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Proposal for new measurements of muonic helium hyperfine structure at J-PARC

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Abstract. The measurement of the ground state hyperfine structure of muonic helium has the potential to improve the precision of the mass of the negative muon by a factor of 50 or more. The mass of the negative muon is very important because it enables us to test the CPT theorem by comparison with positive muon mass. We aim to measure the hyperfine structure of muonic helium with a precision 1000 times higher than previous experiments [1,2] using the high-intensity muon beam at J-PARC and have already obtained results better than the current precision in zero-field measurements in a test experiment in March 2021. To further improve the precision, we plan to measure in a high magnetic field and incorporate a technique that can produce highly polarized muonic helium atom [3]. In this paper, we will report on these developments.

1 Introduction

The muonic helium atom ($^4\mathrm{He}\mu^- e^-$) is an atom in which one of the two electrons of the ^{4}He atom is replaced by a negative muon. Since the orbital radius of the negative muon is about 400 times smaller than the Bohr radius, we can treat $(^4\mathrm{He}\mu^-)^+$ as a pseudo-nucleus that has a magnetic moment similar to that of a negative muon (μ_{μ^-}), and consider $^4\mathrm{He}\mu^- e^-$ as a hydrogen-like atom. The ground state hyperfine structure (HFS) of muonic helium is caused by the interaction between the magnetic moments of the electron and the negative muon. The HFS of muonic helium is similar to muonium, which is a purely leptonic system consisting of positive muon and electron, and it can be measured using the same apparatus and technique as for muonium ground state HFS [4-5].

Since muonic helium is a three-body system, precise HFS measurements of muonic helium will be a powerful probe to test and improve the theory of quantum three-body systems [6]. Measurements at high magnetic field will also allow us to precisely determine the magnetic moment and mass of negative muon, and to test the CPT theorem by comparison with the positive muon. The ground state HFS of muonic helium has been measured with a precision of 13 ppm at zero field [1] and 6.5 ppm at high field [2]. The precision of the magnetic moment ratio of negative muons to protons has been determined as 47 ppm [2]. These uncertainties are mainly statistical uncertainty. The reason for the large statistical uncertainty is not only the beam intensity but also the loss of muon spin polarization (~100% → ~ 6%) due to Auger transitions and Stark mixing associated with the formation of muonic helium [7-12]. For theoretical values, the higher-order QED effect has not been taken into account so far, and uncertainty of about 130 ppm has been estimated [13-14].

For the mass of negative muons (m_{μ^-}), the highest precision is currently 3.1 ppm obtained by precise measurement of characteristic X-rays of muonic Si [15]. In contrast, the mass of the positive muon is determined to be 120 ppb from the measurement of the muonium ground state HFS [16]. In other words, the verification of the CPT theorem for muons is presently limited to the level of 3 ppm. In addition, the magnetic moment of the negative muon (μ_{μ^-}) is necessary for the determination of the magnetic moment anomaly of negative muons at Brookhaven National Laboratory, but due to the large uncertainty of the μ_{μ^-} measurement, it is currently calculated using the magnetic moment of positive muons [17]. Furthermore, muonium 1S-2S transition frequency measurements by laser spectroscopy aiming to determine the positive muon mass in O(1 ppb) are planned by the MuMASS collaboration at PSI [18] and an experiment at J-PARC [19-20].

Currently, we are planning to measure the ground state HFS of muonic helium at zero field and high field of 1.15 T in O(10 ppb) and m_{μ^-} in O(100 ppb). This will be achieved by using the high-intensity negative muon beam from the H-Line of the Muon Science Establishment (MUSE) in the Materials and Life Science Experimental Facility (MLF) at the Japan Proton Accelerator Research Complex (J-PARC), which will be operated from 2022, and repolarizing the muon spin using the Spin Exchange Optical Pumping (SEOP) technique. In addition to the improvement of the measurement precision, we are also investigating the improvement of the theoretical values in collaboration with theorists at RIKEN and Tohoku University.

2 Experimental method and latest result

As shown in Fig. 1, the ground state of the muonic helium atom splits into four sub-levels under a static magnetic field due to the Zeeman effect. By applying a microwave field and measuring the transition frequencies between the levels, the ground state HFS $\Delta\nu$ of the muonic helium atom can be obtained directly at zero field and indirectly as the sum of ν_{12} and ν_{34} at high field. The difference between ν_{12} and ν_{34} can also be used to determine the magnetic moment and mass of the negative muon. Fig. 2 shows the conceptual diagram of the measurement system. The measurement is mainly performed in three steps: (1) formation of muonic helium atoms, (2) state transition induced by microwave field, (3) measurement of the asymmetry of the decay electron emission.

2.1 Formation of muonic helium atoms

A polarized negative muon beam (the polarization is about 30−50% for cloud muons in the H-Line, and about 90% for backward decay muons in the D-Line) is injected into a microwave cavity installed in a the gas chamber. The gas chamber is filled with ^{4}He gas as target and a small amount (~2%) of CH_4 as an electron donor. The muon stops in the ^{4}He gas, is captured by a ^{4}He nucleus, and forms a $(^4\mathrm{He}\mu^-)^+$ ion in the ground state through Auger and radiative transitions. The $(^4\mathrm{He}\mu^-)^+$ ion forms a muonic helium atom ($^4\mathrm{He}\mu^-e^-$) through charge exchange with the surrounding CH_4. During the muon capture process, the polarization of the muon decreases to about 6% of the incident value due to Auger transitions and Stark mixing.

