PHYS 3081 Lab Report: Muon Lifetime Experiment*

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We investigate muon decay and calculate its mean lifetime, correcting for the background via two methods and comparing our results. We collect data for three weeks, utilizing two different interval triggers: [200 ns, 10 μs] for the primary data acquisition and [20 μs, 30 μs] for the background correction. We create a histogram of the decay times and, using a Poisson Maximum Likelihood estimator, fit the data to an exponential decay model described by N(t) = N_0exp(-t/t_0) + c. We then correct for the background and the singles rate to obtain a more accurate estimate of the mean lifetime and compare the results for both corrections. We found the corrected mean lifetime of the muon to be $2.58 \cdot 10^{-6}$ s $\pm$ $7.28 \cdot 10^{-8}$ s.

I. INTRODUCTION

Muons are subatomic particles with properties similar to electrons, yet are two hundred times more massive. Compared to other subatomic particles, muons have relatively long lifetimes, despite their massiveness. These factors make them a particularly interesting subject of study in particle physics. In this report, we investigate the decay process and mean lifetime of muons. By measuring their lifetime, we aim to gain a deeper understanding of the underlying physics that govern muon existence and interactions, expanding our understanding of the subatomic particle. This investigation not only offers insight into the landscape of particle physics, but also has implications for broader areas of fundamental science and cosmology.

We use a digital oscilloscopes with two different interval triggers, [200 ns, 10 μs] for primary data collection and [20 μs, 30 μs] for background data collection, to record time intervals for a large set of data points. This data collection includes the measurement of the time intervals between two events: the incident particle and particle decay emission. To account for the background, data is collected in the [20 μs, 30 μs] interval trigger. the mean decay time interval by subtracting it from the [200 ns, 10 μs] interval We also subtract the rate of single events from the total events - the number of particle detections without decay products - with no measure occurring within 10 μs, comparing it with the lifetime of background events.

The results are further processed by creating histograms with appropriate bin sizes, and subtracting the background contributions. This allows for the visualization of the muon lifetime distribution. Finally, additional data is collected to determine the total cosmic ray rate and the fraction of muons that stop in the scintillator.

The muon lifetime experiment provides valuable insights into fundamental particles and the interactions that govern them. Measuring muon lifetime and decay properties allows scientists to test the predictions of the Standard Model of particle physics, explore the fundamental forces at play, and search for new physics beyond the Standard Model. These experiments can expand our understanding of the universe's composition, the behavior of particles at the quantum level, and lead to potential discoveries that could revolutionize our understanding of particle physics, with possible real-world applications in nuclear energy research and cosmology.

II. THEORY

Cosmic rays originate from and are generated by the sun's magnetic field, which energizes photons, emitting them at relativistic speeds. Cosmic rays were discovered by Victor Hess in his 1912 balloon experiments, in which he resolved why radiation levels were higher in the upper atmosphere. Cosmic ray particles encounter Earth's magnetic field thousands of kilometers before arriving to Earth; thus, they must be sufficiently high energy (or travel along the field lines, which would land them at the poles) in order to collide with particles in the atmosphere. The lowest momentum at which a particle must be arriving to Earth is determined by the magnetic latitude and angle between a particle's velocity and a vector pointed west. When a cosmic ray particle enters the atmosphere, it collides with nuclei, which produces all known fundamental particles, including the muon. The

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muon is generated by pi decay described in Equation 1:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \tag{1}$$

The muon is a particle with a spin of 1/2 and charge -e, where e is the elementary charge of 1.602×10^{-19} C. The muon is not composed of other particles and thus is classified as a lepton, which is a particle with a half-integer spin that does not undergo strong interactions. Muons were discovered by Card D. Anderson and Seth Neddermeyer in 1936, in which they observed particles moving in an electric field following curved paths. They observed that the path the muon differed from the proton and electron, but had the same charge as an electron, indicating it was a more massive particle. It was confirmed to be a separate particle from the meson-mass range particle predicted by Hideki Yukawa's through an experiment conducted by Marcello Conversi, Oreste Piccioni, and Ettore Pancini, in which they showed cosmic ray muons did not decay by being captured by atomic nuclei.

