Muon Decay and Lifetime Analysis

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Muon decay is a fundamental process in particle physics, offering insights into the weak interaction and fundamental symmetries of nature. This experiment investigates the lifetime of muons using advanced detection and timing techniques. By analyzing the decay events and their statistical distribution, we estimate the mean lifetime of muons to be $2.16 \pm 0.17\mu s$ and compare the results with established theoretical predictions, $2.19\mu s$ with negligible uncertainty. This study reinforces concepts of particle physics and demonstrates the application of experimental techniques in precision measurements.

I. INTRODUCTION

Muon decay is a key phenomenon in understanding weak interactions, one of the four fundamental forces in physics. Muons, which are elementary particles similar to electrons but with a greater mass, decay predominantly into an electron, a neutrino, and an antineutrino, all of which are leptons and don't interact strongly. Because the decay of muons is entirely uninfluenced by strong force interactions and the other forces (gravitational and electromagnetic) don't influence decay, it is primarily governed by the weak force and provides insight into the principles that govern weak interactions, a crucial component of the Standard Model of Particle Physics [1].

This experiment utilizes a TeachSpin muon detection apparatus to record and analyze decay events [2]. The TeachSpin device utilizes a timing circuit to provide precise measurements of muon lifetime as the particles interact with the apparatus' plastic scintillator detector. Through a statistical analysis of decay times, the mean lifetime of muons can be determined.

The study of muon decay illustrates the principles of weak interactions and, in doing so, serves as a practical example of how experimental physics can validate theoretical models. This report details the methods, data analysis, and results obtained from the investigation, highlighting the significance of precision measurements in modern physics.

A. Muon Production

At any given moment, high-energy charged particles bombard Earth's upper atmosphere. From observation, we can conclude about 98% of these high-energy particles are protons and other heavier particles, with the remainder primarily composed of electrons. Of this 98%, 87% are protons, alpha particles, other helium isotopes, and heavier elements make up the remainder. When primary particles from cosmic rays interact with the air molecules in Earth's atmosphere they cause a shower of secondary particles including protons, neutrons, pions, kaons, photons, electrons, and positrons. Through interactions with other atmospheric particles, these secondary particles create more secondary particles, leading to a cascade effect. Of particular interest to our experiment are the charged pions created by this process. The pions that don't interact with air molecules through the strong force will decay through the weak force to produce a muon (positively or negatively charged) and a neutrino/antineutrino (Figure 1).

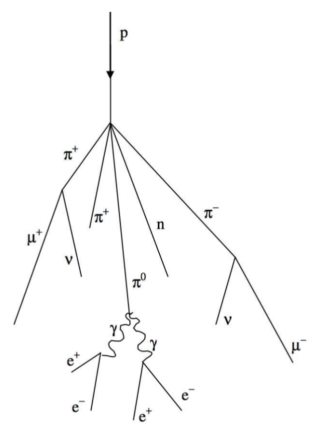

FIG. 1. Illustration of a cosmic ray shower induced by a high-energy proton striking an air molecule. This figure displays that protons decay into pions, which then decay into muons. Figure from ref [2].

While muons are most likely to decay instantly upon their formation, many of them make their way through the atmosphere, interacting with particles they meet by weak and electromagnetic forces. Our experiment is designed to detect the decays of the muons that survive long enough to reach our detector.

B. Muon Decay

The decay rate of muons is proportional to the remaining number of muons within a sample, resulting in an exponential decay rate as seen for typical radioactive decays. However, because we are not monitoring the decay of a given sample of muons, we will be using an exponential function that describes the probability of muon decay, given by Equation 1 and derived from reference [2]. Because decay is a quantum process, making the rules of quantum uncertainty impossible to ignore, the exponential decay law can make no definitive claims about any single particle. Rather, it indicates the expected behavior of a sample of many decaying muons. The fact that the muons whose decay the detector will be observing were created in the atmosphere and not around the detector will not affect the form of the decay plot. Regardless of where you observe an exponential law, as the one that governs the muons' decay, the time to decrease e by any factor is the same.

$$N(t) = \lambda e^{-t/\tau} \tag{1}$$

As given by reference [2], where τ represents muon lifetime and λ represents muon decay rate, defined to be the reciprocal of τ.

II. EXPERIMENT

Our investigation of muon decay relied entirely upon the data extracted from the TeachSpin apparatus detailing the decay times observed for the numerous muons that encountered the apparatus' plastic scintillator. While it is true that the muons that reach the detector will have lost some of their energy from interaction with other particles, many of them will still have energy considerable enough to cause ionization and atomic excitation of the particles in the scintillator of our detector. When charged particles interact with a scintillating material, the material absorbs part of their energy, through excitation of the material, and emits this energy as near visible wavelength photons, as the excited portions of the material return to ground state. The faint light emitted by the excited scintillator is then absorbed by a photomultiplier that amplifies the light to a readable electric signal.

