PHY-462
Advanced Laboratory
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Muon Lifetime

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Introduction

Muons are elementary particles that move at relativistic speeds through the atmosphere. A lepton that has 200 times the mass of an electron, (anti)muon will decay into an (anti)electron with a lifetime of about 2197ns. In this experiment, we measure the mean lifetime of a muon at rest. To do so, we took advantage of these muons' interaction with scintillating oil: producing photons both when muons slow down and succeeding decay inside the oil. We detect these photons and measure the time intervals between the two events. Using these data to form a histogram, we calculate the muon lifetime to be 2196 ns, which is in close agreement with the literature value.

Theory

As muons travel down through the atmosphere, they will experience two processes: 1) decays that happen at the same rate for both positive and negative muons, and 2) captures by nuclei that only apply to electron-behaved negative muons. As a result of muon capture, when they reach sea level (our measurement site), positive and negative muons will present in a ratio (charge ratio) of 1.2766:1, independent of energy for low energy muons that we care about. When this mixture of muons enters our detector filled with scintillating oil, similar processes occur, allowing us to measure the muon decay lifetime, τ. Specifically, signals will be generated when muons enter and decay inside the detector with a measurable time-lapse t. Collecting the data for a long period, we can count how many muons decay, denoted as N', within time-lapse $t \pm \delta t/2$. Meanwhile, muon captures are dominated by carbon atoms at a rate λ. Suppose there are N_0 muons entering our detector initially. Using the charge ratio, we can calculate the positive muon population N_0^+ and negative muon population N_0^- . Then the number of muons that remain and diminished at time at time t are respectively:

$$N(t) = N_0^- \cdot e^{-(\frac{1}{\tau}+\lambda)t} + N_0^+ \cdot e^{\frac{-t}{\tau}}$$

$$|\frac{dN(t)}{dt}| = (\frac{1}{\tau}+\lambda)N_0^- \cdot e^{-(\frac{1}{\tau}+\lambda)t} + \frac{1}{\tau}N_0^+ \cdot e^{\frac{-t}{\tau}}.$$

Since the charge ratio is fixed, the rate of capture and decay is proportional. Thus, the number of muon decays at time t within a bin δt, which we previously denoted as N' is:

$$N'(t) = C'|\frac{dN(t)}{dt}|\delta t = \{(\frac{1}{\tau}+\lambda)N_0'^- \cdot e^{-(\frac{1}{\tau}+\lambda)t} + \frac{1}{\tau}N_0'^+ \cdot e^{\frac{-t}{\tau}}\}\delta t.$$

By fitting our data to N', we can find the muon lifetime τ.

Methods

As mentioned before, we use a bucket of scintillating oil to capture muons. A photomultiplier tube (PMT) is immersed in the oil which produces a pulse of less than 20 ns when it receives photons. The Timing Filter Amplifier shapes the pulse and passes the signal to a Constant Fraction Discriminator, which sets an acceptance threshold that is independent of the height of the pulse and outputs two signals into the Time-to-Amplitude converter (TAC). TAC outputs a positive pulse whose amplitude is proportional to the time difference between the two signals. The output goes to the Multichannel Analyzer (MCA), which displays a histogram of counts on the computer. From here, we can use the histogram and calculation tools to calculate the muon lifetime.
When the muon comes into the bucket, it slows down and the energy got transferred to oil molecules, which get excited and then decay, giving off bursts of light. If the muon decays is in the bucket, it will give off another burst of energy, resulting in another burst of light. In this case, PMT would generate two signals, TAC then generates an amplitude pulse accordingly, and finally MCA would add one count to the corresponding energy level, and we can see which from the computer.

Results

The whole process of data process took 14 days. We calibrated the MCA using a pulse generator before and after the data collection. The average value of two calibrations determines the value of the x-axis to represent the time. We also implement the binner method to increase the statistical stability by decreasing the total number of sampling buckets. All these allow us to generate a histogram of how many muons decay within a time bin $t \pm \delta t/2$. By fitting this histogram to our model described before, we calculate the muon lifetime to be 2192.64 ns ± 6.1 ns. The literature value is 2197 ns.

