Intense Beam of Metastable Muonium for Testing the Standard Model

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Precision spectroscopy of the Muonium Lamb shift and fine structure requires a robust source of 2S Muonium. To date, the beam-foil technique is the only demonstrated method for creating such a beam in vacuum. Previous experiments using this technique were statistics limited, and new measurements would benefit tremendously from low energy muon (< 20 keV) sources where the 2S production is more efficient. Such a source of low energy $\mu^+$ has only become available at large quantities in recent years at the Low-Energy Muon beamline at the Paul Scherrer Institute. Here we report on the successful creation of an intense, directed beam of metastable Muonium. We find that even though the theoretical Muonium fraction is maximal at low energy (2–5 keV), scattering by the foil and transport characteristics of the beamline favour higher energy $\mu^+$ (7–10 keV). We estimate that an event detection rate of few per second for a future Lamb shift measurement is feasible, enabling an improvement by a factor 100 over the previous determinations within days of beam time.

I. INTRODUCTION

Muonium (M) is the bound state of a positive muon ($\mu^+$) and an electron, two particles devoid of internal structure. Therefore, and in contrast to hydrogen, theory and experiment with M can be compared free of finite-size and nuclear effects [1]. Testing bound state quantum electrodynamics (QED) in the muonic sector is highly motivated by the inconsistencies which have turned up there, e.g. the deviation of the measured anomalous magnetic moment of the muon from its theoretical value [2], and the difference between the proton radius as measured by laser spectroscopy of muonic hydrogen [3] and several experiments in electronic hydrogen [4–6].

Until now, precision experiments in M only utilized the ground-state [7, 8]. The $1S \rightarrow 2S$ transition was measured by pulsed laser spectroscopy [9, 10], putting tight bounds on the muon-electron charge ratio. A future precision measurement using a CW laser is planned by the Mu-MASS experiment [11]. The measurement of the hyperfine structure currently determines the muon magnetic moment with the highest precision [12], with an improvement underway by the MUSEUM collaboration [13, 14]. However, the methods used for M production in these measurements do not produce sufficient M(2S) in vacuum, and so cannot be used to study transitions from excited long-lived states. These include the $n = 2$ Lamb shift [15, 16] and fine-structure [17], which were measured previously in M. Other transitions probed in hydrogen with fast beams may be considered as well [18–21].

Similar to hydrogen, metastable M can be formed with the beam-foil technique [22], and indeed M(2S) was first observed at the TRIUMF cyclotron accelerator using surface $\mu^+$ at few MeV impinging on gold and aluminum foils [23], followed by an observation at the Los Alamos Meson Physics Facility (LAMPF) [24]. In the Born approximation, production of M with this beam-foil technique is expected to be comparable to hydrogen with protons at the same velocity [25], favouring energies of few keV [26, 27]. For this reason, the TRIUMF and LAMPF muon beams had to be heavily degraded such that roughly half of the beam was stopped in the last atomic layers of the foil. This resulted in a wide angular dependence for the emitted M [28]. The broad energy distribution of the degraded muon beam, extending from keVs to MeVs, results in a broad M energy distribution peaking at low energy, roughly following the theoretical curve given in Fig. 5.

At TRIUMF, the estimated production rate of M(2S) per incident muon was 0.08% [15]. This low efficiency, combined with large divergence of the beam, resulted in a maximal detection rate of few per hour [29]. This limited the precision of the Lamb shift measurement to 1% [15]. Another campaign was conducted in parallel at the LAMPF accelerator, using similar methods and arriving at a comparable statistical uncertainty of 2% [16].

