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New muonium HFS measurements at J-PARC/MUSE

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Abstract At the Muon Science Facility (MUSE) of J-PARC (Japan Proton Accelerator Research Complex), the MuSEUM collaboration is planing new measurements of the ground state hyperfine structure (HFS) of muonium both at zero field and at high magnetic field. The previous measurements were performed both at LAMPF (Los Alamos Meson Physics Facility) with experimental uncertainties mostly dominated by statistical errors. The new high intensity muon beam that will soon be available at MUSE H-Line will provide an opportunity to improve the precision of these measurements by one order of magnitude. An overview of the different aspects of these new muonium HFS measurements, the current

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status of the preparation, and the results of a first commissioning test experiment at zero field are presented.

Keywords Muonium · Spectroscopy · Fundamental physics

1 Introduction

Muonium, which is also regarded as a light isotope of hydrogen, is a pure leptonic system made of a bound state of a positive muon and an electron with the feature that neither of its constituents have an internal structure. High precision measurements of the muonium ground state hyperfine structure (MuHFS) can be regarded as the most sensitive tool for testing quantum electrodynamics (QED) [1], and for determining precisely fundamental constants of the muon magnetic moment and hence its mass [2]. The magnetic moment ratio between muon and proton is of the utmost importance in the determination of the muon anomalous magnetic moment, also called muon g–2, and being regarded as a keystone at unraveling the physics of the standard model and beyond [3]. Furthermore, precision microwave spectroscopy of muonium can contribute to a possible test of CPT and Lorentz violation incorporated in extensions to the standard model, leading to potentially observable perturbative shifts in the ground state energy levels of muonium [4, 5].

The MuSEUM[1] collaboration is planing new and complementary measurements of the muonium HFS both at zero field and at a high magnetic field of 1.7 T. The previous measurement at zero field [6] is already 41 years old, while the one at high field [2] was published 17 years ago, both performed at LAMPF and with experimental uncertainties mostly dominated by statistical errors. It should be noticed that the values of the muon magnetic moment and mass are still currently determined by the previous muonium HFS experiment at high field. Our goal is to improve the precision of these measurements by one order of magnitude. The new high intensity surface muon beam that will soon be available at J-PARC/MUSE H-Line [7] will provide an opportunity to achieve that goal.

However, as we reduce the statistical uncertainty, understanding and suppressing systematic uncertainty become crucial. Extensive studies have been done and tools have

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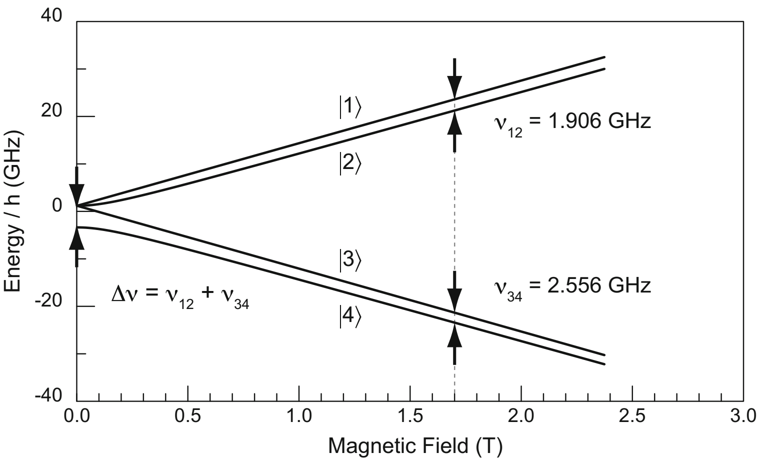

Fig. 1 Breit-Rabi energy level diagram for muonium atom under magnetic field

been developed for the suppression of uncertainties originating from inhomogeneity in the magnetic field, muon stopping distribution, microwave power fluctuation and gas density extrapolation. The progress of the preparation, and the results of a first commissioning test experiment at zero field are presented.