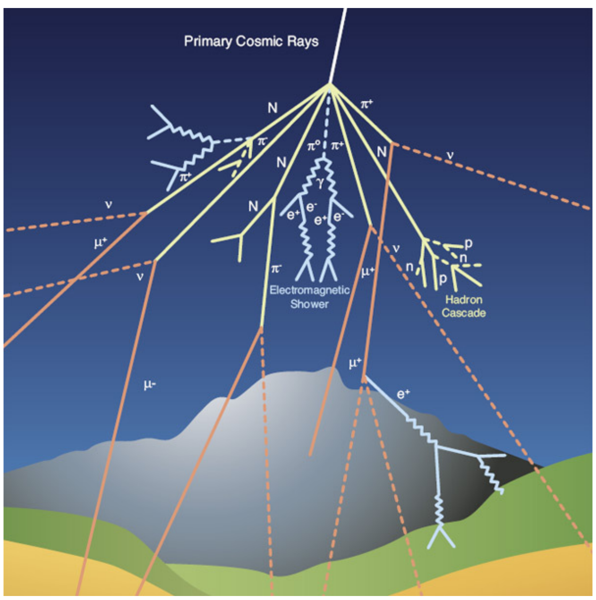

FIG. 1. Cosmic ray generation, illustrated through Feynman diagrams. Primary cosmics rays collide with atmospheric particles and generate elementary particles which quickly decay on Earth, including the muon. (home.cern/science/physics/cosmic-rays-particles-outer-space)

Muons undergo decay in 2.2 μs, which is longer than most subatomic particles, as the decay is only mediated by the weak interaction. The muon arrives at relativistic speeds to a scintillator, and thus its lifetime prior to measurement is negligible compared to the lifetime of the muon as measured in experiment. A muon decays into an electron and two types of neutrinos, which is described in Equation 2:

$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu \tag{2}$$

The electron is emitted in a continuous energy spectrum, and the energy of the emitted electron is determined by the direction in which the two neutrinos escape. The energy of the electron is greatest when the neutrinos escape in the same direction, opposite that of the electron. However, this is impossible, as two identical neutrinos cannot move into the same quantum state by Pauli's exclusion principle. Thus, two different types of neutrinos must be emitted. In order for the helicity (the spin as a projection onto the direction of momentum) of the system to be zero, the two neutrinos can either be an electron antineutrino-muon neutrino pair or an electron neutrino-muon antineutrino pair.

Scintillation is the process by which an energetic ray collides with a scintillating object, such as a crystal, and transfers it energy to a portion of the crystal lattice, which excites an electron. The electron then falls down to its ground state, and in the process releases energy in the form of a photon. Scintillation is an important property of the detectors used to analyze incoming electromagnetic radiation in the experimental setting. Scintillation is an important component of the polythene moderator, which registers excitations by incident cosmic rays and produces interpretable results which can be detected by the photocathode. When the muon enters the moderator, it excites an electron in the atomic lattice, which emits a photon as it de-excites. This is recorded as the time when the incident ray hits the moderator. When the muon decays, it once again excites an electron in the lattice, which, when it de-excites, emits another photon which indicates the second peak. This is recorded as the time of decay.

III. METHODOLOGY AND DESCRIPTION

A. Equipment

An oscilloscope (Figure 2) is a device which is used for visualizing and analyzing electrical signals over time. The vertical selection controls for the amplitude of the display signal, while the horizontal selection controls for the time over which the signal is observed. The oscilloscope is used to get an overview of the energy emission spectrum and waveform of the observed radioactive source. The WaveSurfer 3000z oscilloscope is a digital oscilloscope with advanced multi-instrument capabilities. In our lab, the oscilloscope only reads up to a certain energy, indicating a small rectangular pulse when a signal is received. This is because we are not measuring the energy spectrum of captured particles but only whether a particle has been captured.

