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 measure muons' decay. By generating pulses when muons enter our detector and decay inside of it, we are able to generate a set of data for muon lifetimes. With that data, we can precisely calculate the muon lifetime as 2.02 ± 0.01 μs, and from that, the Fermi coupling constant as $3.12 \pm 0.002 \times 10^{-5}$ GeV^{-2}. 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 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 lost and produce pulses when a muon enters it or when one decays inside it after coming to rest. 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 can use this value to calculate other values such as the Fermi coupling constant and compare them to the accepted standard.

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 this chain of decay from cosmic rays, shown in Figs. 1 and 2, and have a 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

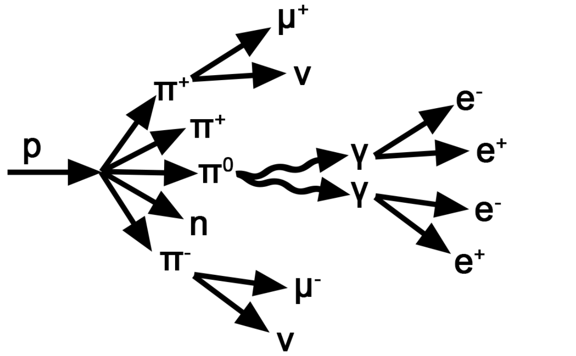

FIG. 1. Cosmic ray decomposition. A proton, the most common cosmic ray, breaks into some pions (and a neutron), which then decay further. Our particles of interest are the π^+ and π^-, which each decay into 1 muon of matching charge and 1 electrically neutral neutrino. Many muons reach the earth's surface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

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

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. We will calculate this lifetime in Section IV fitting histogram 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

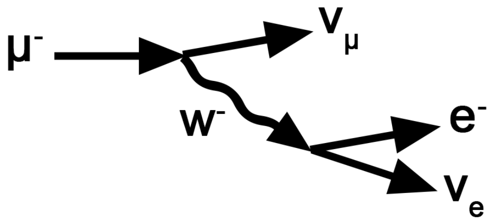

FIG. 2. Muon decay. Each muon produced by cosmic rays as in Fig. 1 decays into an electron and 2 neutrinos. These neutrinos whisk away some of the energy from the muon, but the rest (about a third) goes to an electron. Our apparatus contains a scintillator to detect muon events and a photo-multiplier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

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 particles passing through the detector, including other muons. The muon enter-decay events we are looking for are essentially random with respect to these other events, so this background can be accounted for with a uniform distribution. Coincidences of specifically a second muon entering will be further accounted for in our analysis. Performing a weighted non-linear least-squares fit with Eq. (2) will allow us to find τ.

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

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

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]. We will compare our calculated value to the commonly accepted value of $G_F = 1.1663787 \times 10^{-5} \pm 0.51 \times 10^{-11}\text{GeV}^{-2}$ [3].

III. APPARATUS AND EXPERIMENT

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. A pulse is generated in the scintillator only when a muon enters the detector or when a muon decays inside it. 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 will also generate "dark counts," where random events such as electron generation can occur inside the PMT and cause a pulse, which will have lower energy than a true pulse if it is not generated very close to the start of the tube (since it will have been amplified for a shorter distance). Some dark counts will make it through, and are another factor that is controlled for by A in Eq. (2). This general setup and flow of information is described in Fig. 3.

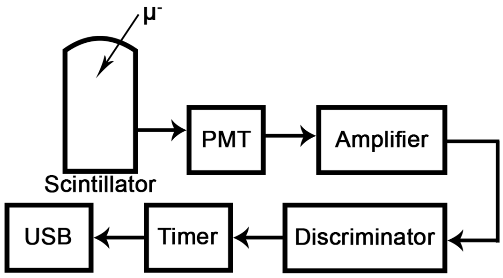

FIG. 3. Experimental Apparatus. Muons enter the plastic scintillator, and arrows show information moving between modules.

