True Muonium and HPS: Potential Discovery

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What is True Muonium?

- True muonium is a bound state of a $\mu^+\mu^-$ pair
  - “Muonium” is a bound $\mu^+e^-$ pair, tauonium is a bound $\tau^+\tau^-$ pair, and tau-muonium is a bound $\tau^\pm\mu^\mp$ pair.

- Positronium and muonium are produced and studied, but muonium, tauonium and tau-muonium have never been observed before.

- Together with ($\tau^+\tau^-$) and ($\tau^\pm\mu^\mp$), true muonium is the most compact pure QED system.

- True tauonium and mu-tauonium are very difficult to detect, since $\tau$ weak decay overwhelms the QED decay

Why is this interesting?

- Detection of true muonium would be a significant discovery and would constitute a further important test of QED.
- Would demonstrate the capability of the HPS experiment to identify rare separated vertex decays.
True Muonium Production

• True muonium can be produced with an electron beam on a target
• There are two spin states:

Paradimuonium, singlet state $n^1S_0$
  • Decays to 2 photons
  • Lifetime $= 0.6 \times 10^{-12}$ s (in ground state)
  • $c\tau \sim 0.181$ mm

Orthodimuonium, Triplet $n^3S_1$
  • Decays to $e^+ e^-$
  • Lifetime $= 1.8 \times 10^{-12}$ s (in ground state)
  • $c\tau \sim 0.543$ mm
  (for $n=1$; lifetime for higher $n$ states $\propto n^3$)

This is the one we are interested in!

Brodsky and Lebed, Phys. Rev. Lett. 102, 213401 (2009)
True Muonium Production

• True muonium can be produced with an electron beam on a target

• Triplet Production Cross-Section:

\[ \sigma_{\text{triplet}} = 1.20 Z^2 \frac{\alpha^7}{m^2_\mu} \left( 1.79 \ln \left( \frac{E_{\text{beam}}}{m_\mu} \right) - 6.12 \right) \]

\[ \sim 6.2 Z^2 10^{-41} \text{cm}^2 \quad (E_{\text{beam}} = 6.6 \text{GeV}) \]

• Cross-section scales like \( Z^2 \) (stay tuned for more on this topic)

• Simplified formula predicts that no true muonium states will be produced at 2.2 GeV, so we focus on the 6.6 GeV beam energy

[Holvik and Olsen, Phys. Rev. D35 2124 (1987)]
True Muonium Production

True muonium breaks up very easily inside the target!

- Triplet dissociation cross section is very large:

\[ \sigma_{diss} \sim 1.3 Z^2 10^{-23} \text{ cm}^2 \]

AND it scales like \( Z^2 \)!

- So, only the states produced in last fraction of target will make it out of target and the total production rate is effectively independent of \( Z \)

- Effective thickness for not breaking up in target is

\[ t_b = \frac{1}{N \sigma_{diss}} \quad (N = \text{number of atoms/cm}^2) \]

[Holvik and Olsen, Phys. Rev. D35 2124 (1987)]
Total Production Rate

Triplet production rate:

\[ \text{Rate} = 0.021 \left( 1.79 \ln \left( \frac{E_{\text{beam}}}{m_\mu} \right) - 6.12 \right) I(\text{mA}) \]

- For running conditions of \( E_{\text{beam}} = 6.6 \text{ GeV} \), 450 nA beam current, 3 months (~7.8\( \times \)10\(^6\) s) and a single foil:
  
  95 n=1 events, with a decay length of about 1.7 cm.

- The search requires a vertex cut at about 1.5 cm to reject almost all QED background events, then searching for a resonance at 2 m\( _\mu \).

- Accounting for efficiencies, we would expect to see about 10 true muonium events (acceptance parameterization is uncertain at the 50% level).
Other Thoughts

Things to be done and thought about:

- Do we understand our backgrounds well enough?
  - Should be the same as for the A' with an O(1 cm) decay length, so we should understand them reasonably well.

- Can we detect the dissociated pairs from true muonium broken up in the target?
  - Dissociated pairs should have collinear, equal-energy $\mu^+\mu^-$ pairs that we can detect in the muon system
  - However, Stanley Brodsky and Rich Lebed don't think we can distinguish these pairs from unbound pairs without a dedicated dissociation foil.
Other Thoughts

Things to be done and thought about:

- Do we want to pursue a dedicated run for true muonium?
  - The production rate can be increased, but would require a different target.
  - Target thicknesses $> t_b$ do not help to increase the production rate; pairs created at front will not make it out the back of the target before breaking apart.
    - Tungsten, $t_b = 2.2 \, \mu m$ (0.064% r.l.)
    - Carbon graphite, $t_b = 190 \, \mu m$ (0.01% r.l.)
Other Thoughts

Things to be done and thought about:

- Do we want to pursue a dedicated run for true muonium?
  - The production rate scales linearly with both current and number of target foils.
    - Using 800 nA, and 2 or 3 target foils (spaced at least 2 cm apart so decays are between foils):
      - 340-500 events, of which 35-40 would be detectable in a vertex search (this needs more study)
      - Compare to 95 events at 450 nA and single foil, with about 10 detectable events.

- Note there is an efficiency decrease for detecting ($\mu^+\mu^-$) decaying between foils; need to make sure that the vertices don't lie near the foils
Other Thoughts

Things to be done and thought about:

• Do we want to pursue a dedicated run for true muonium?
  • With a multiple foil target, downstream foils would also serve as dissociation foils
  • Detect true muonium decaying between the foils as well as ones that dissociate in the downstream foils
  • Have target foils be removable
  • Run with different combinations of foils in/out to study the background pair production spectrum as well as dissociation.
Summary

HPS will be a great place to detect true muonium!

- If we observe it, it will be a great discovery.
- Should we consider a proposal for a dedicated run?

HPS True Muonium Group: Rouven Essig, Guy Ron, and Sarah K. Phillips
Backups
Another physics thought:

• Do we want to take a look at the asymmetry in the unbound pair-produced $\mu^+\mu^-$?

• Another QED observable to compare between muons and electrons?