To enable the next generation of precision measurements with metastable M, we set out to solve the main limitation affecting previous campaigns, namely the necessity to stop an energetic muon beam in a thick foil. In this communication we report on efficient creation and detection of a directed M(2S) beam by the beam-foil technique by impinging slow $\mu^+$ from the Low-Energy-Muon (LEM) beamline at the Paul Scherrer Institute (PSI) accelerator [30, 31], on a thin carbon foil. By tagging each muon and measuring its time-of-flight (TOF), we report for the first time the M creation efficiency over well-defined energies ranging from 2 to 8 keV, and compare with models calibrated by scaled proton data. Through

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quenching in a static electric field, and by detecting the emitted Lyman-α photons, we extract the 2S fraction, and by combining with beamline simulation, the M(2S) beam parameters. We conclude with a realistic estimation of the achievable event rate for a future Lamb shift measurement and show that a significant improvement over the state-of-the-art is within reach.

II. EXPERIMENTAL SETUP

The LEM beamline uses a solid neon moderator to form a slow, monoenergetic (2 – 12 keV) μ⁺ beam [31–33]. In this energy regime, a high conversion rate from μ⁺ to M, as well as a non-negligible amount of M(2S), was expected by inspecting hydrogen formation data [34, 35]. The highest μ⁺ to M conversion efficiencies are expected at the lowest μ⁺ energies. Therefore, in the measurements performed here, three different incident energies of 5, 7.5, and 10 keV were chosen. For each incident energy, the beamline parameters were optimized, utilizing the Geant4-based musrSim simulation [36, 37]. The experimental setup for generating and characterizing the M and M(2S) beam is shown in Fig. 1.

The carbon foil has two simultaneous purposes; to tag incoming μ⁺ and to produce M in various states. Upon impact on the grounded foil, roughly one secondary electron is released per incoming muon [38] and guided to a microchannel plate (Tag-MCP), giving the start time for the experiment. A fraction of the μ⁺ captures an electron while passing through the foil, forming M primarily in the 1S and 2S states. To prevent forward-scattered electrons from creating false signals, each subsequent detector is biased to reject them.

The beam emerging from the foil propagates in a field-free region, and then through an electrical quenching region formed by two ring electrodes that mixes the 2S and 2P states. Unlike the metastable 2S state, the 2P state is short-lived and relaxes to the ground state within a few nanoseconds, emitting a photon of 122 nm (Ly-α). This photon can be detected by four CsI-coated MCPs (Ly-α-MCP) surrounding the quenching area. The beam exiting the quenching region, now formed predominantly of M(1S) and μ⁺, reaches a rejection electrode at high voltage that selects only M(1S). The surviving M(1S) atoms impinge onto an MCP (Stop-MCP), providing the stop signal.

An extension stage can be added between the carbon foil and the quenching electrode to extend the travelling distance. The resulting increase in TOF allows the extraction of the velocity and thus energy distributions of both μ⁺ and M after the foil. Additionally, the extension stage ensures that all 2P states, as well as higher lying states produced in the foil [39], decay prior to reaching the quenching region.

III. M-FRACTIONS AT DIFFERENT ENERGIES

The fraction of M formed out of the incident muon beam, f_M/μ⁺, is extracted from coincidence events between the Tag- and Stop-MCP with the rejection electrode turned on or off for different incident muon energies. The resulting background-subtracted TOF spectra for rejection off (M+μ⁺) and rejection on (M) are divided into multiple time bins, with the results for 10 keV incident μ⁺ shown in Fig. 2.

A Landau distribution was found to describe the TOF spectra with sufficient precision. From the fitted distributions for 10 keV incident μ⁺ with and without the extension stage, shown in Fig. 3, two distinct most-probable time values were extracted. Knowing the length of the additional extension stage and the time shift in the TOF-spectrum, the most probable velocity and thus most probable energy (MPE) of this dataset, was determined. Using this energy, and knowing the entire length between foil and back detector, we determined the time offset of...
FIG. 2. Histograms obtained from the dataset of 10 keV incident energy after background subtraction. The orange data is with rejection electrode on and corresponds to pure M signal. The blue data is with rejection electrode off and corresponds to M and \(\mu^+\) signal. The filled bins were used to extract M fractions, whereas the hollow bins were ignored due to large statistical uncertainty and additional background.

FIG. 3. TOF distributions of M for 10 keV \(\mu^+\) incident on foil, with (blue) and without (orange) extension stage. A landau distribution was used for fitting the spectra.