2 Experimental method and apparatus

The Breit-Rabi energy level diagram for muonium atom is shown in Fig. 1. The ground state hyperfine splitting $\Delta\nu$ is to be measured by a microwave magnetic resonance technique. This transition will be measured directly at zero field and indirectly following the approach of the last experiment [2] at a static magnetic field of 1.7 T. This static field due to the Zeeman effect and the applied external RF field splits the ground state of muonium into four different substates and the two spin-flip resonance frequencies ν_{12} and ν_{34} are measured. The sum of the two transition frequencies ν_{12} and ν_{34} is constant, independent of the applied static field, and equal to the ground state hyperfine splitting at zero field, i.e., $\Delta\nu = \nu_{12} + \nu_{34}$. The difference between those two transition frequencies is directly related to the ratio of the muon and proton magnetic moments, i.e., $\mu_\mu/\mu_p \propto \nu_{34} - \nu_{12}$. Thus, the sum of the measured frequencies gives the QED test, while the difference is used to determine the values of the muon magnetic moment and mass.

Figure 2a shows the schematic view of the experimental apparatus that is common to both experiments at zero and high magnetic field. The experimental procedure can be summarized as follows: (1) muonium formation, (2) RF spin flip, and (3) positron asymmetry measurement. High intensity surface muon (μ^+) beam, 100 % backward polarized with respect of the muon momentum direction, are injected into a RF cavity located inside a gas chamber containing highly pure krypton gas. The profile of the incident muon beam is measured online by a non-destructive beam profile monitor located in front of the entrance

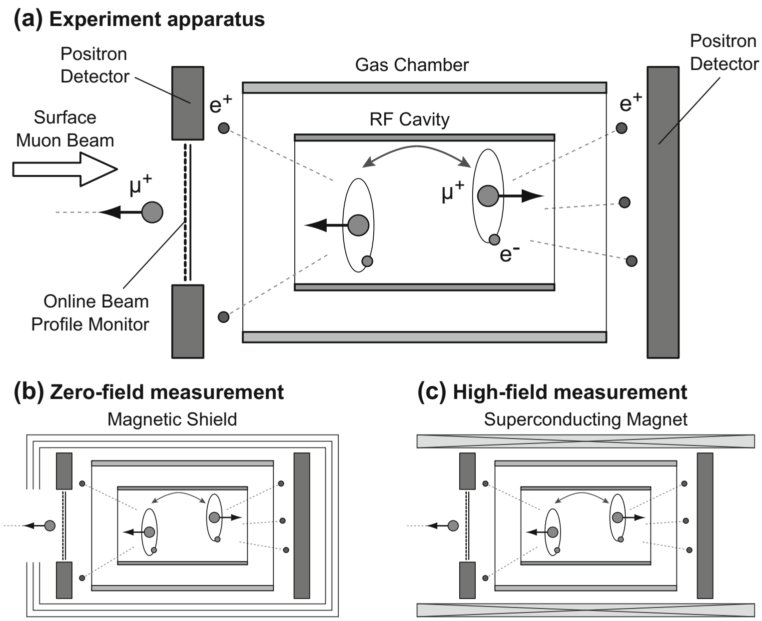

Fig. 2 Schematic view of the experimental setup

window of the gas chamber. The μ^+ are stopped in the Kr gas volume and form polarized muonium atom (Mu) through the charge exchange reaction μ^+ + Kr $\rightarrow$ Mu + Kr^+. The muon spin can be flipped by applying a microwave magnetic field in the RF cavity perpendicular to the muon direction. The positrons (e^+) from muon decay are emitted preferentially in the direction of the muon spin. At the resonance, the RF field induces the muon spin flip changing the angular distribution of the emitted positrons from primarily backward to forward direction. Positrons are then detected with segmented scintillation detectors placed downstream and upstream of the gas chamber. Muonium spectroscopy is then performed by scanning the RF frequency and measuring the positron asymmetry to determine resonance frequencies. i.e., $\Delta\nu$ at zero field and ν_{12} and ν_{34} at high field, respectively.

For the zero-field measurement (see Fig. 2b), the apparatus is enclosed in a magnetic shield box made of three layers of permalloy to suppress residual magnetic field. The experiment will be performed at the existing D-Line (decay muon channel) of the MUSE facility at J-PARC. For the high-field measurement (see Fig. 2c), a large superconducting solenoid with an applied static field of 1.7 T parallel to the muon momentum direction will be used. This static magnetic field and the introduced RF field in the cavity, which is perpendicular to the solenoid field, splits the ground state of the muonium into the four different substates as shown in Fig. 1. The high intensity surface muon beam with an expected intensity of 1×10^8 μ^+/s will be provided by the new H-Line that is under construction at J-PARC/MUSE [7].

