Muon Lifetime Experiment Summary

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I. EXPERIMENT GOALS

The primary objective of this experiment is to measure the lifetime of a muon (τ_μ) by observing its decay and fitting the resulting exponential distribution. This measurement also allows us to infer the Fermi constant (G_F) since $\tau_\mu^{-1} \propto G_F^2$. Additionally, we aim to determine the muon rest mass by analyzing the energy spectrum of decay electrons.

1. Measure the lifetime of a muon τ_μ and extract the weak force coupling constant G_F.
   (a) Muons originate from cosmic ray interactions, where pions and kaons decay into muons and muon neutrinos.
   (b) Muons decay via weak interaction:
   $$\mu^- \to e^- \bar{\nu}_e \nu_\mu,$$
   $$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu.$$
   (c) Negative muons can also be absorbed in matter:
   $$\mu^- p^+ \to n \nu_\mu.$$
   The probability of capture depends on the atomic number Z and scales roughly as Z^4 for low Z. Since we use a plastic (hydrocarbon) scintillator, we approximate it as carbon.
   (d) The decay rate follows:
   $$-\frac{dN}{dt} = N_0 \Gamma_\mu e^{-\Gamma_\mu t}.$$
   Taking the logarithm, we obtain a linear form:
   $$\ln\left(-\frac{dN}{dt}\right) = \ln(N_0 \Gamma_\mu) - \Gamma_\mu t.$$
   We fit this to extract Γ_μ, from which τ_μ can be determined.

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2. Measure the muon rest mass by analyzing the decay electron energy spectrum.
   (a) In the decay $\mu^- \to e^- \bar{\nu}_e \nu_\mu$, energy conservation dictates that the electron carries roughly half of the muon's rest energy.
   (b) The energy spectrum of electrons is analyzed to identify the high-energy cutoff, which provides an estimate of the muon mass.
   (c) Calibration is performed using the energy deposition (dE/dx) of minimally ionizing muons.

II. EXPERIMENTAL CONSIDERATIONS

1. **Trigger Calibration:** The detection system must effectively filter out non-muon events. The muon signature is identified using:
   - **Start Signal:** $T \wedge M \wedge \bar{B}$, indicating a muon stopping in the middle detector.
   - **Stop Signal:** Any secondary signal in M, or an event where the electron escapes upward ($T \wedge M \wedge \bar{B}$) or downward ($\bar{T} \wedge M \wedge B$).

   A gate lasting several muon lifetimes is implemented, and the B signal is extended to prevent false triggers.
2. **Scintillation and Detection:** Muons excite the plastic scintillator, producing light that is detected by the photomultiplier tubes (PMTs).
   - The PMT converts light into an electrical signal via the photoelectric effect.
   - The signal is amplified through a cascade of dynodes, creating a measurable output.
   - Possible issues include afterpulsing from ionized residual gases inside the PMT.
3. **Data Acquisition and Analysis:** The oscilloscope and LabVIEW software record time intervals between the start and stop signals. A histogram of these delays should follow an exponential decay, allowing τ_μ extraction through curve fitting.

III. SAFETY CONSIDERATIONS

1. **High Voltages:**
   - PMTs operate at -2.0 kV to -2.4 kV. Handle cables carefully.
   - DO NOT hot-plug high voltage connections.
2. **Radiation:**
   - Cosmic ray muons pose no significant health risk.
   - Ensure proper shielding of electrical components.

IV. QUESTIONS

1. Why do we only consider muons that stop in the middle detector for lifetime measurements?
2. Are we fitting τ_μ from the decay rate equation, or are we directly measuring lifetimes from individual events?
3. What are the primary sources of background noise in the signal, and how do we mitigate them?
4. How does the discriminator threshold affect the efficiency of the detector, and how should it be calibrated?
5. How does the afterpulsing effect in PMTs influence our measurements, and what techniques can be used to suppress it?