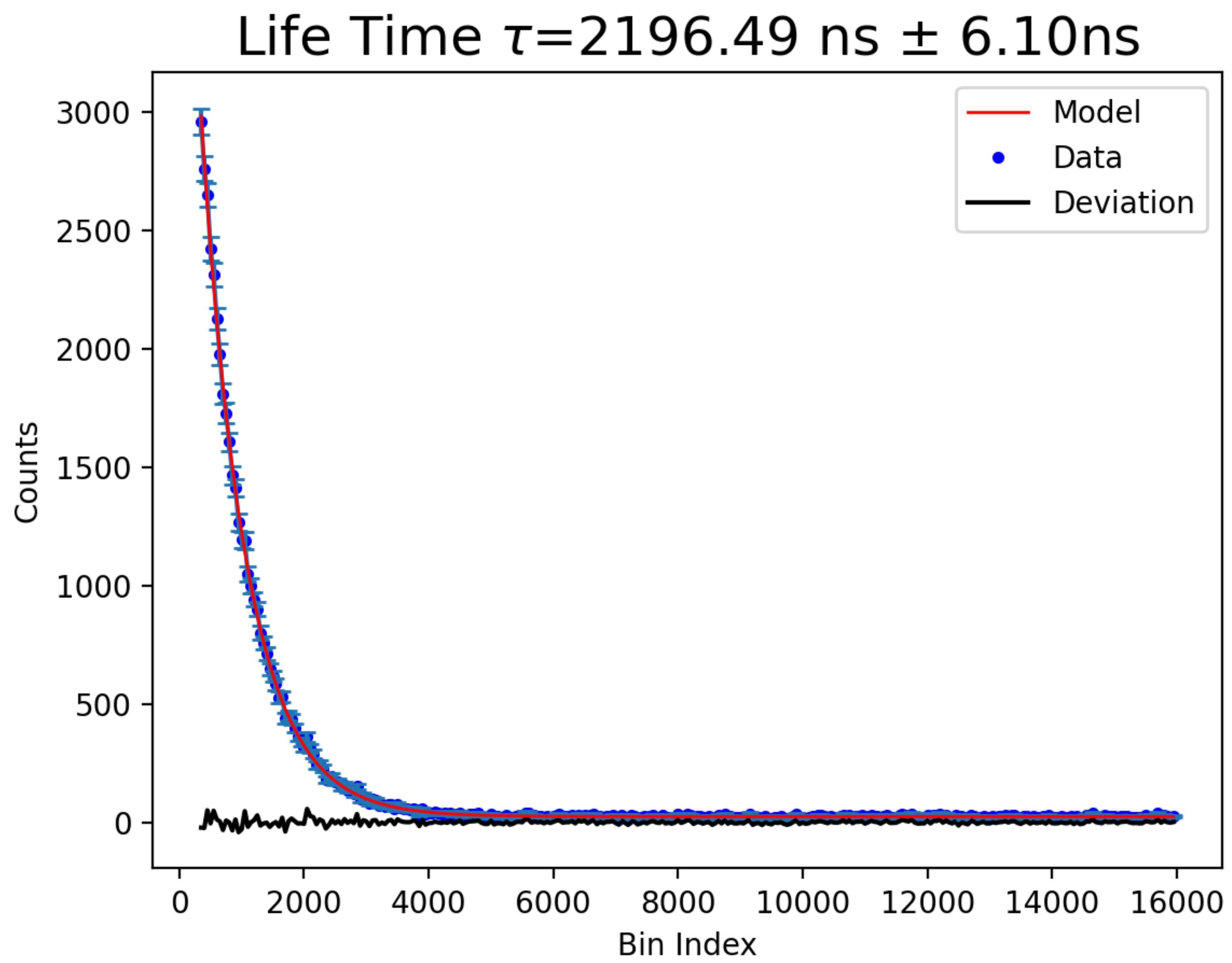

Figure 1. This is the plot of count v. bin index. The blue points are the counts and error bars from the data, and the red line represents the trendline of which.

Conclusions

Using scintillating oil, we capture muons and calculate their decay time. With 14 days of counting, we form a histogram of counts vs. decay time for muon. Through calculation, we determine the muon lifetime to be 2192.64 ns ± 6.1 ns, 0.14% off from the literature value.

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References

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