3 Current status of the preparation

3.1 RF system and gas chamber

A RF cavity was already constructed for the high-field measurement, and was designed to have two frequency modes, TM110 and TM210, to match the resonance frequencies ν_{12} and ν_{34}, respectively. However, for the zero-field measurement, another RF cavity with an inner diameter of 40.9 mm was required so that the resonance frequency of the TM110 mode matches the MuHFS transition frequency $\Delta\nu$ of 4.463 GHz [8]. The new cavity is also made of oxygen-free copper with windows 25-μm thick to let muons in and positrons out. Its length is 230 mm (304 mm for the high-field cavity) as compared to 160 mm for the LAMPF experiment, to allow measurement at lower Kr gas density, thus reducing the systematic uncertainty on the gas density extrapolation to the zero density limit. The gas pressure can be changed from 0.3 to 1.5 atm. The microwave frequency is delivered though a coaxial cable to the cavity by an input loop. Then the power is picked up by a feedback loop and measured with a power meter. The RF cavity frequency can be tuned in a 20 MHz range by displacing a conductive tuning bar, covering the full sweep range to observe the resonance line shape. The remote control of the tuning bar was done first through a linear actuator located outside of the gas chamber and then later through a piezo-actuator directly attached to the cavity. Since resonance lines are distorted by fluctuating RF power, the signal from the pickup antenna in the cavity will be used to monitor and regulate the power to achieve a stability of 0.1 %.

The target gas chamber containing the Kr gas, common to both zero-field and high-field measurements, is made of pure aluminum with a 100-μm thick muon beam window. The gas pressure is monitored by a capacitance gauge at a level of 10 Pa with an absolute precision of 0.2 % of reading. In the future, a more precise silicon pressure transducer will used to monitor the gas pressure at a level of 2×10^{-5}. The Kr gas purity in the chamber is currently estimated from build-up tests and residual gas Q-mass spectroscopy measurements before and after the experiment. Oxygen is responsible for the depolarization of muonium through electron spin exchange collision. An oxygen contamination of below 4 ppm was measured during the test experiment, corresponding to an estimated signal drop of 7 %. Later, gas samples will be collected in small cylinders during the measurement to monitor the gas purity. The climate control of the experimental area will keep the temperature variation below 1 degree and be monitored during the experiment to reduce fluctuation on the gas pressure and RF system.

3.2 Positron detector

Positrons are detected with highly segmented scintillation counters to have high-rate capability due to the pulse nature of the muon beam. The total detection area is 240 mm $\times$ 240 mm, divided into 576 segments. Each segment consists of a small plastic scintillator (10 mm $\times$ 10 mm $\times$ 3 mm) with a SiPM (Silicon PhotoMultiplier) directly attached and fast readout electronics with ASIC-based (Application Specific Integrated Circuit) amplifier, shaper and discriminator (ASD), and multi-hit TDC (Time-to-Digital Converter) implemented in the FPGA (Field Programmable Gated Arrays). The 576 SiPM's are arranged in a 24 $\times$ 24 matrix on a printed circuit board. The detector is made of two such layers, and a coincidence hit is required on two matching SiPM's to suppress accidental background due to dark noise.

From a simulation, the maximum expected event rate is approximately 3 MHz, resulting in a pileup loss of 2 % of the total statistics. After pileup correction, systematic uncertainty due to pileup can be suppressed to an acceptable level. The pileup loss is dominated by the analog pulse shape, which depends on the amplifier parameters. Uniform performance of the detector is ensured by tuning the operation voltage for each SiPM. The latest development of this integrated detector system is described in details in Ref. [9, 10].

3.3 Fiber beam profile monitor

The online beam profile monitor is used to suppress systematic uncertainty related to the muon beam profile and intensity stability. It is required to be non-destructive as little as possible to measure the muon beam pulse by pulse to reject any irregularities in the beam shape and pulse intensity. A new beam profile monitor with extremely thin scintillation fibers (ϕ100 μm) was constructed in 2015. The detection area is 100 mm $\times$ 100 mm. Each axis comprises 16 segments made of an array of 40 plastic scintillation fibers bound together in a bundle and directly connected to a SiPM at both ends. Fibers are bounded on a polyimide film 25-μm thick with epoxy resin for rigidity. Test results showed that higher efficiency with better uniformity along the fiber was achieved as compared to a thin scintillator detector. Fibers have less light reflection loss and a better optical coupling to the SiPM can be achieved, resulting in smaller position dependence. The muon beam profile and intensity was also successfully measured. Details of this new fiber beam profile monitor were reported in Ref. [11].

