Muon Physics Experiment

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I. INTRODUCTION

Cosmic rays are entering the earth's upper atmosphere all the time, decaying into many particles that bombard the surface below [1]. One of these such particles is the muon, which is very abundant and simple to detect. Cosmic rays are still not fully understood, but they are protons, neutrons, or other particles with high energy coming from somewhere else in the universe. When these particles enter the earth's atmosphere, they collide with molecules and atoms in the air, undergoing a nuclear reaction or decaying as in Fig. 1.

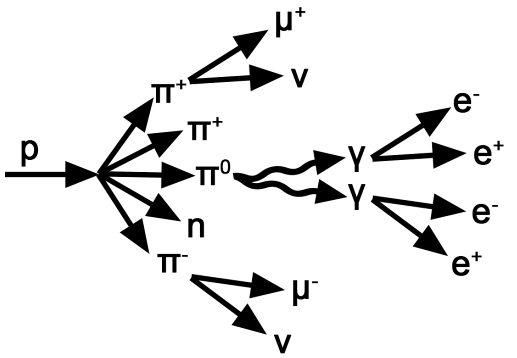

FIG. 1. Cosmic ray decay. This figure shows a proton, the most common cosmic ray, decaying into two pions (and some other particles), which decay further into 1 muon and 1 neutrino each. Most muons reach the surface before decaying, and their decay is shown in Fig. 2.

Muons produced in this way are not electrically neutral, meaning they will interact electromagnetically with whatever material they come into contact with, losing some energy as they do so. This is how we can detect muons; muons pass through the scintillator and deposit some energy, causing ionization which triggers the photo-multiplier tube (PMT) and creates a measurable pulse. Similarly, a muon that loses enough energy will decay inside the scintillator to produce an electron, triggering the PMT and creating a pulse. In this experiment, we will measure the time differences between pulses and perform an analysis in order to determine the average lifetime of a muon. We will be paring out these enter-decay pulse pairs and disregarding enter-enter pulse pairs caused by two different muons. This experiment can be performed at different elevations to measure the effects of special relativity.

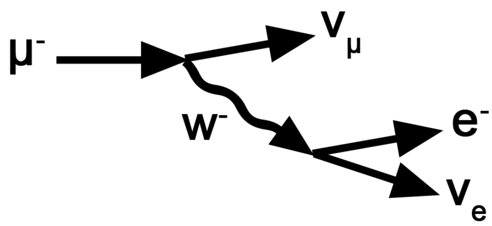

FIG. 2. Muon decay. μ^+ decay looks similar with all signs reversed. Each muon produced by cosmic rays as in Fig. 1 decays into an electron and 2 neutrinos. These neutrinos whisk away some of the energy from the muon, but the rest (about a third) goes to an electron. Our apparatus contains a scintillator to detect muon events and a photo-multiplier tube that is triggered by this produced electron.

II. THEORY AND BACKGROUND

Muons are produced in the chain of decay from cosmic rays, shown in Fig. 1 and Fig. 2, and have a relatively long lifetime on the order of microseconds, meaning they survive long enough to make it to the surface, unlike the intermediate short-lived pions. The longer lifetime alone does not allow them to survive to the surface, but their high speed combined with the effects of special relativity dilates their lifetime in the earth's frame of reference. This dilated time is described as

$$\Delta t = \frac{\Delta t_0}{\sqrt{1-\left(\frac{v^2}{c^2}\right)^2}} \ , \tag{1}$$

where t is the observed time in the earth's reference frame, t_0 is the proper time (in the muon's reference frame), v is the speed of the muon with respect to the earth, and c is the speed of light. The dilated time is longer than the proper time by a factor depending on the measured lifetime. This factor is $\exp(-t/\tau)$, obtained by putting our data in a histogram and fitting it to

$$N(t) = Be^{-(t/\tau)} + A \ , \tag{2}$$

where $N(t)$ is the number of counts expected in the bin at time t in the histogram of our data points, A is a vertical shifting parameter corresponding to a uniform distribution of uncorrelated events, and B is a scaling factor relating to the decaying exponential curve of correlated events. In other words, we are looking for the slope of the linear curve when the vertical axis is $\log(N(t))$ instead of $N(t)$. Finding this factor gives us $-B/\tau$, and we can solve for τ, the average lifetime of the muon [2].

After finding the muon lifetime τ, we can further calculate the Fermi coupling constant G_F with

$$\tau = \frac{192\pi^3\hbar^7}{G_F^2 m^5 c^4} \ , \tag{3}$$

where π, $\hbar$, and c are known constants and m is the muon mass which we obtain from the Particle Data Group as $105.6583745 \pm 0.0000024$ MeV [3].

III. APPARATUS AND EXPERIMENT

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IV. ANALYSIS AND DISCUSSION

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V. CONCLUSIONS

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[1] David Van Baak, *A Conceptual Introduction to 'Muon Physics'* (6/18/2010).
[2] Thomas Coan and Jingbo Ye *Muon Physics (MP1-A) User's Manual* (TeachSpin Instruction Manuals, Southern Methodist University).
[3] M. Tanabashi et al.(Particle Data Group), *Phys. Rev. D98, 030001 (2018) and 2019 update* (Lawrence Berkeley National Laboratory, created 8/2/2019).