Parity Violation of Captured Cosmic Ray μ^+ Particles And Their Lifetime

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The parity violation and mean lifetime of the μ^+ particle is measured using high voltage scintillators. The mean μ^+ lifetime was calculated using an exponential fit on a spin up event distribution. And parity violation was tested through the fitting of an asymmetry distribution, $\mathrm{U-D/U+D}$. The expected lifetime taken from the PDG is 2.2 µs, and the estimated mean lifetime found was 2.0880(1138) µs, which is within $1\,\sigma$. And parity was exhibited to be clearly violated.

I. INTRODUCTION

Background. High energy protons and atomic nuclei originating from space interact with atmospheric particles, forming a "cosmic ray shower." The shower creates ionized particles, including the π^+ which decays via the weak force as $\pi^+ \rightarrow \mu^+ + \nu_\mu$. In this experiment we study the μ^+ particles, also weakly decaying through $\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$.

Devices and Setup. For this experiment, five scintillators are used for detection. In top down order, the first scintillator $C1$ is followed by a 3 inch iron filter, two scintillators $C2, C3$, a 1 inch copper target with an electromagnet, and finally two more scintillators $C4, C5$. The iron filter prevents lighter particles from getting through to the next counter so that μ^+ can be isolated, and the target is used to capture μ^+ in order to study their decay rates.

To detect when a μ^+ has been captured in the copper target we use a trigger, $M = C1 \otimes C2 \otimes C3 \otimes \overline{C4}$. When the magnetic field is turned on, the spins of the μ^+ will align, causing the decay products to have opposite momenta up and down relative to the target, to conserve angular momentum. The decay events are detected after a 50 ns delay, using the triggers $U = \overline{C1} \otimes C2 \otimes C3 \otimes \overline{C4}$ for an "up" event and $D = \overline{C1} \otimes \overline{C3} \otimes C4 \otimes C5$ for a "down" event. The time differential between the two events is measured using two TDC units for up and down.[2], [3]

Expected Event Rate. For our experiment, muon candidates must penetrate 3 inches of iron and then get trapped in 1 inch of copper. From energy loss calculations, such muons should have a momentum of 220(20) MeV. From the Particle Data Group[4], we find a muon flux of 70 muons/m^2/s/sr. We can assume the differential flux is linear between 0.1 GeV and 2 GeV[1], and so detectable muons comprise 2.1 % of the total flux. Thus we expect to detect 1.47 muons/m^2/s/sr. Our apparatus measures 65 cm by 34 cm by 29 cm, and so its surface area is 0.1885 m^2. Integrating through the solid angle, we find that the apparatus has a field of view equal to 1.80 sr. Thus, we should expect to detect $N = (1.47\,\mathrm{muons/m^2/s/sr})(0.1885\,\mathrm{m^2})(1.8\,\mathrm{sr}) =$ 0.51 muons/s, or one muon detected every 2 seconds.

II. PLATEAUING SCINTILLATORS

Method of Coincidence. In order to get a clean trigger from the 5 scintillators, the high voltage must be set to give a maximum number of detections before reaching noise pulses from high voltage currents. To achieve this we used the method of coincidence[2], varying the voltage of one scintillator in reference to two other constant voltage scintillators. For example, the ratio of coincidences,

$$R = \frac{C1 \otimes C2 \otimes C3}{C1 \otimes C3} \tag{1}$$

is plotted with respect to the varied voltage, V_2 corresponding to scintillator count $C2$, to find the most efficient voltages. The plateaus chosen (Fig. 1 are, $V_1 = 1.499\,\mathrm{kV}, V_2 = 1.408\,\mathrm{kV}, V_3 = 1.381\,\mathrm{kV}, V_4 = 1.379\,\mathrm{kV}, V_5 = 1.542\,\mathrm{kV}$.

