Journal of Physics: Conference Series

Precise measurement of the hyperfine splitting in muonium with a high intensity pulsed muon beam at J-PARC

Journal of Physics: Conference Series **2462** (2023) 012019 doi:10.1088/1742-6596/2462/1/012019

Precise measurement of the hyperfine splitting in muonium with a high intensity pulsed muon beam at J-PARC

R Iwai[1], M Abe[1], S Fukumura[2], M Hiraishi[1], S Kanda[1], S Kawamura[2], S Nishimura[1], H Okabe[1], K Sasaki[1], P Strasser[1], K Shimomura[1], H Tada[2], N Teshima[1] and H A Torii[3]

[1]High Energy Accelerator Research Organization (KEK), Ibaraki, Japan
[2]Nagoya University, Nagoya, Japan
[3]The University of Tokyo, Tokyo, Japan

E-mail: `riwai@post.kek.jp`

Abstract. At J-PARC, the MuSEUM (Muonium Spectroscopy Experiment Using Microwave) collaboration aims to precisely measure the ground-state hyperfine splitting of muonium atoms arising from the muon and electron spins. The pulsed muon beam is stopped in a krypton gas cell to form muonium atoms. The transitions of spin states are induced with a microwave cavity, which are then measured by positron counters. After the previously performed successful measurements with a nearly-zero magnetic field, we are currently planning a measurement with the 2.9 T magnetic field by measuring two Zeeman-split sub-levels, so that increased statistics will allow us to more precisely determine the transition frequency down to ∼1 ppb. Moreover, a new microwave cavity with a unique geometry is being designed to perform the measurement at an even stronger field of 2.9 T in the future.

1. Introduction

A muonium is a two-body exotic atom of a positive muon and an electron. Fundamental properties of this simple leptonic bond-state can be precisely calculated by QED, free from nuclear structure effects. The most precise measurement of the muonium is the ground-state hyperfine splitting (HFS). This split in the energy level of the ground-state arises from the magnetic interaction of the muon and electron, which was measured at 12 ppb precision at LAMPF [1].

Whereas, according to [2], theoretical QED writes the HFS transition frequency $\nu_{\rm HFS}$ as,

$$\Delta_{\rm HFS} = \nu_F[1 + F(\alpha, Z\alpha, \frac{m_e}{m_\mu})] + \Delta_{\rm weak} + \Delta_{th} \tag{1}$$

$$= 4\ 463\ 302\ 872(515)\,\mathrm{Hz}, \tag{2}$$

which has been calculated at 115 ppb precision. In Equation 1, the term $\nu_{\rm F}$ is the Fermi frequency,

$$\nu_{\mathrm{F}} = \frac{16}{3} Z^4 \alpha^2 \frac{m_e}{m_\mu} \Big(1 + \frac{m_e}{m_\mu}\Big)^{-3} c R_\infty, \tag{3}$$

where Z is the charge ratio of the positive muon and positron charge, α is the fine structure constant, m_e is the electrons mass, m_μ is the muons mass, c is the speed of light and R_∞ is the Rydberg constant. The term $F(\alpha, Z\alpha, \frac{m_e}{m_\mu})$ includes all known QED contributions, while, the term Δ_{th} includes unknown QED contributions. The term Δ_{weak} includes the contribution of the weak interaction. The uncertainty in Equation 2 is dominated by the knowledge of the electrons to the muons mass ratio $\frac{m_e}{m_\mu}$ (512 Hz). However, this will be reduced by an order of magnitude by the future independent measurements via laser spectroscopy of muonium 1S-2S transition [3, 4].

Hence, the combined effort to improve both theoretical and experimental precisions of the Δ_{HFS} paves the way for a high precision test of QED and Standard Model of particle physics. At J-PARC, a new measurement by the MuSEUM (Muonium Spectroscopy Experiment Using Microwave) collaboration is in progress. The collaboration aims to improve the current experimental precision by an order of magnitude ($\sim$1 ppb).

2. The MuSEUM experiment

The basic experimental scheme of measuring Δ_{HFS} is similar to the previous experiment at LAMPF (also see the next section); a muon beam is stopped in a noble gas forming muonium atoms, and spin flips are induced by a microwave. The muon decay preferably emits the positrons along the muons spin direction because of parity violation in weak interactions. Thus, at the resonant microwave frequency, the transition of the HFS can be observed via a change of the angular distribution of the emitted positrons. The highest precision in the previous experiment at LAMPF was attained by selecting "old muonium" atoms in the analysis, which have lived several times longer than muon lifetime of 2.2 µs, to reduce the natural line width of the resonance curve. To use this method, facility utilizing continuous muon beams such the LAMPF needs cutting away some parts of the muon beam to have a long time window for observing muon decays, thus, statistics is largely reduced. Hence, the MuSEUM collaboration utilizes high intensity pulsed muon beams to overcome this trade-off.

