Experiment to measure the Lamb shift in muonic hydrogen *

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The contribution of the root mean square (RMS) proton charge radius to the Lamb shift (2S–2P energy difference) in muonic hydrogen (μp) amounts to 2%. Apart from the uncertainty on this charge radius, theory predicts the Lamb shift with a precision on the ppm level. We are going to measure ΔE $(2\,\mathrm{S}_{1/2}(F=1)\text{–}2\,\mathrm{P}_{3/2}(F=2))$ in a laser resonance experiment to a precision of 30 ppm (i.e., 10% of the natural linewidth) and to deduce the RMS proton charge radius with 10^{-3} relative accuracy, 20 times more precise than presently known.

The most important requirement for the feasibility of such an experiment, namely the availability of a sufficient amount of long-lived metastable μp atoms in the 2S state, has been investigated in a recent experiment at PSI. Our analysis shows that in the order of one percent of all muons stopped in low-pressure hydrogen gas form a long-lived μp(2S) with a lifetime of the order of 1 µs.

The technical realization of our experiment involves a new high-intensity low-energy muon beam, an efficient low-energy muon entrance detector, a randomly triggered 3-stage laser system providing the 0.5 mJ, 7 ns laser pulses at 6.02 µm wavelength, and a combination of a xenon gas-proportional-scintillation-chamber (GPSC) and a microstrip-gas-chamber (MSGC) with a CsI-coated surface to detect the 2 keV X-rays from the μp(2P $\rightarrow$ 1S) transition.

Keywords: proton, proton radius, muon, muonic hydrogen, Lamb shift

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1. Introduction

The hydrogen atom has played an important role in the development of modern physics. The detailed investigation of the hydrogen atom led to the development of quantum mechanics and the discovery of the Lamb shift in 1947 [1] motivated the description of physical processes via quantum field theory.

Optical spectroscopy of electronic hydrogen has recently reached a point where the measurements are able to determine the RMS charge radius of the proton to a precision of a few percent [2–4]. Older measurements of the RMS proton charge radius using low energy electron scattering [5–8] are inconsistent and suffer from normalization problems [9].

Muonic hydrogen, however, is even better suited to obtain a precise value of the RMS proton charge radius, because the effect of the finite proton size contributes as much as 2% to the μp Lamb shift (the 2S–2P energy difference). We are setting up a new experiment to measure the energy difference ΔE ($2\,\mathrm{S}_{1/2}(F=1)$–$2\,\mathrm{P}_{3/2}(F=2)$) in a laser resonance experiment to a precision of 30 ppm, i.e., 10% of the natural linewidth, to deduce the proton radius with 10^{-3} relative accuracy, 20 times more precise than presently known. The 2P fine and hyperfine splittings are only a few percent of the Lamb shift and can be calculated with high precision.

QED calculations are available on the ppm level [10], and the limiting factors for the determination of the RMS proton charge radius are the proton polarizability and the magnetization distribution of the proton. The latter affects the 2S hyperfine splitting and can be determined by measuring a second transition energy in muonic hydrogen. So, the final accuracy for both theory and experiment will be on the 10 ppm level. A combined analysis of the experiments in electronic and muonic hydrogen will test bound state QED on the ppm level or below, and vacuum polarization up to three-loop contributions [11].

In this paper we first give an overview of our experiments to determine the population and lifetime of μp(2S) atoms at hydrogen gas pressures of a few hPa pressure. The second part is then dedicated to the experimental setup of the laser experiment which has only been made possible by recent advances in muon beam quality, laser technology, and low-energy X-ray detectors.

2. Long-lived metastable μp(2S)

A number of experiments have been performed to investigate the creation of long-lived metastable μp(2S) when muons are stopped in low-pressure hydrogen target gas. X-ray measurements [12–14] have shown that, depending on the hydrogen gas pressure, around 4% of the muons reach the 2S state. Collisional quenching with H_2, however, may lead to deexcitation. At a kinetic energy below 0.31 eV, the μp(2S) $\rightarrow$ μp(2P) threshold energy in the lab frame, collisional quenching of the μp(2S) state is energetically impossible. Moreover, theoretical considerations [15] show that μp(2S)