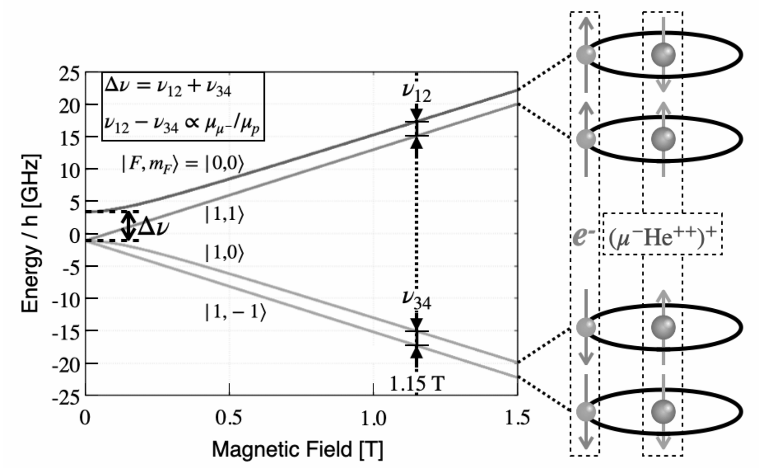

Figure 1. The energy level diagram for muonic helium. F is the total angular momentum, and m_F is the quantization axis component of F.

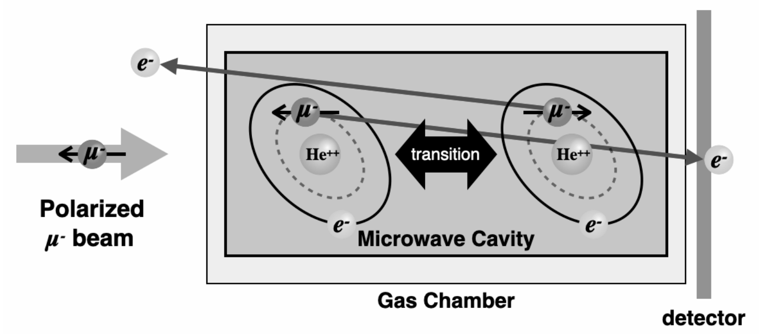

Figure 2. Schematic view of the experimental setup. This apparatus is either enclosed in a magnetic shield box for zero-field measurements or inserted in a large superconducting solenoid magnet for high-field measurements.

2.2 State transition induced by microwave field

When a microwave field is applied to $^4\text{He}\mu^- e^-$, the state transitions occur with a probability corresponding to the difference between the transition frequency and the microwave field frequency, flipping the spin of the negative muon in muonic helium.

2.3 Measurement of the asymmetry of the decay electron emission

The decay electrons tend to be emitted antiparallel to the muon spin. Using backward decay muons (spin antiparallel to the muon momentum direction), when the applied microwave frequency is close to state transition frequency, the amount of decay electrons emitted in the downstream direction is reduced because of the spin-flip. The electrons are detected by a segmented scintillation detector downstream of the gas chamber. The resonance curve is obtained by sweeping the frequency of the applied microwave field and measuring the difference in the number of detected electrons with and without the microwave field. The center of the resonance curve corresponds to the transition frequency between states. The ground state HFS of muonic helium is directly determined by measuring $\Delta\nu$ at zero field and indirectly obtained by summing ν_{12} and ν_{34} at high field.

2.4 A result of preliminary tests

The ground state HFS of muonic helium at zero field was measured using a pulsed muon beam at J-PARC MUSE D-Line in March 2021. The ^{4}He gas was mixed with 2% of CH_4 and the total pressure was 4 atm. The momentum of the negative muon beam was set to 27 MeV$/c$ to maximize the amount of $^4\text{He}\mu^-e^-$ produced. We are still analyzing the measurement results. The asymmetry spectra of the decay electrons with an applied microwave field frequency of 4465.050 MHz and 4465.650 MHz are shown in Fig. 3. When the applied microwave frequency was 4465.050 MHz, the asymmetry was negative. In contrast, when the applied microwave frequency was 4465.650 MHz, the asymmetry was nearly zero. This is because the ground state HFS of muonic helium is near 4465.050 MHz. Considering the beam intensity, the precision from this measurement is expected to be comparable to the current highest precision of 6.5 ppm at high magnetic field [2].