With the scheme described above, the Δ_{HFS} can be measured in two different ways: without or with a magnetic field in the spectroscopy region. Figure 1 (so-called Breit-Rabi diagram) shows the normalized energy levels of the ground-state in muonium in different external magnetic field strengths. Without having magnetic field, the Δ_{HFS} can be directly measured via transition between the spin singlet and triplet states. Whereas, with the magnetic field, the spin triplet state splits into three states, and two sub-levels transition frequencies (indicated as ν_{12} and ν_{34} in Fig. 1) can be measured. The Δ_{HFS} can be determined as the sum of these frequencies ($\Delta_{\mathrm{HFS}} = \nu_{12} + \nu_{34}$).

The MuSEUM collaboration has already performed the measurements at the zero-magnetic field in several beamtimes at J-PARC. The first successful observation of the HFS transition of the muonium atoms was obtained in 2016 beamtime, nevertheless, with a limited precision of 4.9 ppm [5]. In 2017 beamtime, the broadening of the signal line shape was reduced by optimizing the microwave power in the cavity, resulting in a precision of 0.9 ppm [6]. In the latest measurement in 2018 beamtime, the background counts in the positron detectors have been reduced by increasing the inner diameter of the microwave cavity, resulting in a precision of 0.5 ppm [7]. Furthermore, combining with a newly developed analysis technique (Rabi-oscillation spectroscopy) [8], the attained precision has been further improved down to 511 ppb.

As the next step, we will measure the Δ_{HFS} at the magnetic field strength of 1.7 T to improve the current best precision in [1] by an order of magnitude ($\sim$1 ppb). With the strong magnetic field, the statistical precision can be boosted. One reason is an enhancement of the angular asymmetry of the decay positrons by spin flips. The initial muon spins are fully polarized when using the positive muon beam at around 28 MeV/c momentum (so-called surface muon beam), and this polarization can be maintained by having a strong magnetic field to fix the spins. Another reason is an improved capturing of the decay positrons at the positions of the positron detectors placed along the magnetic field lines.

It should be noted that an additional fundamental constant of the proton to muon magnetic moment ratio (μ_μ/μ_p) can be measured with the external magnetic field. This is because the frequencies ν_{12} and ν_{34} depend on the magnetic field strength, which can be measured by a proton nuclear magnetic resonance (NMR) technique. Hence, the ν_{12} and ν_{34} can be related to the proton magnetic moment via the Lamor relation $2\mu_p H = h\nu_p$, where the μ_p is the proton magnetic moment, the h is the Plank constant and the ν_p is the proton processing frequency.

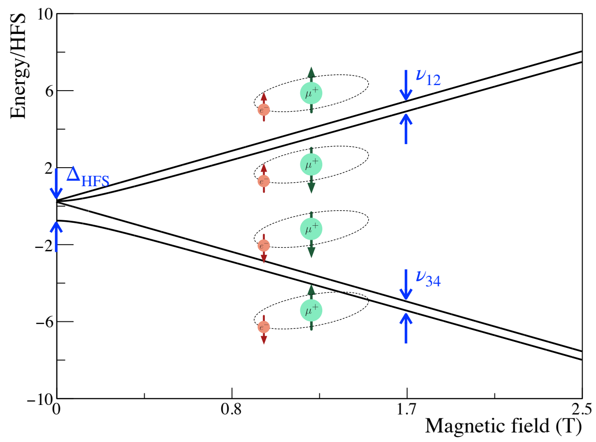

Figure 1. The energy level of the ground-state HFS in muonium with different external magnetic field strengths. The vertical axis is normalized with the Δ_{HFS} ($\sim$ 4.46 GHz). Muons and electrons spin configurations are schematically illustrated for each split lines. The blue arrows indicate the transition frequencies measured by MuSEUM: direct measurement of Δ_{HFS} at the zero-magnetic field and measurement of the ν_{12} and ν_{34} at 1.7 T magnetic field.

3. Setup for the measurement with a strong magnetic field

The first measurement with the strong external magnetic field will be performed at the H-line in Material and Life science Experimental Facility (MLF) at J-PARC, which is currently commissioned. This beamline is designed to provide the highest intensity of the surface muon up to $\mathcal{O}(10^8)\,\mu^+$/s at around 28 MeV/c momentum [9], and it will be available for the measurement towards the end of 2022.