3.4 Offline 3D muon beam monitoring system

The muon beam profile in the Kr gas chamber is measured by an offline 3D muon beam monitor to suppress systematic uncertainty related to the muonium atom distribution in the chamber. This monitor, which is based on a muon beam profile monitor developed to diagnose pulsed muon beams at J-PARC/MUSE [12], is composed of a scintillation screen, a gated image intensifier, and a cooled CCD camera. The scintillation screen is placed inside the Kr gas chamber, without the RF cavity installed, and closed with an acrylic plate. The scintillation light from the screen is then capture by a large aperture lens and sent to the image-intensified CCD unit. By moving the scintillation screen together with the detector unit, i.e. keeping the focal length of the lens constant, the muon stopping distribution can be measured along the gas chamber. The monitoring system is now remotely controlled with an actuator coupled to a stepping motor to move the scintillation screen in the gas chamber, while the image intensifier and CCD camera mounted on a stage are moved simultaneously by a linear actuator. This system was tested, and muon beam distributions were successfully measured at several Kr gas density. The precision of the beam center measured along the beam axis in the chamber is better than $\pm$ 2 mm. The development of this 3D muon beam monitoring system is explained in details in Ref. [13, 14].

3.5 Magnetic field

For the zero-field measurement, a magnetic shield made of three layers of 1.5-mm thick permalloy was fabricated to enclose completely the gas chamber to suppress residual magnetic field. The magnetic field in the cavity must be bellow 100 nT to minimize the Zeeman effect and rotation of the polarization [6]. The magnetic field map was measured, and some parts in the cavity were found as high as 700 nT [8]. After demagnetization of the cavity, the residual field dropped to around 70 nT, sufficient to perform precise measurements. The magnetic field stability is monitored during the measurement by a 3-axis fluxgate placed in the magnetic shield outside the gas chamber.

The high-field measurement will be performed with a superconducting solenoid recycled from an old MRI magnet that was designed for high magnetic field homogeneity. Our choice of a longer cavity to allow measurement at lower Kr gas density imposes strict requirements on the magnet. We aim at a field homogeneity of less than 1 ppm with absolute calibration in a spheroidal volume of ϕ200 mm $\times$ 300 mm (muon stopping region). A continuous wave NMR (CW-NMR) system with a field-sweep coil is being developed for the magnetic field monitoring of both g–2/EDM and MuSEUM experiments at J-PARC. Test measurements showed that the resolution could reach 18 ppb [15]. The fine adjustment of the magnetic field homogeneity is carried out by shim coils and insertion of iron shim plates. Shim plate positioning are calculated using a singular value decomposition method; an iterative process of field correction and precise field measurement. Commissioning tests of the solenoid magnet were performed in 2015. The long term stability was measured at 0.003 ppm/hour over a 10 days period. The helium evaporation rate was 3 L/day. After three iterative shimming processes, a field inhomogeneity of 1.4 ppm peak-to-peak in the muon stopping region spheroid was achieved, that is relatively close to our design value.

3.6 Estimated experimental accuracy

The present accuracy is 12 ppb for $\Delta\nu$ and 120 ppb for μ_μ/μ_p, respectively, when measured at high field in the previous LAMPF experiment [2]. At zero field the accuracy for $\Delta\nu^{ZF}$ was 300 ppb [6]. As already mentioned, the uncertainty was mainly dominated by statistical error. Considering the expected beam intensity at the H-Line of J-PARC/MUSE, a measurement time of 100 days would give ten times better statistics. However, as we improve the statistics, the systematic uncertainty becomes more severe and needs to be carefully considered. It should be noted that understanding of the systematical error in an experiment is often limited by the measurement time. Longer the measurement time, the lower the systematic uncertainty. A tool to estimate systematic uncertainty was developed [16, 17], and is currently being used to investigate the effect a particular fluctuation on the final result. The required precision is determined by a Monte Carlo simulation that calculates the resonance line from muonium distribution, RF distribution and detection efficiency. The main sources of systematic uncertainty include in order of importance inhomogeneity in the magnetic field, RF power, muon stopping distribution, and gas density extrapolation. Here are the latest considerations:

(1) For the high-field measurement, the magnetic field inhomogeneity and measurement seems to be under control. According to the previous experiment at high field, it has little effect on the determination of $\Delta\nu$, but is very important in μ_μ/μ_p. An measurement accuracy of $\sim$ 30 ppb would account for 15 ppb in $\delta(\mu_\mu/\mu_p)$. However, a recent simulation shows that the field inhomogeneity seems to have a larger effect than first anticipated. At zero field the error on $\Delta\nu^{ZF}$ is presently estimated to 32 Hz, or 7 ppb.