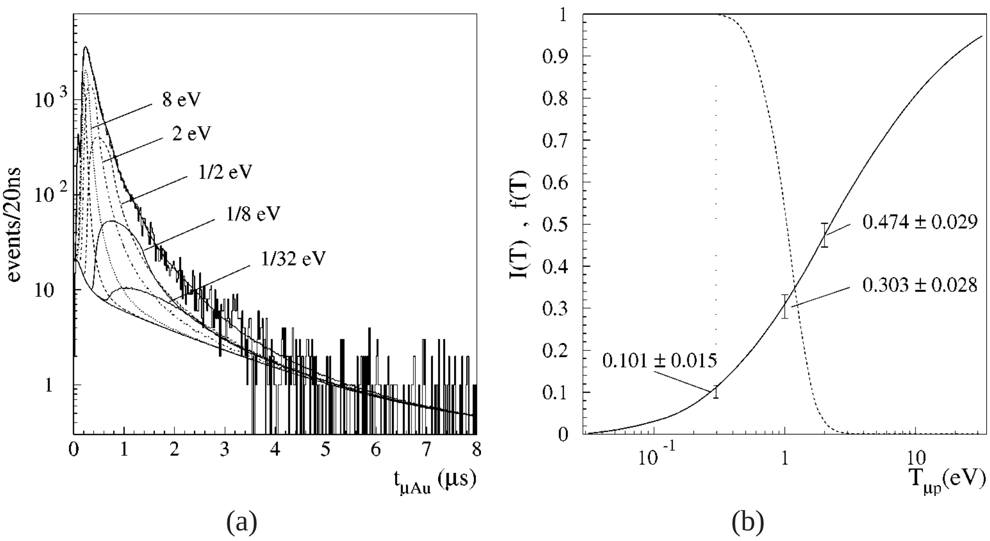

Figure 1. (a) Time spectrum of μAu X-rays measured with the 7 mm target at 16 hPa H_2 pressure. For better clarity the fit is a superposition of only 6 time spectra. (b) Integrated energy distribution $I(T_{\mu p}) = P(E_{ini} \leqslant T_{\mu p})$ measured at 16 hPa H_2 gas pressure (solid line) and the probability $f(T)$ for a μp(2S) being thermalized without being quenched (dashed line) [15].

formed at kinetic energies up to 2 eV can slow down without undergoing collisional quenching (figure 1(b)).

To determine the initial kinetic energy distribution of muonic hydrogen atoms we have recently performed an experiment at PSI. Low energy muons were stopped along the axis of a cylindrical low pressure gas target, and we measured the time difference between the muon stop and the arrival of the μp atom at the inner gold-coated surface of the cylinder. On the cylinder wall the muon was transferred to gold and μAu X-rays of MeV energies were emitted, which were detected in CsI crystals surrounding the target. We obtained spectra using five different inner diameters of the gas target (7–58 mm) and for various pressures between 0.063 and 64 hPa.

The measured time spectra were fitted using Monte Carlo generated time spectra for a grid of 50 kinetic energies between thermal energy and 200 eV. The Monte Carlo code includes the effect of elastic scattering of muonic hydrogen on hydrogen molecules [16] as well as backscattering of muonic hydrogen atoms from the gold layer of the target chamber walls. A preliminary result is that about 10% of all μp reaching the gold walls have initial kinetic energies below 0.31 eV (the μp(2S) quenching threshold energy). An example of a measured spectrum together with a fit (using only a reduced set of 6 functions for illustrative purposes) and the initial kinetic energy distribution can be seen in figure 1.

This experiment only determines the initial kinetic energy distribution of muonic hydrogen atoms in the ground state, as the μp(2S) atoms are thermalized too quickly and do not reach the target chamber walls. However, a cascade code, which also reproduces the measured K-yields and initial kinetic energies at all hydrogen gas densities under consideration shows that the initial kinetic energy distribution of the μp(2S) atoms differs only very little from the one of μp(1S).

With 4% of all muons reaching the 2S state and ∼10% of the μp atoms having kinetic energies below 0.31 eV, and assuming a conservative number for the slowing down probability of μp(2S) initially formed at energies between 0.31 eV and 1 eV, we can give a preliminary number of ∼1% metastable μp(2S) per muon stopped in H_2.

3. Laser experiment

With the ability to produce a sufficiently large number of long-lived μp(2S) atoms in a very small volume (some 10 cm^3 at a few hPa pressure) we have now come to the point where a laser resonance experiment to measure the Lamb shift of muonic hydrogen is possible. Such an experiment is being prepared at PSI and will start data taking in 2001 [17]. It consists of three major parts which will be described here, namely the high-intensity low-energy muon beam line, the three-stage laser system for 6 μm light, and the low-energy X-ray detectors to observe the laser-induced 2 keV Lyman-α X-rays following the laser excitation of μp(2S) to μp(2P).