The polythene (or polyethylene) moderator (Figure 3) is a large block of polythene which as a neutron modera-

FIG. 2. Teledyne LeCroy WaveSurfer 3000z Oscilloscopes, from teledynelecroy.com. The screen shows the time and energy of signals detected by the photomultiplier tube after passing through the discriminator, and stores data in a .csv file format.

tor and scintillation crystal in order to slow down and absorb the energy of incoming particles. The moderator is composed of polythene, a common plastic polymer which is used due to its crystalline structure that simulates the properties of a scintillation crystal, and because on large scales it is cheaper to make the moderator from plastic. Additionally, a typical scintillation crystal has an instantaneous time profile for photon emissions, which, when measuring muon decay, is not very useful; plastic has a longer emission time profile, which makes it more useful for measuring emissions. The moderator is wrapped in metal foil in order to block interference from Earth's magnetic field, and further wrapped in black tape in order to achieve total internal reflection within the block. Although the moderator acts to slow down particles, it primarily absorbs the incoming energy of particles and emits photons through scintillation.

FIG. 3. Polythene Moderator, large block of transparent plastic in which incident rays are trapped, and whose decay products are received by the photomultiplier tube.

The photomultiplier tube (Figure 4) is a detector which contains a photocathode positioned before an array of dynodes and an anode. Photons are emitted from the polythene moderator, which are produced in the process of scintillation generated from incident cosmic rays and other radiating sources. When a photon strikes the photocathode, an electron is emitted through the photoelectric effect. The electron is then amplified along the dynode-anode array, so that the signal received by the oscilloscope through the discriminator will have a large enough voltage to produce observable results. The tube is coupled to a transparent focus coated in optical grease and bound with aluminum foil and black tape, as with the moderator, to block out background interference. The focus is connected at 180 degrees to the moderator so as to achieve total internal reflection within the system and allow photons from the moderator to travel to the detector.

FIG. 4. Ortec Photomultiplier Base Assembly Model 265, consisting of NaI scintillation crystal and anode-diode cascade amplifier, from ebay.com

The discriminator (Figure 5) is a device used to read the voltage from the photomultiplier tube through a wire connected between the two devices. For our set-up, it only reads the voltage below a certain threshold, producing distinct square wave-forms which allow easy observation of when an excitation has occurred and for what time frame. The discriminator can be used to gather the singles rate over a time period.

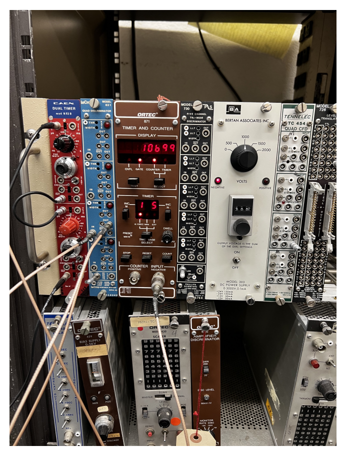

FIG. 5. Discriminator (the silver wire) and associated machinery, used to filter signals received from the photomultipler tube.

During the previous group's experiment, the photomultiplier tube had been disconnected from the polythene moderator, which prevented total internal reflection within the system and prevented any data from being collected. The set up had to be repaired, optical grease reapplied, and the tube re-wrapped in tape to fix the conductance of light through the system.

B. Method

Data is collected for over a week in the trigger interval [200ns, 10μs] during primary data collection and for over another week in the trigger interval [20μs, 30μs] during background data collection. The data is processed in Python, where the decay time of each event is evaluated and added to a list that is presented in a histogram.

IV. RESULTS

A. Mean Time to Decay

First, we want to find the mean time to decay for an initial set N_0 integrated over all time from the initial time, $t_0 = 0$. We know that:

$$N(t) = N_0 exp(-t/t_0) \tag{3}$$

and:

$$dN(t) = N_0/t_0 exp(-t/t_0) dt \tag{4}$$

Which govern the rate of decay for an initial sample size. Thus, to find the mean decay rate, defined by:

$$t_r = \int_0^\infty t N_0 exp(-t/t_0)\, dt \tag{5}$$

Which evaluates to:

$$t_r = \int_0^\infty \frac{1}{t_0} exp(-t/t_0)\, dt \tag{6}$$

$$t_r = t_0 \tag{7}$$

Thus, for all time, the mean time to decay is t_0.