FIG. 4. Energy distributions of M measured at three different \(\mu^+\) incident energies. Areas are normalized to 1.

mental data fit well to the model not including electron tunneling. The errors in M-fraction are dominated by statistics. The errors in mean residual energy are correlated and arise from the uncertainty of \(t_0\). The results show that in the energy range probed, a high conversion rate to M is achieved. The agreement with the hydrogen data leads to the expectation that a sizeable amount of M(2S) is also produced [34].

IV. DETERMINATION OF THE 2S FRACTION

The fraction of M(2S) of the total M produced, \(f_{2S/M}\), is extracted from triple coincidence events between the Tag, Ly-\(\alpha\), and Stop-MCPs with the quenching electrodes turned on or off. Taking data only with the rejection electrode turned on, the rate of triple coincidence events, \(R_T\), indicative of M(2S), is then compared to the rate of double coincidence events between the Tag and.
Stop-MCPs, \( R_D \), indicative of M, to determine \( f_{2S/M} \). The clear triple-coincidence Ly-\( \alpha \) signal is shown in figure 6 for an incident \( \mu^+ \) energy of 10 keV. The Ly-\( \alpha \) signal can be seen in the expected time window calculated using the energy distributions from Fig. 4 and the distance, including the extension stage, between foil and the quenching area.

Taking into account the photon detection efficiencies, the resulting fraction of M(2S) out of the total M is

\[
f_{2S/M} = \frac{R_T}{R_D \cdot \epsilon_{MCP} \cdot \epsilon_{QG}},
\]

where \( \epsilon_{MCP} \) stands for the Ly-\( \alpha \) detection efficiency of the MCP and \( \epsilon_{QG} \) for the combined efficiency for quenching as well as solid angle covered by the detectors. The quenching and geometrical efficiency of the Ly-\( \alpha \) detection stage are correlated, and depend on the M velocity, since the position where M(2S) reaches before quenching affects the solid angle. To determine \( \epsilon_{QG} \), we performed a full 3D Monte-Carlo simulation of the particle motion and photon emission inside the static electric field using the SIMION 8.1 package [40]. The position distribution of the particles at the detector entrance was taken from the GEANT4 beamline simulation with the calibrated foil thickness, taking into account the coincidence detection in the Stop-MCP. Additionally, the anisotropy of the photon emission relative to the electric field direction [41], and the transparency of the grids on the detectors, were included. The total efficiency folded with the measured energy distributions after the foil (Fig. 4), is 37.0 ± 0.3\% and 36.4 ± 0.3\%, for incoming energy of 10 and 7.5 keV, respectively.

The MCP detection efficiency for Ly-\( \alpha \) can be estimated through \( \epsilon_{MCP} = \text{OAR} \cdot \epsilon_{CsI} \), where OAR stands for the open-area-ratio of the MCP itself and is in our case 0.45. The quantum yield of the conversion from Ly-\( \alpha \) to an electron in the CsI, \( \epsilon_{CsI} \), is in the range of 0.45 – 0.55 [42, 43]. This leads to \( \epsilon_{MCP} = 0.22 ± 0.02 \). The calculated M(2S) fractions \( f_{2S/M} \) of total amount of M produced according to Eq. 1 are summarized in Table I for incident energies of 7.5 and 10 keV. Strong scattering of the muon beam by the foil at 5 keV incident energy prevented us from obtaining the reliable triple-coincidence signal needed to extract the 2S fraction. Assuming, in accordance with hydrogen in a comparable velocity range (see [29] figure 3.1), that the 2S fraction is nearly constant above 1 keV, we obtain a weighted average value of \( f_{2S/M} = 10 ± 2\% \). This value agrees with estimations in the literature which span 10 – 13\% in this energy range [15, 23, 29].

