Muon Physics Experiment

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Muons are a common particle produced by the cosmic rays hitting the earth's atmosphere constantly, and in this experiment we detect muons' travel and decay. By generating pulses when muons enter a scintillator or come to rest and decay inside of it, we are able to generate a set of data for muon lifetimes. With that data, we can calculate with high precision the muon lifetime, and from that, the Fermi coupling constant. Both values that we calculated are comparable to the commonly accepted values.

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 [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 (such as our detector), losing some energy as they do so. Our apparatus will detect this energy and produce pulses when a muon enters it or when one decays inside it. 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.

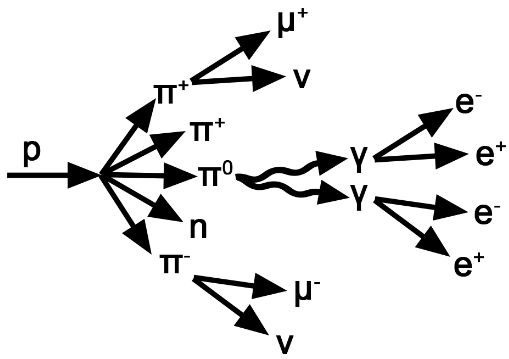

FIG. 1. Cosmic ray decomposition. This figure shows a proton, the most common cosmic ray, breaking into some pions (and a neutron), which then decay further. Our particles of interest are the π^+ and π^-, which each decay into 1 muon of matching charge and 1 electrically neutral neutrino. Many muons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

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.

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 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. The uncorrelated events accounted for by A are mostly other par-

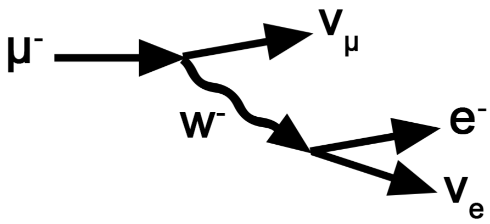

FIG. 2. Muon decay. Each muon produced by cosmic rays as in Fig. 1 decays into an electron and 2 neutrinos. These neutrinos whisk away some of the energy from the muon, but the rest (about a third) goes to an electron. Our apparatus contains a scintillator to detect muon events and a photo-multiplier 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.

ticles passing through the detector such as pions, lower energy muons produced by a different cosmic ray decay, and other low energy particles that wouldn't be confused for a muon entering and decaying. These events have nothing to do with the muons we are looking for, so they are essentially random with respect to our events and as such can be accounted for as a uniform distribution. 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 $105.6583745 \pm 0.0000024$ 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. 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 within the scintillator. 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. Any lower pulses are discarded and not passed on through the discriminator to be counted. This is included in part because the PMT has a potential for "dark counts," where thermal radiation or other factors inside the PMT could cause a fake pulse, which will have lower energy than a true pulse if it is not generated very close to the start of the tube. Some dark counts will make it through, and are another factor that is controlled for by A in Eq. (2). Low energy particles that trigger the PMT will similarly be filtered out. This general setup and flow of information is described in Fig. 3.

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FIG. 3. Experimental Apparatus. Arrows show information moving 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 too common in our data. The reason this is a problem is that the likelihood of measuring a second muon entering within a time frame increases as the time frame gets longer, but the likelihood of measuring the decay of a muon that already entered falls off exponentially, and becomes very unlikely after a certain point. As such, we use a cutoff time of 20 μs to attempt to catch nearly all cases of enter-decay but limit enter-enter pairs to the highest extent possible. As such, the data we measure for these pulse-separations will contain many points at $t = 20$ μs denoting the timer running out without a second pulse, and the points of interest having t less than the cutoff time. We will control for accidental coincidences in our analysis to get an accurate measurement of the muons' lifetime once entering the scintillator.

IV. ANALYSIS AND DISCUSSION

Our apparatus was left running for a few weeks, and gathered XXXX data points, XXXX of which were useful pulse-separation times less than the cutoff. With this many data points, we expect that the number of accidental coincidences will follow

$$N = r^2 T\tau \tag{4}$$

where N is the number of predicted accidental coincidences in our data given the muon rate r, the total duration of data collection T, and the bin width of our histogram τ. We set T as XXXX seconds and τ as XXXX seconds. We measured r as XXXX $\pm$ XXXX s, so we can calculate N to be XXXX $\pm$ XXXX events.

Our data was binned into a histogram with XXXX bins, each of size XXXX, covering our full data range. These frequencies were then used to fit Eq. (2) and find τ, the muon lifetime. The fitting function with our data is shown in Fig. 4, and the log plot is shown in Fig. 5.

We can now use this measured muon lifetime τ and the accepted muon mass of $m = 105.6583745 \pm 0.0000024$ MeV with Eq. (3) to calculate the Fermi coupling constant $G_F =$ XXXXX.

V. CONCLUSIONS

We gathered data of muon events for several weeks, and was able to fit the data with a simple formula which takes into account most of the background noise. This fit allowed us to easily see the muon lifetime of XXXX, which is fairly close to the commonly accepted value of XXXX. Using our calculated value, we found the Fermi coupling constant to be XXXX, as compared to the accepted value of XXXX. Both of these values are fairly accurate,and our fitting error is fairly low, so we are confident that our experiment and analysis are sound, and that the values we have found are acceptable.

[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).

figures/figure4.png

FIG. 4. Our data, with the fitting function overlaid. The fitting parameters are XXXXXXXXX, and our residual standard error is XXXX.

figures/figure5.png

FIG. 5. Natural log of the frequency plotted against time. Our lifetime is the slope of the linear section of this curve.