B. Data for Time Interval [200 ns, 10 μs] Before Correction

Figure 6 shows a histogram of the muon data. There were 1345 events collected over the duration of two weeks for the time interval [200 ns, 10 μs]. The time differences between the peaks were calculated in Python, the values of which were added to a .txt file. The values were plotted in a histogram. To obtain the exponential fit for the model, the initial guesses for N_0, t_0, and c (the constant added to the exponential model) were determined using a Poisson maximum likelihood estimator to approximate the values for a best fit exponential function.

Without corrections, the exponential fit is described by the equation $N(t) = 101e^{-t/2.97\cdot10^{-6}} - 2.51 \cdot 10^{-15}$ with a mean of $2.97 \cdot 10^{-6}$ s $\pm$ $8.38 \cdot 10^{-8}$ s.

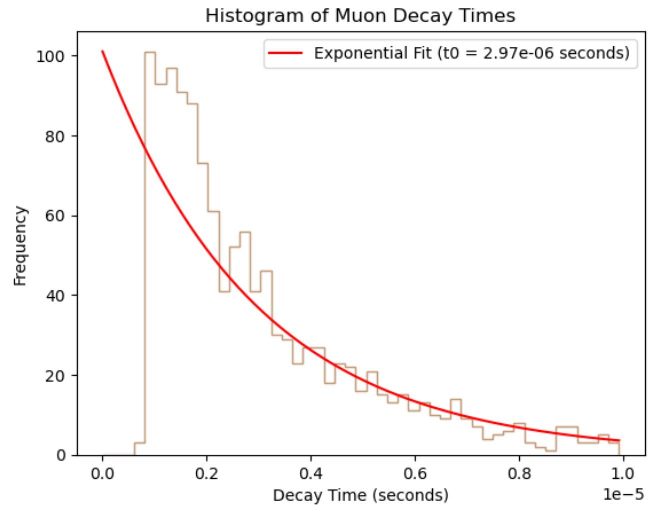

FIG. 6. Histogram of muon decay times, fit to exponential decay.

C. Mean Lifetime Within [200 ns, 10 μs] Interval

The mean lifetime within the primary collection interval can be calculated similar to the above method:

$$t_r = \int_{200ns}^{10\mu s} \frac{1}{t_0} exp(-t/t_0)\, dt \tag{8}$$

$$\begin{aligned} t_r = &-10\exp\left(-\frac{10}{t_0}\right) - t_0\exp\left(-\frac{10}{t_0}\right) \\ &+ 0.2\exp\left(-\frac{0.2}{t_0}\right) + t_0\exp\left(-\frac{0.2}{t_0}\right) \end{aligned} \tag{9}$$

Using $t_0 = 2.97$ μs, then the mean lifetime t_r of the interval is 2.51 μs. We can calculate t_r/t_0 under the assumption t_1 is the first approximation of the lifetime:

$$\frac{t_r}{t_0} = \frac{2.51\mu s}{2.97\mu s} = 0.42 \tag{10}$$

D. Correction Due to Background

To correct for background measurements, we collected data for a week, gathering sixteen events. These were processed with the same methods as the muon event data and are plotted in a histogram, shown in Figure 7.

These values are normalized and then subtracted from the decay time histogram values to correct for the background. This is shown in Figure 8. With these corrections, the exponential fit is described by the equation $N(t) = 104e^{-t/2.58\cdot10^{-6}} - 2.19 \cdot 10^{-15}$ with a mean of $2.58 \cdot 10^{-6}$ s $\pm$ $7.28 \cdot 10^{-8}$ s.

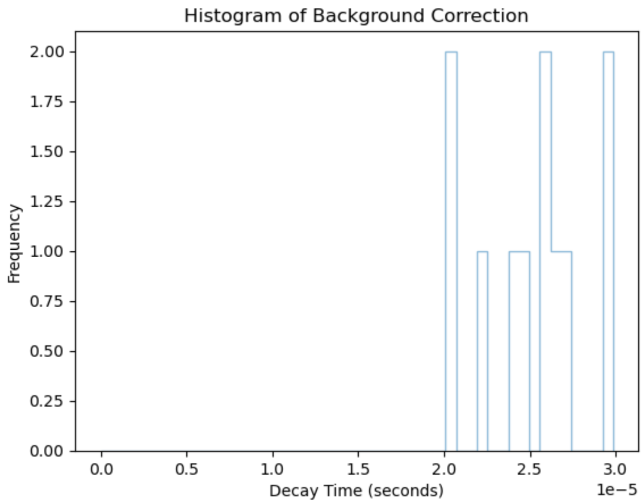

FIG. 7. Histogram of background for [20 μs, 30 μs] interval.