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 the decay of a muon that already entered falls off exponentially and becomes very unlikely after a certain point, while the likelihood of measuring a second muon entering remains constant. This means that as time progresses, the chance that a pulse is a second muon rather than a decay becomes relatively more and more likely the longer we keep allowing pulses to count. As such, we use a cutoff time of 20 μs to attempt to catch nearly all cases of enter-decay but limit the region where enter-enter pairs take over to the highest extent possible. (Enter-enter pairs refer to situations

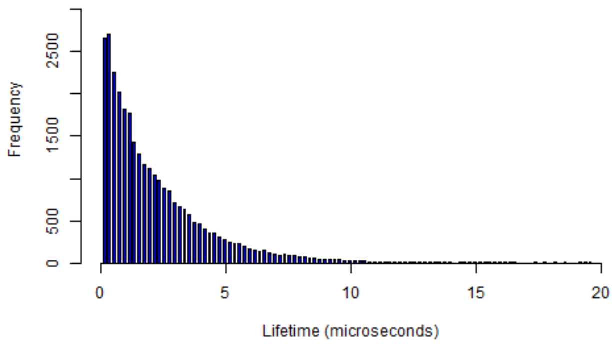

FIG. 4. Our binned data. Lifetimes are grouped into 100 bins, each of width 0.2 μs, representing our full range of 0 to 20 μs.

where the timer is stopped by a second muon entering the detector.) 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 three weeks, and gathered 34940 data points of useful pulse-separation times less than the cutoff. The raw (useful) data was binned into a histogram with 100 bins, each of size 0.2 μs, covering our full data range, shown in Fig. 4. These frequencies were then used to fit Eq. (2) and find τ, the muon lifetime. The fitted data are shown in Fig. 5.

We also took the binned data from Fig. 4 and created a log-log plot, which should show us a linear section in the region where our data is good for calculating the muon lifetime. This plot is shown in Fig. 6, and does appear linear in the first half of the data. We then rearrange Eq. (2) as

$$\tau = \frac{-t}{\log \frac{N-A}{B}} , \tag{4}$$

and plotting this with the values we get from our fitting function for A and B gives the result shown in Fig. 7. This plot should ideally be constant at τ, and thus we expect it to be approximately horizontal in the region where our data is best for finding τ. This is in fact what we see.

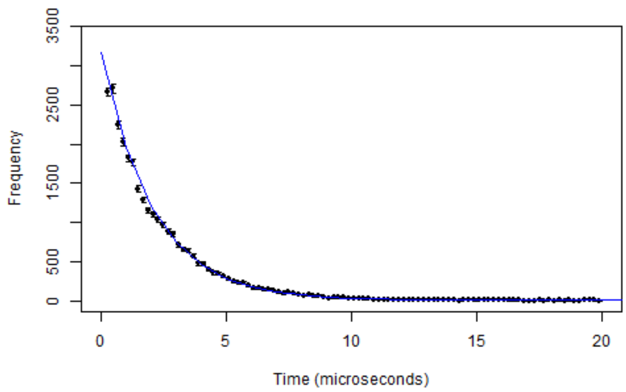

FIG. 5. Our binned data, with the fitting function overlaid. The fitting parameters are $B = 3.07 \pm 0.02$, $\tau = 2.02 \pm 0.01$ μs, $A = 0.013 \pm 0.002$, and our residual standard error is 18.47. The error on each bin is $\sqrt{N}$, where N is the number of counts in that bin.

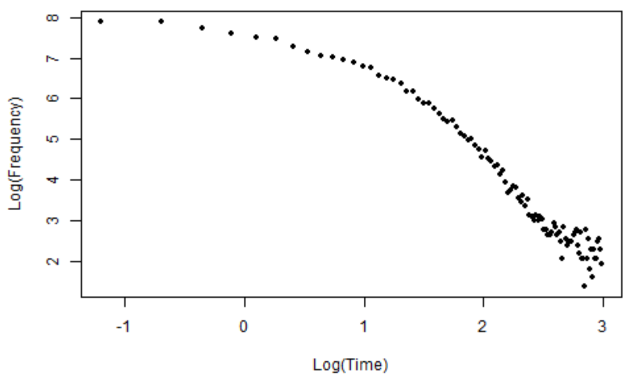

FIG. 6. Natural log of the frequency plotted against the log of time. Our lifetime is the slope of the linear section of this curve, in the range of log(time) approximately -1 to 2.