Figure 2 illustrates the general experimental setup for the measurement with a strong magnetic field. A bunch of surface muons from the H-line enters the setup following the magnetic field lines and slows down in a krypton gas chamber. The profile of the incoming muon beam is measured at the entrance of the setup with a beam monitor based on a thin layer of scintillating fibres readout with Silicon PhotoMultipliers (SiPMs) [10]. In the gas chamber, muonium atoms are formed with copious numbers by capturing the electrons from the krypton gas atoms. Then, captured electrons immediately cascade down to the ground-state. The transitions of the HFS are induced by a cylindrical microwave cavity with an inner diameter of 198 mm. The cavity generates two modes of the microwave, TM110 and TM210, for the transitions of $\nu_{12} = 1.896$ GHz and $\nu_{34} = 2.567$ GHz, respectively [11]. Two detectors are placed for counting decay positrons in the upstream and downstream of the gas chamber. They are based on segmented tiles of the plastic scintillator ($1\times1\,\mathrm{cm}^2$) readout with SiPMs, minimizing pileup counts under the high muon rate operation [12].

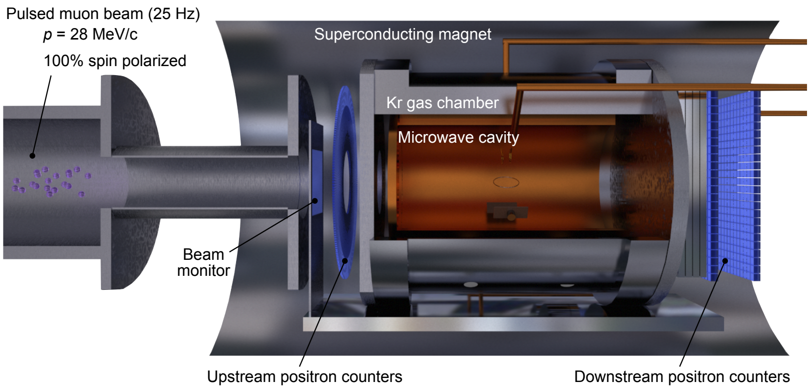

Figure 2. Sketch of the general setup for the MuSEUM experiment with magnetic fields. The surface muon beam enter the setup from the left after passing through the beam monitor. The muons are slowed down and stopped in the krypton gas chamber, forming muonium atoms in the ground-state. The HFS transition is induced by the microwave stored in a copper cavity shown in brown. The induced spin flips are observed by counting decay positrons with the upstream and downstream detectors placed along the beam axis. The whole setup is placed in a superconducting magnet bore hole.

4. Status and Prospects

Towards the end of 2022, we are preparing for the first measurement with the 1.7 T magnetic field by integrating the setup in Fig. 2 at the H-line. One of the challenge in this measurement is to produce a homogeneous magnetic field in the spectroscopy region. We are currently developing a mapping system with multiple CW (Continuous Wave)-NMR probes [13] and a passive shimming system with iron plates [14] to establish the homogeneity of 0.2 ppm (peak to peak).

Once the measurement with the 1.7 T magnetic field has been successfully performed, we will move to the next step: measurements at different magnetic field strengths. The left panel of Fig. 3 shows the frequencies of the transition frequencies ν_{12} and ν_{34} with various magnetic field strengths. The new measurements are mainly motivated by more precise determination of the μ_μ/μ_p, to check systematic effects related to the magnetic field strength or reduce such an effect. Higher precisions in measuring the magnetic field with the proton-NMR can be, in principle, improved at a higher value of the magnetic field of 2.9 T, which is the maximum applicable magnetic field with our magnet. Whereas, in Fig. 3 left, the derivatives of the frequency curves become zeros at $\sim$1.137 T magnetic field (so-called magic field), where the μ_μ/μ_p can be determined the most freely from the accuracy of measuring the magnetic field (for example, see [15]). We expect that our current cylindrical microwave cavity designed for 1.7 T magnetic field can be also tuned to $\nu_{12} = 1.921$ GHz and $\nu_{34} = 2.542$ GHz at $\sim$1.137 T magnetic field, with a small extension of the tuning scheme of TM110 and TM210 modes. However, the measurement at 2.9 T magnetic field ($\nu_{12} = 1.778$ GHz and $\nu_{34} = 2.686$ GHz) requires to upgrade the microwave cavity. This is because, in general, a ratio of TM110 and TM210 frequencies yields a certain value in the cylindrical cavity, although, this can be modified at certain amount depending on tuning schemes as mentioned above.

Currently, we are designing a new rectangular shaped microwave cavity, which has more flexibilities in tuning two modes. The right panel of Figure 3 shows the dimension of such a cavity for the measurement with 2.9 T magnetic field. With this dimension on the transverse plane (xy, perpendicular to the magnetic field), we can generate two desired modes, having oscillating magnetic fields on the transverse plane. Currently, we are designing mechanical schemes to tune these two modes using a simulation tool. Various other parameters (e.g. the length of the cavity in the z-direction) are optimized to avoid other modes overlapping the desired modes.