However, scintillators are excited through interactions with charged particles, not just muons. We can circumnavigate this fact using knowledge of the muon decay process. Depending on the charge of a muon, muons either decay into an electron or a positron and a combination of neutrinos. Because the neutrinos are incredibly light, effectively massless, the electron/positron often inherits most of the muons kinetic energy, enough to leave its own trail of scintillation signals. Knowing this, we can tune the circuitry of the detector to only count two pulses – one from the muons entrance into the detector and the second from the high energy electron – that occur within a short enough time period, the discrimination period, as a muon decay. To make sure the detector is not simply counting the number of muon decays, the detector also notes the time in between the two pulses. Now it is still possible that two particles that hit the detector at approximately the same time could be counted as a muon decay. However, because the expected average lifetime of a muon's decay is on the order of microseconds, the odds that two particles enter the scintillator within the discrimination period are low. These odds are also fairly constant throughout the duration of data collection and will thus serve as a source of systematic error that can be explained.

III. DATA ANALYSIS

The collected data consisted of timestamped decay events recorded over a total run time of approximately 6 hours (5:56:50). During this period, the detector registered 465,292 incident muons and cosmic rays passing through the scintillator, producing an average incident rate of 20 detections per second. Out of these, 709 were classified as valid muon decays — characterized by a primary pulse from the incoming muon and a secondary pulse from the decay within the detector's discrimination window.

A discrimination threshold of 40,000ns or 40 µs was used to determine which pairs of incident signals would be counted as decays. This threshold was chosen because events beyond this timescale are too long to plausibly represent muon decay. The selected discrimination threshold is also small enough to reduce the odds of background coincidences being counted as decays. The filtered decay time distribution was then fit to the exponential model introduced in Equation 1.

Prior to fitting, an initial estimate for the muon lifetime, τ_{guess}, was calculated from the mean of the decay times in the dataset using Equation 2. This guess served as a starting point for the nonlinear curve-fitting algorithm used to extract our final estimation of muon lifetime.

$$\tau_{\text{guess}} = \frac{1}{N} \sum t_i \tag{2}$$

Where N represents the total number of events classified as muon decays and t_i represents the recorded decay time for a given decay event. The actual fitting was performed using the `curve_fit()` function from Python's `scipy.optimize` library, which optimized the parameters of the model to minimize the residuals between the experimental histogram and the exponential curve. The resulting value of τ, $2.16 \pm 0.17\mu s$, and its associated uncertainty were extracted from the fit, and the statistical methods used to evaluate the uncertainty are detailed in Section V.

IV. RESULTS

To extract the muon lifetime τ, the decay time distribution was fit to the exponential model given by Equation 1 using the nonlinear least squares method outlined in Section III. A plot of the resultant histogram overlaid with the best-fit exponential decay curve provided by the nonlinear least squares method is shown in Figure 2. The fit yielded a mean muon lifetime of $\tau = 2.16 \pm 0.17\,\mu s$.

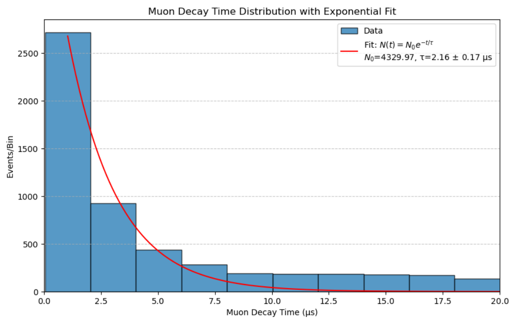

FIG. 2. 10 bin histogram of muon decay times with an overlaid exponential fit of the form given by Equation 1. The best-fit parameters were observed for $\tau = 2.16 \pm 0.17\,\mu\text{s}$, consistent with the expected muon lifetime of $2.19\mu s$. The bin width is 2.5 µs, and the distribution clearly exhibits an exponential decay trend.

The measured value of $\tau = 2.16 \pm 0.17$ is in close agreement with the accepted mean muon lifetime of 2.19 µs, and has a relatively small percent error of approximately 1.8%. Minor deviations can be attributed to statistical noise, detector limitations, and background coincidence events. Nevertheless, the results strongly support the exponential nature of muon decay and the predictions of weak interaction theory.

V. ERROR ANALYSIS

The primary sources of error in our muon lifetime measurement arise from statistical fluctuations, binning effects, detector efficiency limitations, and false decay counts caused by the incidence of two or more background particles within the discrimination period.

