How Well Can the Heavy Photon Search Discover True Muonium?

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Abstract

The Heavy Photon Search (HPS) is a new experiment at Jefferson Laboratory to search for heavy photons in the mass range of 20 MeV/c^2 to 1000 MeV/c^2. The experiment also has the potential to discover "true muonium", a bound state of a muon and an antimuon that is predicted to exist, but has never been observed. The true muonium "atom" should be produced by an electron beam incident on a target, such as the tungsten target used in the HPS experiment. Similar to the decay of the heavy photon, a triplet state of true muonium will decay to an electron-positron pair, allowing it to be detected in the same way. Since the mass of the "atom" will be about twice the mass of a muon, or approximately 210 MeV/c^2, and the decay length is expected to be on the order of centimeters, a precise search window can be specified. Simulations of this experiment can be performed to show us how well we can expect to observe true muonium. The accuracy and efficiency of these observations found in simulation should be enough to tell us whether the experiment will be enough to confirm a discovery.

Introduction

One of the greatest mysteries in modern astrophysics is the observable effects of "dark matter" and "dark energy" in our universe. The presence of dark matter implies that there is more to the Standard Model of particle physics than initially predicted. Many of these extensions to the Standard Model require the existence of additional particles called heavy vector bosons, more often referred to as "heavy photons" or "dark photons". The Heavy Photon Search experiment (HPS) aims to search for evidence of a heavy photon. It is theorized that heavy photons weakly couple to electrons through interactions with ordinary photons, and consequently should radiate in electron scattering.

The HPS experiment also has the potential to discover a new form of matter called "true muonium", a bound state of a muon and an antimuon. A muon is an elementary particle similar to an electron, although more massive. Unlike positronium (electron-positron bound state) and muonium (muon-positron bound state), true muonium has yet to be observed. The muon has a long lifetime, so any decay observed with true muonium will be a result of quantum electrodynamic (QED) processes. The decay of other QED "atoms", such as tauonium (another pairing of an electron-like particle and its antimatter counterpart), is a result of the weak nuclear force and the decay occurs at much shorter lengths. This makes true muonium important to the study and advancement of QED.

True muonium occurs in both a singlet and triplet state, but it is the triplet state that is found to decay in an identical way to the heavy photon. As a result, it is possible to search for true muonium using the same experiment. With a mass of approximately twice that of a muon, and a long decay length, true muonium leaves its own signature that will allow it to be detected. To predict how likely a discovery will be, simulations of the experiment can be set up and run while easily changing initial conditions. The resulting data can then be analyzed to find out how accurate and efficient we expect our observations of true muonium to be, and what can be done to improve these results.

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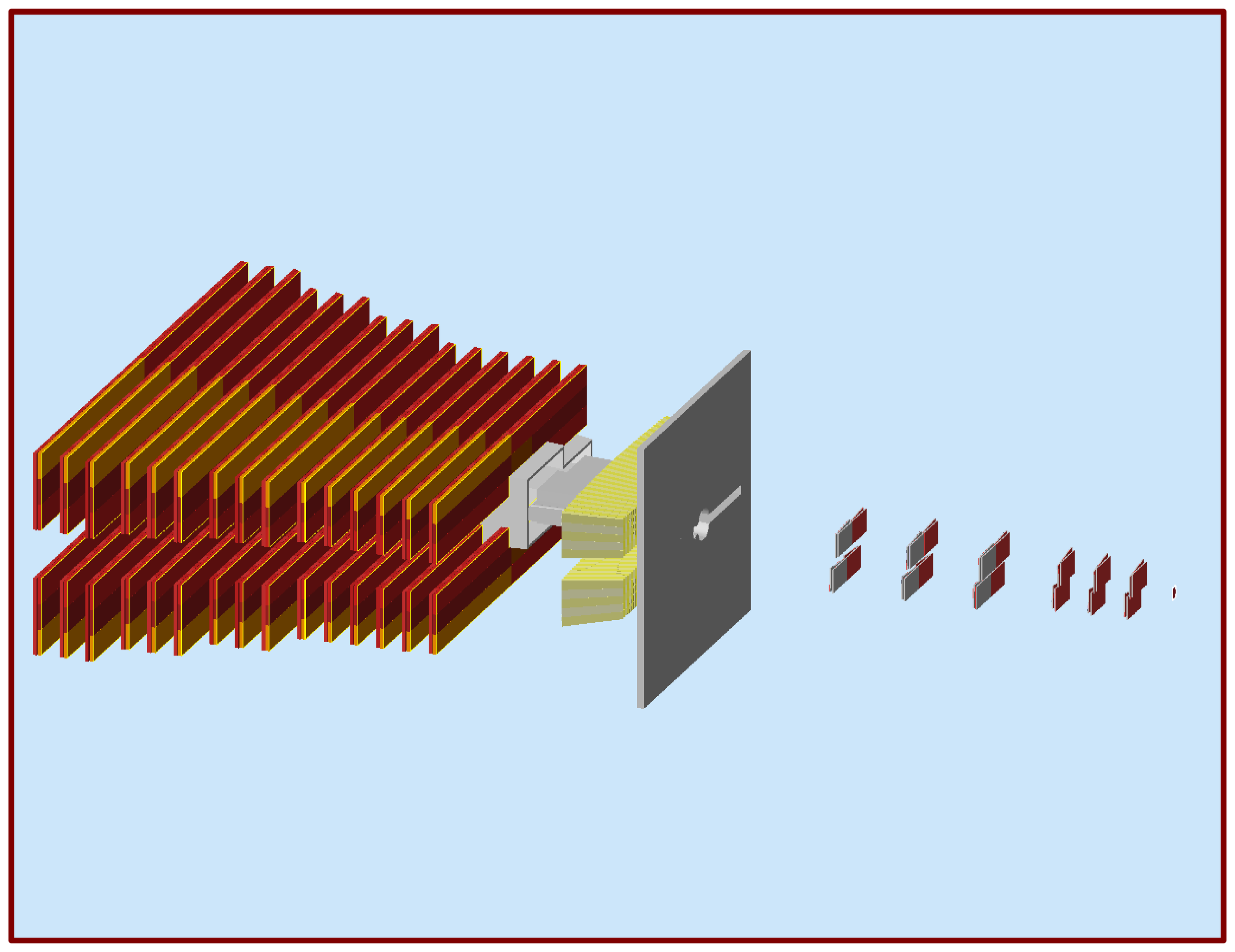
Experimental Setup

