Muon Physics Experiment

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I. INTRODUCTION

Cosmic rays are protons, neutrons, or other particles with high energy that bombard the earth and whose source is still not fully understood (beyond that they come from somewhere else in the universe) [1]. These particles are entering the earth's upper atmosphere all the time, decaying into many particles that bombard the surface below as in Figs. 1 and 2. One of these such particles is the muon, which is very abundant and thus a good focus for detection and experimentation.

The muon is a lepton, and like electrons and tau particles, can be positively or negatively charged, but cannot be electrically neutral. As such, 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. The results of this experiment would be different if it were performed at a different elevation because of the effects of special relativity.

II. THEORY AND BACKGROUND

When cosmic rays enter the earth's atmosphere, they collide with molecules and atoms in the air, causing nuclear reactions and decaying as in Fig. 1.

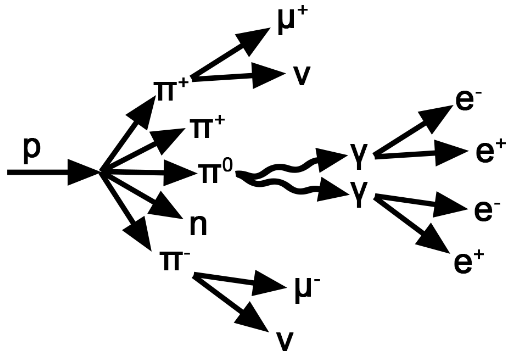

FIG. 1. Cosmic ray decomposition. This figure shows a proton, the most common cosmic ray, breaking into some pions (and a neutron), which then decay further. Our particles of interest are the π^+ and π^-, which each decay into 1 muon of matching charge and 1 electrically neutral neutrino. Many muons reach the earth's surface before decaying, and their decay is shown in Fig. 2.

Muons are produced in the chain of decay from cosmic rays, shown in Figs. 1 and 2, and have an observable lifetime on the order of microseconds, meaning they survive long enough to make it to the earth's surface, unlike the intermediate short-lived pions. The longer lifetime alone does not allow them to survive to the surface, but their relativistic speed 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

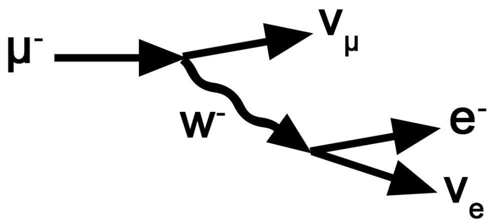

FIG. 2. Muon decay. Each muon produced by cosmic rays as in Fig. 1 decays into an electron and 2 neutrinos. These neutrinos whisk away some of the energy from the muon, but the rest (about a third) goes to an electron. Our apparatus contains a scintillator to detect muon events and a photo-multiplier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

longer than the proper time, which is ultimately why the muons can survive "longer" than their proper lifetime and travel far enough to reach the earth's surface. This lifetime can be calculated from measurements by binning our data into a histogram and fitting the bin frequencies 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, and τ is the muon lifetime. Performing a weighted non-linear least-squares fit to Eq. (2) will allow us to find τ.

We can also find τ by plotting $\log(N(t))$ vs. t and finding the slope of the linear part [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 ± 0.0000024 MeV [3].

III. APPARATUS AND EXPERIMENT

The bulk of this experiment lies in the analysis portion; as such, the physical components are fairly straightforward. The main apparatus is a scintillator, which does the actual detecting of muons that enter, come to rest, and decay. As described in section I, muons have either a positive or negative charge, allowing them to interact electromagnetically with the material of the plastic scintillator. Muons that come to rest inside the scintillator will decay as in Fig. 2, producing an electron or positron which similarly interacts. These interactions send a photoelectron down the photo-multiplier tube (PMT), amplifying the pulse to a measurable level. This output pulse goes through further amplification and ultimately a discriminator, which only counts pulses above a certain threshold voltage. This general setup is described in Fig. 3. The scintillator picks up lots of other events from background radiation and other non-relevant particles, but these other events are uncorrelated and can be mostly removed with the discriminator, and controlled for with a constant added to our fitting function.

figures/figure3.png

FIG. 3. Experimental Apparatus. Arrows show flow of information between modules.

Aside from the pulse being propagated through the setup, we also have an electronic timer which allows us to determine the time between adjacent pulses. To find the muon lifetime, we want to start the timer when one pulse is received and stop the timer when either another pulse is received or a cutoff time is reached. In either case, the timer is stopped, the time recorded, and the timer waits to start until receiving another pulse. The cutoff time should be long enough to catch any single muon producing two pulses (enter and decay), but not so long that accidental coincidences (two separate muons entering) are rampant in our data; we use a cutoff time of 20 μs. As such, the data we measure for these time gaps will be mostly $t = 20$ μs with some points where t is less than the cutoff time. These lesser times are the data of interest, and we will control for accidental coincidences in our analysis to get an accurate measurement of the muon lifetime once entering the scintillator.

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).