III. ANALYSIS

Experimental Event Rate. An event rate was determined by dividing the total number of muon events by the total experimental runtime (approximately three days with the magnet off), giving a value of 0.016 767 Hz. When compared to the previously calculated value, there is a 96 % error. Although this error is huge, it reasonable since the expected rate calculation did not take the building (or anything within the building) into consideration.

Mean Lifetime. In Fig. 2a, a distribution of up events with respect to decay time was fitted to an exponential decay, which was used to find the lifetime of the muon. Exponential decay is represented as

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

where N_0 is the initial amount of particles and τ is the lifetime of the muon. This fit gave a lifetime of

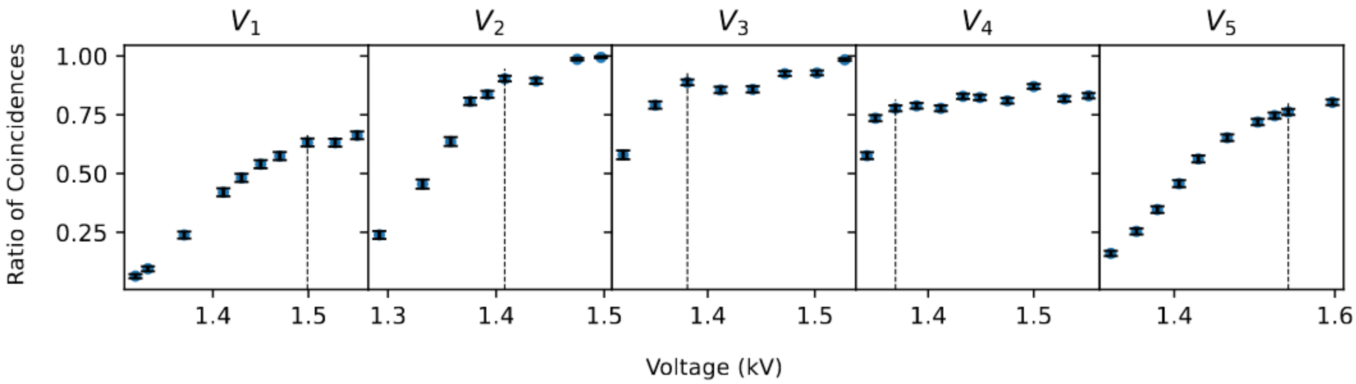
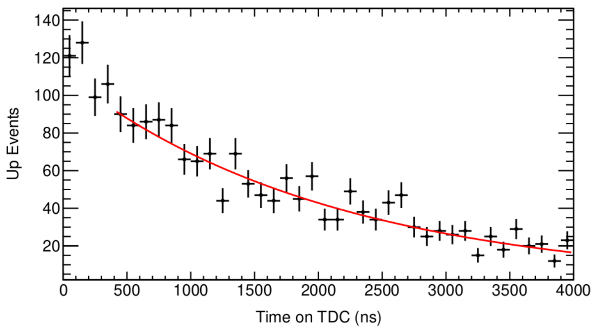
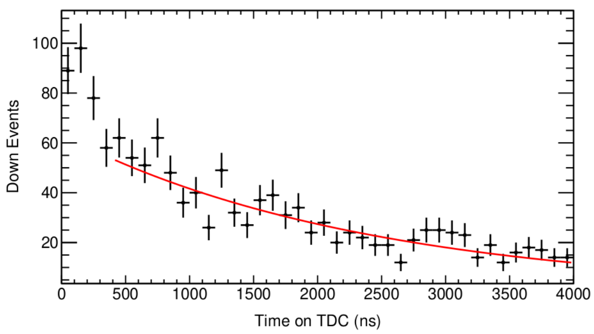


FIG. 1: Plateaus of the five scintillators, using ratio of coincidence with respect to voltage. The vertical line indicates a plateau.



(a) Up event distribution



(b) Down event distribution.

FIG. 2: Event distributions for up events (a) and down events (b) with exponential fits.