(2) A fluctuation of 0.2 % in the RF power results in a shift of 4 Hz in the measured frequency, thus contributing 0.8 ppb to $\delta(\Delta\nu)$ and 8 ppb to $\delta(\mu_\mu/\mu_p)$, respectively. A position drift of the muon beam distribution during the scan also affects the resolution, thus requiring a constant monitoring of the beam profile.

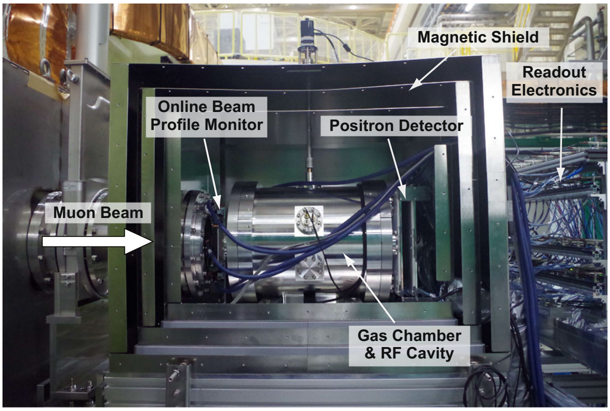

Fig. 3 Picture of the apparatus for the zero-field measurements installed at the D2 experimental area of MUSE D-Line

(3) The error from the beam profile monitor measuring every muon pulse with a precision of 1 mm would result in a shift of 3 Hz, or 0.6 ppb and 6 ppb, respectively. The effect on the longitudinal muon stopping distribution measured with an equal precision by the offline 3D muon beam monitor is less severe, and would only account in a shift of 1 Hz, or 0.2 ppb and 2 ppb, respectively.
(4) The quadratic dependence of the gas density extrapolation to the zero density limit will be improved by our ability to measure at lower Kr gas density with a longer cavity. The systematic uncertainty would be reduced to a shift of 5 Hz, thus contributing 1.0 ppb and 5 ppb, respectively.

After considering all other error sources, the tentative error budget for systematic uncertainty in our experiment is at present estimated to about ~ 2 ppb for $\delta(\Delta\nu)$ and ~ 20 ppb for $\delta(\mu_\mu/\mu_p)$, respectively, and at zero field ~ 8 ppb for $\delta(\Delta\nu^{ZF})$.

4 Commissioning test experiment

Commissioning test experiments at zero field were performed in February and June 2016 at the D2 experimental area (D-Line) of the MUSE facility. A picture of the apparatus is shown in Fig. 3. As already briefly mentioned, the 3D muon stopping distribution in the gas chamber and the magnetic field map in the cavity were measured. The gas chamber and the gas handling system were baked out, and build-up tests and residual gas Q-mass spectroscopy measurements were performed. The RF power stability was determined by a RF power meter, and a network analyzer was used to measure the resonance line by adjusting the resonance frequency.

During the first beam measurement of 30 hours carried out in February, no significant signal could be observed, mainly due to the lack of statistics. In June, however, after several trials we could observe our first resonance peak by measuring alternatively RF ON and OFF for two minutes over a period of one hour, and by taking the difference. This method reduces frequency drift from RF power dissipation in the cavity. Only backward positron counters were used due to a relatively large prompt background from positrons in the beamline. The resonance was measured at pressure of 1 atm, and scanned over a range of ± 1500 kHz. The data are now being analyzed and details will be reported elsewhere.

5 Summary

The improvement of the MuHFS measurement is important for further QED testing and new fundamental physics experiments. Improving the overall accuracy, estimating and understanding systematic uncertainties are essential in reaching that goal. Initial commissioning tests at zero field proved that the overall system is working. Precision measurement are planned at the MUSE D-Line at the end of 2016. At present, it is unclear when the new H-Line will be operational, but we are aiming at a first test experiment at high field sometime in 2017.

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