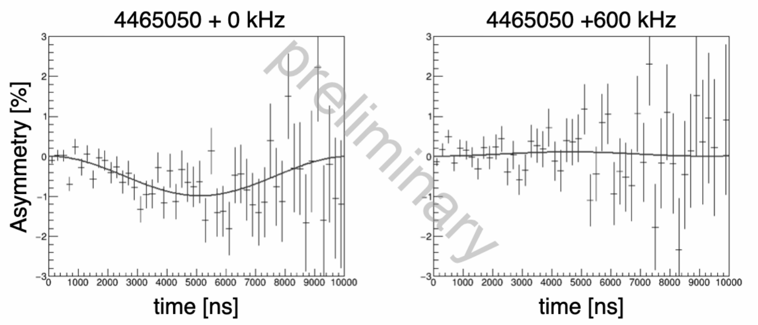

Figure 3. Asymmetries of electron emitted direction applied microwave frequency detuned 0 kHz and 600 kHz from 4465.050 MHz. The asymmetry is defined as the $N_{\text{on}}/N_{\text{off}} - 1$. N_{on} is the number of detected electron with microwave field, and N_{off} without, respectively.

3 Toward higher precision

3.1 H-Line

To obtain more statistics, we will use the J-PARC MUSE H-Line, which is expected to start operation in 2022. The beam intensity of the H-Line is 10 times higher than that of the D-Line. H-Line will enable us to perform measurements under high magnetic field using superconducting magnets. At high magnetic field, decay electrons are focused along the longitudinal direction, so more electrons can be detected with the same detector as in zero-field measurements. After 100 days of measurement in the H-Line under a magnetic field of 1.15 T, the measurement precision is expected to improve by a factor of ten from the previous measurement [2] to 600 ppb.

3.2 Spin Exchange Optical Pumping for Muonic Helium repolarization

The statistical uncertainty in $\Delta\nu$ is presently limited by the negative muon depolarization associated with the formation of $^4\mathrm{He}\mu^-e^-$. We aim to further improve the measurement precision by repolarizing the negative muons through SEOP of $^4\mathrm{He}\mu^-e^-$. Before $^4\mathrm{He}\mu^-e^-$ repolarization, the outermost shell electrons of alkali metal atoms are polarized by optical pumping. Then a muonic helium atom collides and spin-exchanges with an electron-polarized alkali metal atom and the electron of $^4\mathrm{He}\mu^-e^-$ is polarized. Afterward, the electron polarization is shared with the pseudo-nucleus via the hyperfine interaction, and polarizing μ^-. In a previous experiment [3], the spin exchange between Rb and $^4\mathrm{He}\mu^-e^-$ was performed and the μ^- was repolarized in $^4\mathrm{He}\mu^-e^-$ from 6% to 44% . The spin-exchange cross section was obtained as $\sigma_{\mathrm{SE}} = (4.47 \pm 0.67 \pm 0.82) \times 10^{-14}$ cm^2. Using this value in a Monte Carlo simulation, the time evolution of the polarization of μ^- at 1 mT and 200°C is expected to be as shown in Fig.4. In this simulation, we assume the number of Rb is 4.37×10^{14} cm^{-3} and the spins of electron and muon are determined according to the ratio of the square of Clebsch-Gordan coefficients. This means that if we measure decay electrons 2000 ns after each muon beam pulse is injected, we can measure the ground state HFS of muonic helium with almost 100% polarized μ^-. In practice, the achievable polarization decreases with laser power and gas impurities. Assuming a 7-fold improvement in the polarizability of μ^- based on the previous study [4], we can expect a direct improvement by a factor of seven in measurement precision.

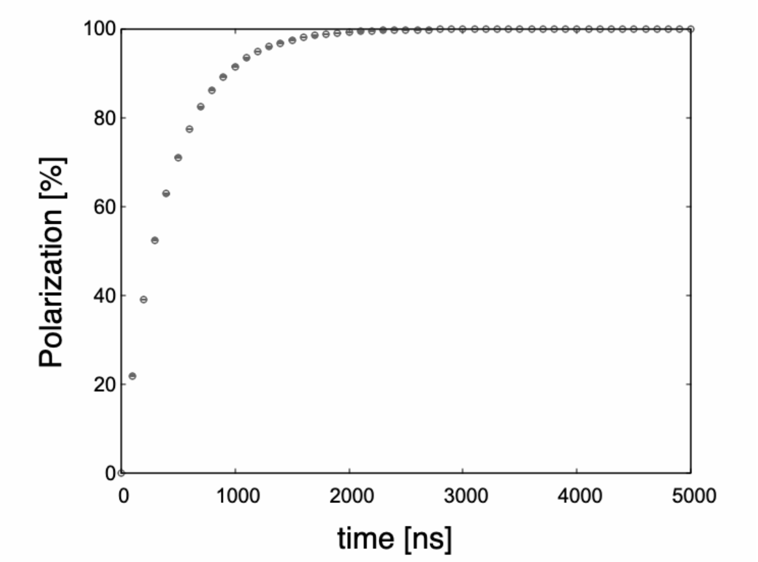

Figure 4. Simulation result of the pseudo-nucleus polarization of muonic helium with electron-polarized Rb at 1 mT and 200°C .

4 Summary

Precise measurements of muonic helium HFS are important for the verification of quantum three-body theory and CPT theorem. We are currently working on zero-field measurements at the MUSE D-Line, and preparations for high-field measurements at the H-Line are underway.

We are also planning to repolarize the muonic helium to further improve the measurement precision by using SEOP.

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