signal indicates the presence of subsequent decay of a muon inside of the block and is used to stop the TAC. Since the starting requirements include the stopping requirements, we delay the start signal to prevent the start of the time measurement from being immediately aborted by the accompanying stop signal. The output of the TAC is sent to the input of the SPECTECH UCS30 pulse height analyzer (PAC). The PHA spectrum displays the muon decay times with a proportionality of $8 \, \mu\text{s}/1000$ channels.

II. THEORY

The muon is unstable and decays with a mean lifetime of 2.197×10^{-6} s. The principle decay mode of the μ^+ is

$$\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$$

whereas the principal mode the the μ^- is

$$\mu^- \to e^- + \overline{\nu}_e + \nu_\mu$$

The probability that a particle decays in a given time interval dt is independent of how long the particle may have existed since its creation. Given a population of N particles, the change in the population dN in the time interval dt is given by

$$\frac{dN}{dt} = -\frac{N}{\tau} \tag{1}$$

The solution to (1) is given by

$$N = N_0 e^{-t/\tau}$$

where N_0 is the population at $t = 0$. The rate at which decays occur is thus

$$-\frac{dN}{dt} = \frac{N_0}{\tau} e^{-t/\tau}$$

III. RESULTS

In order to determine the mean lifetime of the muon, we first calculate the mean $A \cdot B$ counting rate. The rates are determined by counting the number of $A \cdot B$ events that occur in 20-s intervals. We calculate the mean rate r_{AB} to be

$$r_{AB} = 19.3531 \text{ counts/s}$$

The standard deviation in this calculation is

$$\sigma_{r_{AB}} = 1.05$$

The theoretical value of the standard deviation given by $\sqrt{N}$ predicts that the standard deviation of our $A \cdot B$ rate date should be 0.9837 counts/s. This theoretical value depends on a precisely defined time interval, so the small discrepancy with our value of $\sigma_{r_{AB}}$ is likely a result of reaction time in stopping the counter.

We next look at the response curves obtained to set the high voltages for the T and V scintillators. The curves are shown in figures ... and ...
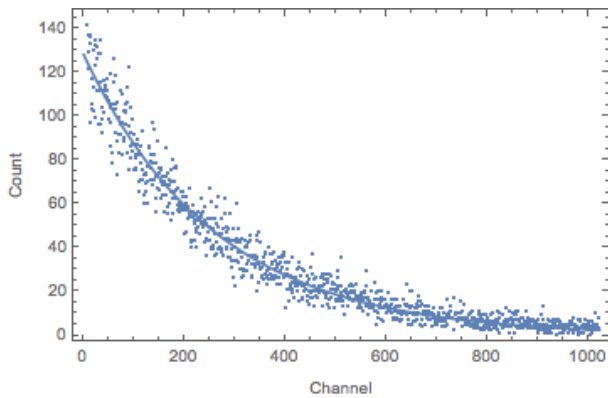
FIG. 1. Exponential fit of decay time data

Fitting the decay time histogram to an exponential, we obtain a first estimate of the muon lifetime. The fit is shown in figure 1. The value of τ obtained from the fit is $\tau = 259.427$ channels. Since the PHA has an overall proportionality of $8\,\mu$s$/1000$ channels, we have that the mean lifetime of the muon is

$$\tau = 2.075 \times 10^{-6}\,\text{s}.$$

Not all of the events shown in figure 1 are from true muon decays. Since the TAC stops at any $A \cdot B$ signal, the TAC may be stopped prematurely due to background processes. However, we may use the measured $A \cdot B$ counting rate to remove some of this background and thus obtain a more precise measurement of the muon lifetime.

IV.   ERROR

V.   CONCLUSION