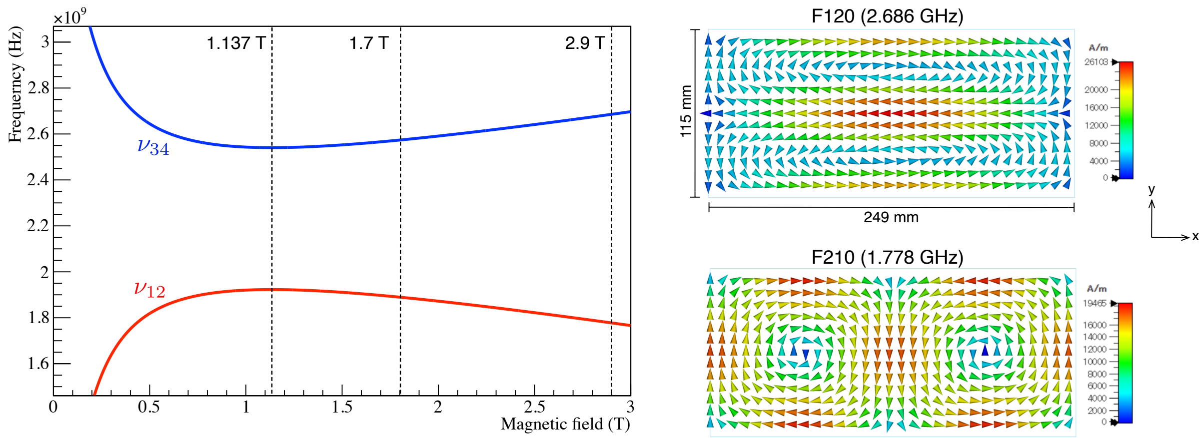

Figure 3. Left: The transition frequencies ν_{12} (red) and ν_{34} (blue) of the ground-state HFS in muonium with different external magnetic field strengths. The magnetic field strengths of 1.137 T, 1.7 T and 2.9 T are indicated with black dased lines. Right: The simulated two modes of the rectangular cavity for the measurement with 2.9 T magnetic field. The shown dimensions on the xy-plane can generates F210 and F120 modes for $\nu_{12} = 1.778$ GHz and $\nu_{34} = 2.686$ GHz, respectively. Cones represent the magnetic field with the magnitudes represented by the colours.

5. Conclusion

Precise determination of the $\Delta_{\rm HFS}$ is recently progressing in both theory and experiment. Upcoming results of the muonium 1S-2S spectroscopy experiments will soon reduce the theoretical uncertainty of $\nu_{\rm HFS}$. Whereas, the new H-line at J-PARC will soon start providing the highest intensity of the pulsed muon beam. The MuSEUM collaboration is integrating the setup at the H-line towards the first measurement with the 1.7 T magnetic field at the end of 2022. In the future, the measurement can be also performed at stronger magnetic field of 2.9 T. A new microwave cavity is currently being designed with a rectangular geometry to generate the desired frequencies.

6. Acknowledgment

We gratefully acknowledge the KAKENHI grants No. 20H05646, 21H04463, 21H04481 and 21J00903.

References

[1] Liu W *et al.* 1999 *Phys. Rev. Lett.* **82** 711–714
[2] Eides M I 2019 *Physics Letters B* **795** 113–116
[3] Crivelli P 2019 *Hyperfine Interactions* **239** 49

[4] Yamamoto S 2022 Muonium 1S-2S spectroscopy with improved statistics Presentation at the 15th International Conference on Muon Spin Rotation, Relaxation and Resonance
[5] Kanda S 2017 *PoS* **INPC2016** 170
[6] Kanda S *et al.* 2021 *Physics Letters B* **815** 136154 ISSN 0370-2693
[7] Ueno Y 2018 Doctoral thesis at the University of Tokyo
[8] Nishimura S *et al.* (MuSEUM Collaboration) 2021 *Phys. Rev. A* **104** L020801
[9] Kawamura N *et al.* 2018 *Progress of Theoretical and Experimental Physics* **2018** ISSN 2050-3911
[10] Kanda S (MuSEUM) 2014 *RIKEN APR* **48**
[11] Tanaka K S *et al.* 2021 *Progress of Theoretical and Experimental Physics* **2021**
[12] Kanda S (MuSEUM) 2016 *PoS* **PhotoDet2015** 039
[13] Tada H *et al.* 2022 *IEEE Transactions on Applied Superconductivity* **32** 1–5
[14] Sasaki K *et al.* 2022 *IEEE Transactions on Applied Superconductivity* **32** 1–7
[15] Ehrlich R D *et al.* 1972 *Phys. Rev. A* **5** 2357–2375