The experiment will take place at Jefferson Laboratory in the newly renovated Hall B. The true muonium atom will be produced by a 6.6 GeV electron beam incident on a tungsten target. The true muonium atom will either dissociate into a muon and antimuon before leaving the target, or decay into an electron-positron pair. The energies of the decay products will be measured by an electromagnetic calorimeter downstream from the target, while the muon particles will be measured by a muon detector behind the calorimeter. In between the target and these detectors are six silicon vertex trackers. The six trackers placed in a vacuum with a magnetic field will allow the path of the particles to be measured as they travel from the target to the calorimeter and muon detector.



A geometric rendering of the experimental setup. The beam will enter from the right, hit the target, and continue through the silicon vertex trackers, calorimeter, and muon detector, from right to left in the picture above.

Simulation and Reconstruction Software

The process of simulating and analyzing HPS accelerator events is done with software developed by members at SLAC National Laboratory. The two primary parts of this software are:

- **SLIC**: a GEANT4-based event generator and simulation package
- **lcsim**: the core of the distribution, containing track reconstruction and analysis code. Within lcsim are many sub-categories, most notably hps-java, a package containing HPS-related reconstruction and analysis Java code. Individual reconstruction and analysis steps are organized in corresponding drivers, which can be called sequentially in the desired order by a steering file.

When running through the process, a detector geometry description must be written to accurately reflect the conditions of the experiment, which is then converted to a readable format for SLIC. An input file specifying beam conditions is then run through SLIC with the detector geometry file to simulate events. The output from SLIC is run through the desired lcsim/hps software to simulate detector response, reconstruct physics objects and form a reconstructed event file. With the reconstructed event file, analysis tools can be used to create plots and discover any information contained within the file. There is also a graphical analyzing tool named JAS3 that can take the data file at any step after SLIC to step through the events, view event displays, and run through some analysis.

Expectations

The amount of true muonium produced depends on both the production and dissociation cross sections. For a beam energy of 6.6GeV and looking at the triplet state we find [1]:

$$\sigma_{pro} \sim 6.2\,Z^2\,10^{-41}\,cm^2 \qquad \sigma_{diss} \sim 1.3\,Z^2\,10^{-23}\,cm^2$$

The large dissociation cross section implies that true muonium breaks up easily in any target. In fact, only the true muonium produced in a small fraction of the target will escape.

We will identify the true muonium event by taking a vertex cut of 1.5cm to reject QED background events, and then look for a resonance at $2m_\mu$. The number of true muonium events expected are calculated by [2]:

$$N = 200 \times \left(\frac{I}{(450\,nA)}\right)\left(\frac{t}{(1\,month)}\right)$$

With a beam energy of 6.6 GeV, a beam current of 450 nA, 2 weeks of beam time, and a single foil target, we can expect to observe 10-20 true muonium events.

Reconstruction and Analysis Process

Physically, when a true muonium "atom" decays we are left with an electron-positron pair. As such, we expect to see two tracks travel through the 12 silicon vertex tracker (SVT) layers. The reconstruction process looks at the simulated data, and reconstructs the two tracks based on the trackers. However, due to the vertex cut to reject background events, and an energy cut for triggering, the efficiency of reconstructing the tracks is predicted to be about 98%. There are also "bad" hits that occur when a high energy electron from the beam scatters backwards. Greater than 98% of reconstructed tracks have 0 bad hits though.

While reconstructed tracks will give us the amount of true muonium events that we observe, the resolution of these tracks is important to tell us how accurate our observations are. Analysis of the reconstructed tracks will help determine the vertex resolution and mass resolution of our measurements. These resolutions are affected by the momentum of the particle, the position of the vertex relative to the beam, the vertex and energy cuts, the number of bad hits, the invariant mass of the pair, and the most likely decay position of the particle.

Future Work

In the past year, we have been successful in running simulations and reconstructing the events. Reconstruction and analysis are both continuously changing processes, being improved to give better reconstruction efficiencies and resolutions. Soon we will have a functioning analysis tool to show us this data, and we will be able to conclude whether we should be able to claim a discovery of true muonium.

Acknowledgements and References

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