As aforementioned in section III, nonlinear least-squares fitting was used to fit the measured muon decay time distribution to the exponential decay function outlined by Equation 1. The `curve_fit` function from the `scipy.optimize` library was used to perform the nonlinear least-squares fitting to the data and the covariance matrix provided the uncertainties for the fitted parameters:

$$\sigma_\tau = \sqrt{\mathrm{Var}(\tau)} \tag{3}$$

where $\mathrm{Var}(\tau)$ is extracted from the diagonal of the covariance matrix. Dividing the uncertainty of mean muon lifetime, Equation 3, by the measured value of muon lifetime, $2.16\mu s$, provides the relative uncertainty of our measurement, shown in Equation 4.

$$\frac{\sigma_\tau}{\tau} \times 100 \approx 7.87\% \tag{4}$$

The primary source of statistical error likely arises from the distribution of muon decays. The muon decay time distribution follows a Poisson process [3], which causes natural statistical fluctuations within the data. Increasing the sample size would allow for these statistical fluctuations to average out, reducing the uncertainty in the extracted decay parameter [3].

Systematic uncertainty within this investigation can be primarily credited to the timing resolution/precision of the TeachSpin apparatus, false decay events caused by background particles, and the number of bins used to plot the exponential fit used to extract the experimental decay rate, as outlined in Section IV. The timing resolution of the photomultiplier tube and associated electronics limit the precision with which decay events can be recorded and thus introduce uncertainty into all recorded values of muon lifetime. The incidence of two or more atmospheric particles within the discrimination period is also possible and would introduce a source of error. However, because the probability of two or more cosmic rays interacting with the detector within the discrimination threshold is constant throughout the entire experiment, this phenomena serves as a systematic source of error. The choice of 10 bins also introduces uncertainty by influencing histogram smoothness which can introduce minor bias in fitting.

Increased data collection time to reduce statistical noise, improved background discrimination by refining pulse timing algorithms, and further calibration of detector electronics to enhance timing accuracy would all serve to reduce sources of error within our investigation. Despite these limitations, our result, $2.16 \pm 0.17\mu s$, is in close agreement with the accepted muon lifetime of $2.19\,\mu s$, validating the experimental approach.

VI. DISCUSSION

Following data analysis, the estimated muon lifetime τ was found to be $2.16 \pm 0.17\mu$s, which is in agreement with the theoretical value of 2.19μs within the limits of the measured value error. The small deviations from the expected value can be attributed to the statistical and systematic uncertainties outlined in Section V.

As mentioned in Section IA, the primary production reaction of muons, pion decay, has the same likelihood of producing a positively charged muon as it does a negative muon. And because muons are not electrons, the Pauli Exclusion Principle does not restrict it from inhabiting an orbital already full of electrons. This absorption of negatively charged muons by atomic nuclei acts as a second way for negative muons to disappear and leads to an effective shorter lifespan of negatively charged muons. However, because the muon detector doesn't discriminate between positively or negatively charged muons, it follows that the observed average lifespan – effectively the average of positive and negative muons' lifespan – would be slightly lower than that observed in vacuum, as observed.

As expected, the dataset did contain evidence of systematic error. Instead of decaying to zero, the collected data showed an exponential decay towards a constant value. However, this result is nothing to cause despair nor anything unexpected. As mentioned in the introduction, this noise can be credited to the background activity of other charged particles and can be credited with little influence upon the calculated value of muon lifespan.

Despite these limitations, the results confirm the exponential nature of muon decay and validate the underlying principles of weak interactions in particle physics. Future improvements could include collecting a larger dataset and refining the detection apparatus to reduce systematic errors.

VII. CONCLUSIONS

The results of the experiment proved realistic by providing a lifespan of muon decay, $2.16 \pm 0.17 \mu s$, comparable to the expected value of $2.19 \mu s$ and by corresponding very well to expectations regarding background noise. Possible discrepancies between the observed value and the accepted value include statistical uncertainties, detector inefficiency, and systematic error introduced by background noise. Future experiments could remedy these discrepancies through various methods, including collecting larger sample sizes and tuning the precision of the detector's circuitry.

[1] A. Gutarra-Leon, C. Barazandeh, and W. Majewski, Exigence: A Journal of Student Inquiry **2** (2018), accessed: April 14, 2025.

[2] T. E. Coan and J. Ye, Muon lifetime apparatus manual, https://www.teachspin.com/muon-lifetime (2024), accessed: February 11, 2025.

[3] S. Keeling, Probabilistic models for radioactive decay, https://imsc.uni-graz.at/keeling/modII_ss19/radiodecay.pdf (2019), accessed: April 14, 2025.