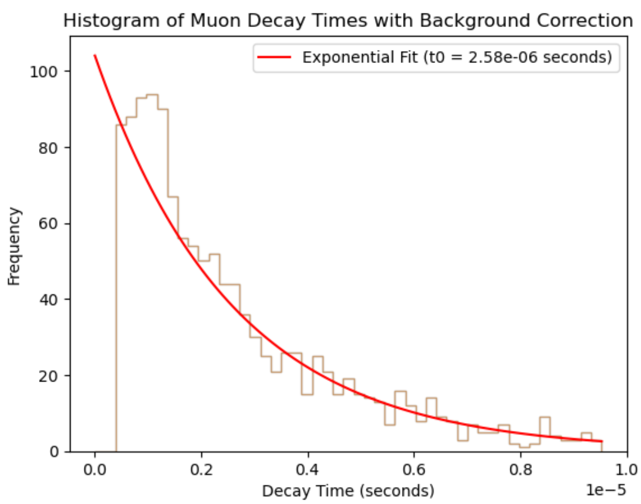

FIG. 8. Histogram of muon decay time with correction for background, fit to exponential decay.

E. Mean Lifetime Within [200 ns, 10 μs] Interval

The mean time interval can be found with the following equation:

$$t_r = \int_{20\mu s}^{30\mu s} \frac{1}{t_0} exp(-t/t_0)\, dt \tag{11}$$

Which evaluates to:

$$\begin{aligned} t_r = &-30 \exp\left(-\frac{30}{t_0}\right) - t_0 \exp\left(-\frac{30}{t_0}\right) \\ &+ 20 \exp\left(-\frac{20}{t_0}\right) + t_0 \exp\left(-\frac{20}{t_0}\right) \end{aligned} \tag{12}$$

Using the mean lifetime from the uncorrected data, t_0=2.97 μs, we can evaluate Equation 12 to find that t_r = 0.026 μs. The rate is thus 0.011 μs.

F. Singles Rate Correction

We counted 131 single peak events over the time interval of 600s, giving a singles rate correction r_0 = 0.22 events/s. For each bin the singles rate was subtracted by a factor of $r_0^2 \Delta t$ to account for corrections during the interval. The result is plotted in Figure 9. The exponential decay function is given by the equation $N(t) = 908e^{-t/2.91 \cdot 10^{-6}} - 9.87 \cdot 10^{-15}$ and the mean is $2.82 \cdot 10^{-6}$ s $\pm$ $7.98 \cdot 10^{-8}$ s. This is significantly greater than the background measurement corrections, and thus we infer that the background measurement produces more a accurate correction.

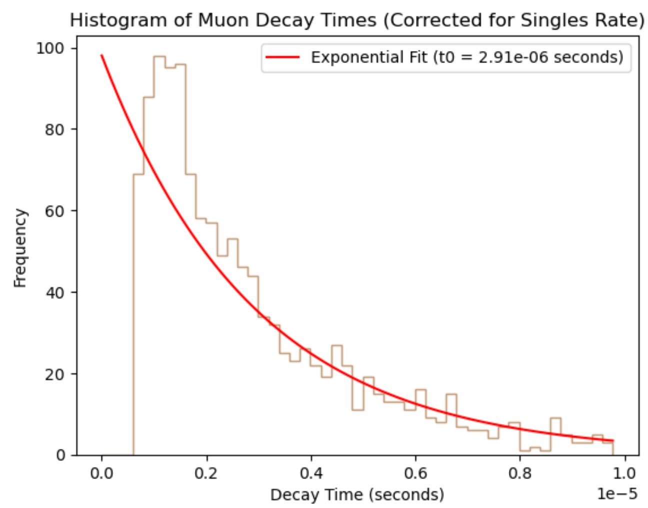

FIG. 9. Histogram of muon decay time with correction for singles rate. Note difference in mean time of decay from background measurement.