With how many data points we have, we can make a good approximation for the percent of our data that are accidental coincidences by using

$$N = r^2 T \tau_{\text{bin}} , \tag{5}$$

where N is the portion 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 $\tau_{\text{bin}} = 0.2$ μs. We measured r in each bin, so we can plot N using our fitted data. The accidental coincidences are shown in Fig. 8, and they line up with Fig. 7, showing that the background is a higher fraction of the total counts at higher times.

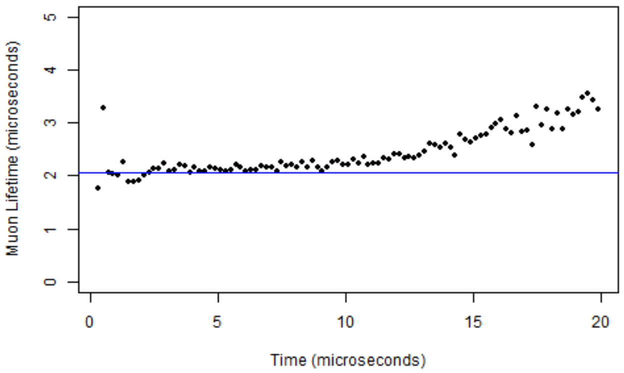

FIG. 7. Calculation of τ in each bin, using Eq. (5) and values from our fitting function. A flat line is shown at 2.02 μs, our calculated τ from the fitting function, and it lines up fairly well with the constant section until about 8 μs.

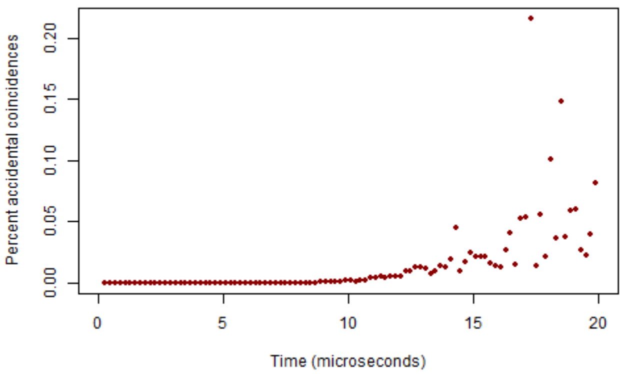

FIG. 8. Calculation of accidental coincidences from Eq. (5). This plot shows the percent of our data that are estimated to be comprised of accidental coincidences, i.e., an enter-enter muon pair rather than a single muon enter-decay pair. The frequency of accidental coincidences remains constant, but the relative frequency increases as time goes on and enter-decay pairs become rarer. When comparing this plot to Fig. 7, it explains the deviation of τ values from the horizontal as times increase.

We can now use this measured muon lifetime $\tau = 2.02 \pm 0.01$ μs and the accepted muon mass of $m = 105.6583745 \pm 0.0000024$ MeV with Eq. (3) to calculate the Fermi coupling constant $G_F = 3.12 \pm 0.002 \times 10^{-5}$ GeV^{-2}.

V. CONCLUSIONS

We gathered data of muon events for several weeks, and were able to fit the data with a simple formula which takes into account the background noise. This fit allowed us to see the muon lifetime of 2.02 ± 0.01 μs, which is fairly close to the commonly accepted value of 2.1969811 ± 0.0000022 μs. Using our calculated value, we found the Fermi coupling constant to be $3.12 \pm 0.002 \times 10^{-5}$ GeV^{-2}, as compared to the accepted value of $1.1663787 \times 10^{-5} \pm 0.51 \times 10^{-11}$ GeV^{-2}. Our measured muon lifetime is fairly accurate, and our calculated Fermi coupling constant is on the same order of magnitude. Since these values are decent and our fitting error is fairly low, we are confident that our experiment and analysis are sound, and that the values we have found are acceptable.

We see from Figs. 8 and 9 that as our cutoff time gets longer, the number of accidental coincidences increases significantly, decreasing the quality of our data. It may be better to lower this cutoff from 20 μs to around 10 μs when performing this experiment in the future in order to minimize the coincidence-decay data ratio.

[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).