V. METASTABLE BEAM AND LAMB SHIFT OUTLOOK

We now estimate the rate of M(2S) passing the foil. Using a Ne moderator, the measured rate of moderated \( \mu^+ \) per mA of proton beam current is 8 k/s [31]. This measurement was done with a “box-like” target geometry for the generation of surface muons [44]. In our beam time, a rotated slab target was installed, increasing the surface muon rate. Unpublished data by the LEM group indicates that the increase is of the order of 40\%. Plugging in the measured current of 1.6 mA during our beam time, the estimated rate of moderated \( \mu^+ \) emerging is 18 k/s. Using the LEM beamline simulation [37, 45], with the same conditions as in our experiment, we estimate the rate \( R_{\mu^+} \) of \( \mu^+ \) passing the foil for each incident energy. The rate of metastable M is obtained by multiplying with the measured formation efficiencies \( R_{2S} = R_{\mu^+} \cdot f_M / \mu^+ \cdot f_{2S/M} \). The results are given in table...
I. We find that when increasing the beam energy, \( f_{M/\mu} \) decreases and the transmission of the beamline increases, so that the final metastable rates are comparable. Nevertheless, the angular distribution of the beam at 10 keV is narrower and so we focus on this energy for considering the rates available for a future Lamb shift experiment.

TABLE I. Summary of values extracted from different incident energies \( E_{\text{inc}} \). MPE is the Most Probable Energy for M that traversed the foil and reached the back detector.

| \( E_{\text{inc}} \)    | 10 keV | 7.5 keV | 5.0 keV |
|-----------------------|--------|--------|--------|
| MPE                   | 7.0 ± 0.3 keV | 4.7 ± 0.2 keV | 2.7 ± 0.1 keV |
| \( f_{M/\mu^+} \)     | 31.8 ± 0.8 % | 43.2 ± 2.4 % | 56.8 ± 9.0 % |
| \( f_{2S/M} \)         | 9.7 ± 3.0 % | 10.6 ± 3.7 % | no events |
| \( R_{\mu^+} \)        | 2.84 k/s | 2.07 k/s | 1.45 k/s |
| \( R_{2S} \)           | 88 ± 27 /s | 95 ± 34/s | 83 ± 21/s * |

* For \( R_{2S} \) at 5 keV, \( f_{2S/M} = 10 \pm 2\% \) was assumed (see text).

Observing Fig. 1, the main missing component for precision microwave spectroscopy experiments is a broadband microwave apparatus designed to resonantly quench the 2S beam by driving the Lamb shift transitions, which we will place in the extension stage. To obtain a clean symmetric resonance, we focus on the 2S \( F = 0 \rightarrow 2P_{3/2} \) transition around 580 MHz, which is isolated from the next transition by 0.6 GHz. This situation is favorable to that of hydrogen, in which the difference is only 0.2 GHz. In this ‘opt-out’ scheme, the Ly-\( \alpha \) signal decreases the closer we are to resonance. Our projected DC quenching and detection efficiency is based on minor improvements to the setup used here, namely, grounding the first electrode in the DC quench region to increase \( e_{GE} \) to 52\%, and bias the MCPs positively to collect electrons produced on their surface [46], increasing their efficiency to 40\%. We found damage to the foil surface during this experiment, reducing its coverage considerably and decreasing the tagging efficiency by an order of magnitude. However, based on an average of one backscattered electron per incident \( \mu^+ \), we estimate a 50\% tagging efficiency for a future measurement. Based on the above, the expected off-resonance coincidence signal between the Ly-MCP and foil is 9/s. This rate is four orders of magnitude larger then the coincidence rate of 5/hour measured at TRIUMF [47], and 4/hour at LAMPF [24].

To prevent the 2S \( F=1 \) levels from contributing to the background we will introduce a hyperfine selection stage in the extension section, which deexcites most of the 2S\( F=1 \) population to the ground state, leaving a clean beam of roughly 22/s \( M(2S) \) \( F = 0 \), and an off-resonance coincidence signal of 2/s. To avoid saturation broadening, we will quench half the 2S \( F=0 \) population on resonance. For a 100 hours of beamtime, we will collect roughly half a million events above background, enough to resolve the 100 MHz linewidth to 0.2 MHz. This will enable an improvement two orders of magnitude over the best determination from the literature [15].

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