G. Additional Data Measurements

We measure the total cosmic decay rate and show the histogram of decay in Figure 10. We observed that there is a greater quantity of events measured at higher decay times when compared to the muon decay time interval. We infer that other cosmic particles decay at these intervals.

Approximately 1 muon passes through a 1 cm^2 area a minute on Earth. If we assume the polythene moderator is 0.25 m^2, we can estimate that 2500 muons are passing through it per minute. In a two-week period there are 20160 minutes, and thus $5.04 \cdot 10^7$ muons pass through the scintillator. We only detected 1345 events during this period, so we can estimate that the fraction of muons which

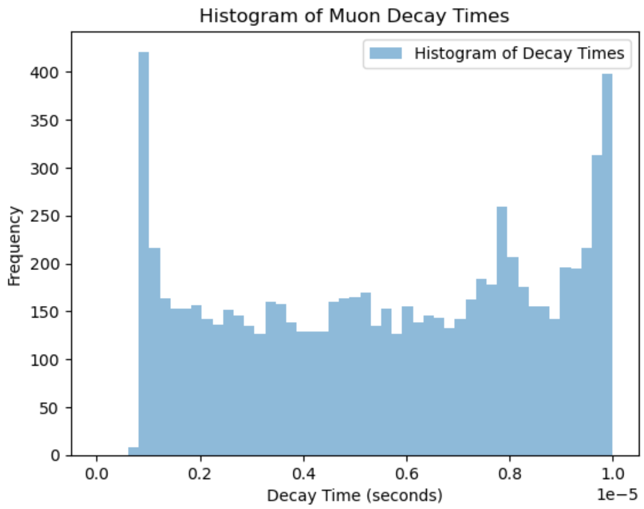

FIG. 10. Histogram of total cosmic ray rate without set interval. Note the greater quantity of events at greater time intervals when compared to the interval in which we measure muon decay.

stop in the scintillator is $2.67 \cdot 10^{-5}$, or only 0.0026%.

V. DISCUSSION

The data was processed through Python and the initial guesses were obtained through a Poisson maximum likelihood estimator for the exponential decay model. We attribute some error to the computational process of finding the mean decay lifetime, although in general there was no significant difference between the mean lifetime and the exponential mean life time from the decay time. For our corrected background, we found the muon decay time to be $2.58 \cdot 10^{-6}$ s. The accepted value for the muon lifetime is 2.2 μs, and thus our obtained value is 17.8% different from the accepted value. Thus, our experiment was relatively successful in reaffirming the value of the lifetime of the muon.

A. Errors

The root mean square (rms) error is calculated (using a proof provided R. Peierls) with the equation $\frac{t_0}{sqrtN}$, where N is the number of measurements. Given our small confidence intervals our measurement of the muon lifetime is significantly statistically different from the accepted value.

The laboratory experiment was previously damaged and thus some experimental error can be concluded as being a result of slightly uncalibrated equipment. Since the experiment is running smoothly, we infer that the bulk of our errors come from not obtaining a statistically significant sample size of data. When compared to other muon decay experiments, we find that our sample size of approximately one thousand data points is often only a tenth of that performed by similar experiments which measure closely to the accepted value.

VI. CONCLUSION

In this experiment we learned how to process large data sets of different file sizes; determine what constitutes faulty data and filter it from our data set; and perform general statistical analysis on large data sets, greatly strengthening our skills in Python and computational analysis. Through the course of the laboratory we also gained an intimated understanding of muon decay and cosmic ray interactions, as well as their generation through astrophysical phenomena. We greatly expanded our skills in data science, understanding how to process and visualize information to quickly understand the contents of our data collection and retrieve accurate results.

This experiment could be expanded upon by analyzing and collecting the decay times of other cosmic rays. The equipment is sensitive enough to discover the lifetime of pi-meson decay, for instance, and thus multiple cosmic particle experiments could be performed during the six-week duration of the experiment. Additionally, the students could build the experiment from scratch, gathering skills in laboratory experimentation and reducing the computational aspect of data collection. I would recommend this laboratory experiment to students wishing to expand their understanding of data science and computational physics.

VII. REFERENCES

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