True Muonium and HPS: Potential Discovery

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What is True Muonium?

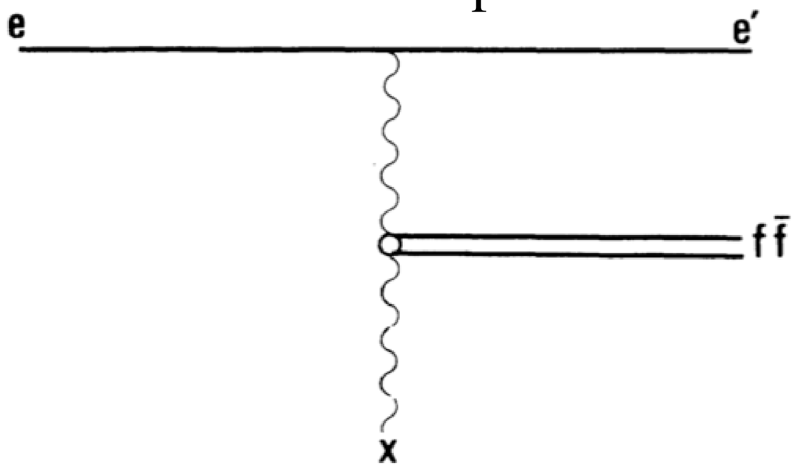
- True muonium is a bound state of a $\mu^+\mu^-$ pair
  - "Muonium" is a bound μ^+e^- pair, tauonium is a bound $\tau^+\tau^-$ pair, and tau-muonium is a bound $\tau^\pm\mu^\mp$ pair.
- Positronium and muonium are produced and studied, but muonium, tauonium and tau-muonium have never been observed before.
- 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 τ weak decay overwhelms the QED decay

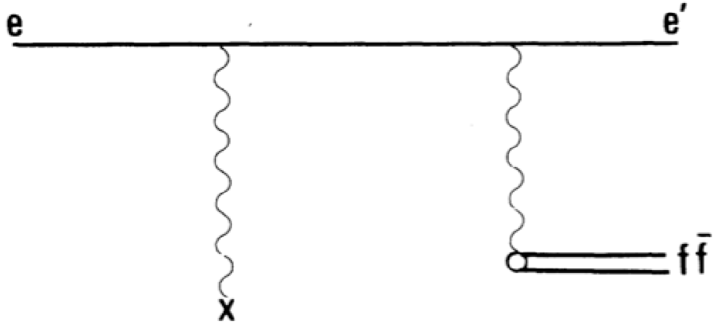
Why is this interesting?

- 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 = 0.6×10^{-12} s (in ground state)
- $c\tau \sim 0.181$ mm

Orthodimuonium, Triplet n^3S_1

- Decays to $e^+ e^-$
- Lifetime = 1.8×10^{-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!

Holvik and Olsen, Phys. Rev. D35 2124 (1987)
Arteaga-Romero, Carimalo, Serbo, Phys. Rev A62, 032501 (2000)
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:

$$\sigma_{triplet} = 1.20\, Z^2 \frac{\alpha^7}{m_\mu^2}\left(1.79 \ln\left(\frac{E_{beam}}{m_\mu}\right) - 6.12\right)$$

$$\sim 6.2\, Z^2\, 10^{-41}\, cm^2 \qquad (E_{beam} = 6.6\, GeV)$$

- 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:

$$\sigma_{diss} \sim 1.3\, Z^2\, 10^{-23}\, cm^2$$

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

$$t_b = \frac{1}{N\,\sigma_{diss}} \qquad \text{(N = number of atoms/cm2)}$$

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

Total Production Rate

Triplet production rate:

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

- For running conditions of E_{beam} = 6.6 GeV, 450 nA beam current, 3 months (~7.8×10^6 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_μ.

- 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 µm (0.064% r.l.)
    - Carbon graphite, t_b = 190 µm (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

Other Thoughts

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?