3.1. High-intensity low-energy muon beam line

The rate of keV-muons is enhanced by more than one order of magnitude relative to a conventional cloud muon beam using a novel high-intensity low-energy muon beam line under construction at PSI.

Negative pions are injected into the cyclotron trap [18], where they decay into muons. These are slowed down to keV energies and then extracted by an electrostatic field. This method has already been successfully tested [19]. A new device, the so-called Muon Extraction Channel (MEC), guides the muons in a curved solenoidal field from the cyclotron trap to a 5 T solenoid (PSC) where the laser experiment takes place. Particles with momenta above ∼4 MeV/c (e.g., electrons) are not transported through the curvature of the MEC while about 90% of the good muons (typically 20 keV energy, 2 MeV/c momentum) are transported from the trap to the solenoid. Inside the PSC solenoid the muons are detected and stopped in a low pressure hydrogen gas target surrounded by laser cavity mirrors and X-ray detectors.

The muon rate can be inferred from test measurements [19] to reach about 300 muon stops per second in a 10 hPa H_2 target, 15 cm long, for a beam size 5×15 mm, including a muon detector efficiency of 50%. Most of the components of our new experiment have been successfully used in our previous measurements.

3.2. Three-stage laser system for 6 μm light

A XeCl Excimer laser was chosen as the first stage of our laser system because it is able to produce a high energy light output only 300 ns after the detection of a randomly arriving muon.

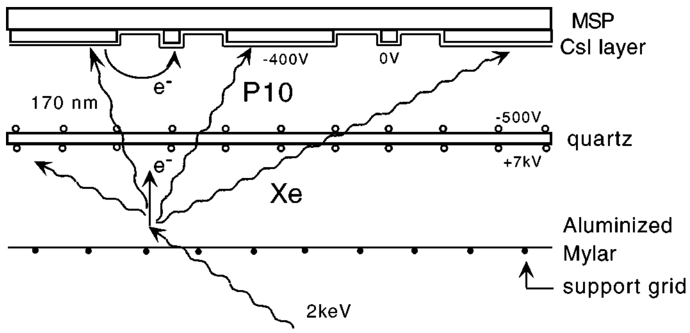

Figure 2. Schematic view of the operation of a MSGC based GPSC. X-rays of a few keV produce primary electrons which in turn produce secondary scintillation light. Photoelectrons are emitted in the CsI coated MSGC cathode and multiplied near the anode.

The second step, conversion of the 308 nm light from the Excimer laser into an intense high-quality 708 nm laser beam, is done in two substeps. The 308 nm light pumps a dye cell, which in turn delivers the ∼500 nm light required to pump a cavity dumped Ti:Sapphire laser. The Ti:Sapphire laser delivers 7 ns long TEM_{00} pulses of 12 mJ at 708 nm.

The third step then converts the 708 nm light to the 6.02 μm needed to drive the transition $2\,S_{1/2}(F = 1) \rightarrow 2\,P_{3/2}(F = 2)$ in muonic hydrogen. The 0.5 mJ, 7 ns long pulses are created via third Stokes Raman shift in a high pressure hydrogen cell [20]. The light will be injected into a multipass cavity inside the solenoid in order to efficiently illuminate the muon stop region.

3.3. X-ray detector

The 2 keV X-ray detector (figure 2) consists of two xenon gas-proportional-scintillation-chambers (GPSC) as were used in previous experiments [21,22]. X-rays produce secondary scintillation light at 170 nm with low statistical fluctuations.

Recent developments in Coimbra [23,24] permit the detection of the secondary scintillation light using a Microstrip Gas Chamber (MSGC). The UV photons are detected by CsI-coated thin-film photocathodes deposited directly onto a microstrip plate (MSP). A thin quartz window separates the xenon GPSC from the MSGC, filled with P10 ($Ar + 10\%\ CH_4$) gas or xenon gas.

The MSGC based GPSC resembles a compact detector configuration with good energy resolution and a large detection area, and it is insensitive to the magnetic field in which our experiment is going to take place.

4. Conclusions

Long-lived (∼1 μs lifetime) muonic hydrogen atoms in the 2S excited state can for the first time be created in a sufficiently large number inside a small stopping volume of only a few tens of cm^3. Together with the rapid development of laser technology and X-ray detection schemes we have now come to the point where a laser resonance experiment to measure the Lamb shift in muonic hydrogen is possible. Our experiment aims to a precision of 30 ppm for the transition $2\,S_{1/2}(F=1)$–$2\,P_{3/2}(F=2)$ in muonic hydrogen, i.e., a relative uncertainty of 10^{-3} on the proton radius, more than one order of magnitude more precise than the present values.

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