$\tau = 2.0800(1138)\,\mu s$, which is within $1\,\sigma$ of the actual lifetime $\tau = 2.2\,\mu s$[4], demonstrating that the device setup gave reasonable statistics. A distribution (Fig. 2b) shows the distribution of down events which produced similar results.

Up and Down Event Difference. The distribution of the difference of up and down events, $U - D$, is represented as[3]

$$(U - D) = e^{\Gamma t}(A + B\cos(\omega t)). \tag{3}$$

This fit matches up with the collected data, as seen in Fig. 3.

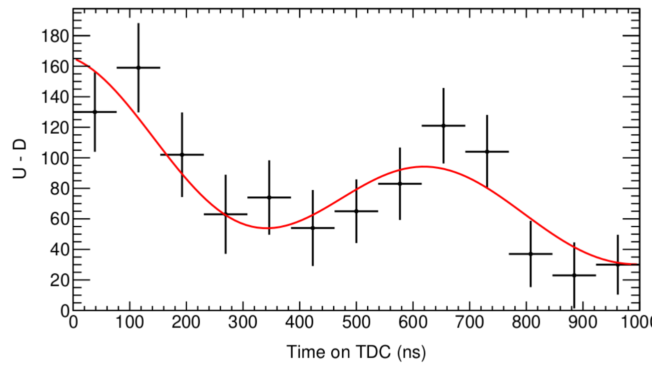


FIG. 3: Difference Distribution of $(U - D)$ vs. decay time measured by the TDC in ns.

IV. RESULTS

Angular Frequency. From the fit in Fig. 4, the angular frequency ω at which the muon spin is precessing is found to be 5.57×10^{-3} MHz. The magnetic field of the coil is

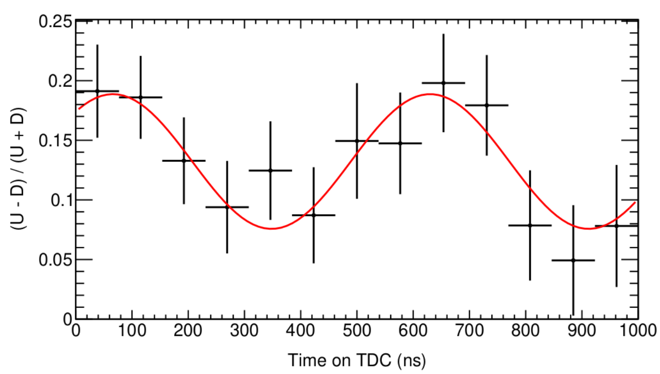


FIG. 4: Asymmetry plot of $(U - D)/(U + D)$ vs. decay time measured by the TDC in ns. There are 13 bins (all above zero) and 68 % of these bins should include the fit within error. Only one of the bins' error does not include the fit, which is reasonable.

then

$$B = \frac{\hbar\omega}{\mu} = 3.167 \times 10^{-5}\,\mathrm{T}. \tag{4}$$

This magnetic field polarizes the muons such that their spins are aligned in the z direction, allowing for the measurement of up and down spin events.

Parity and Asymmetry. An asymmetry between up and down events will demonstrate that parity is violated. This asymmetry is expressed as $(U - D)/(U + D)$ to outline a clear bias towards up or down while removing the decay trend, such that positive bias implies more up events than down and negative bias implies more down events. The asymmetry distribution is modeled as

$$\frac{U - D}{U + D} = A + B\cos\left(2\omega t + \phi_0\right) \tag{5}$$

and is seen in Fig. 4 to be above zero i.e. $A > 0$, exhibiting that the muons are polarized with spin up more often than spin down . Therefore parity is violated.

V. CONCLUSION

We have performed an experiment in which cosmic muons were detected after decaying in a target material. A lifetime for the μ^+ particle was found to be $2.0800(1138)\,\mu$s — within $1\,\sigma$ of current estimates. Furthermore, we used a magnetic field to polarize the muons and confirmed that they exhibit parity violation in their weak interaction decay. The asymmetry plot shows the violation that muons favored spin up over spin down in the decays events.

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