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Rabi-oscillation spectroscopy of the hyperfine structure of the muonium atom for high-precision determination of the muon mass

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Abstract
Muonium (Mu) is a hydrogenlike atom comprising a positive muon and an electron, both pointlike leptons. Spectroscopy of Mu is a promising method in the search for new physics in particle-physics research, superior to that of hydrogen for which the uncertainty in the proton radius and its internal structure gives limitations. Microwave spectroscopy of the Mu hyperfine structure (HFS) provides the most precise estimation of the magnetic moment and the mass of the muon, opening a way to search for a physics beyond the Standard Model. MuSEUM Collaboration is studying Mu-HFS at the J-PARC muon facility in Japan, aiming at a precision one order of magnitude better than before. With our new spectroscopic technique which does not require any frequency sweep or Fourier transformation, the resonance frequency can be obtained directly by fitting a simulated function to the time evolution of the Rabi oscillation at a fixed microwave frequency. This method, named Rabi-oscillation spectroscopy, can improve the precision by eliminating systematic uncertainties due to power fluctuations. After a decade of our study under zero magnetic field with fruitful results, we are about to start our experiment under a high magnetic field.

Keywords Muon · Muonium atom · Hyperfine structure · Magnetic moment · Microwave spectroscopy · Quantum Electrodynamics (QED) · Rabi-oscillation spectroscopy

1 Introduction

Ordinary atoms and molecules are made up of a nucleus composed of protons and neutrons, and electrons bound by the Coulomb force. Atoms containing other particles are generally called exotic atoms. The muonium atom (with its chemical symbol Mu) is an exotic atom consisting of a positively charged muon and an electron bound by the Coulomb force, and can be considered as a light isotope of the hydrogen atom.

for MuSEUM Collaboration

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The strategy of listening to the whispers of nature, in which the properties of elementary particles are measured gently in an atomic bound system containing them, rather than by hard-collision experiments at high energies, has attracted attention in recent years because of its potential for high-precision measurements in spectroscopy. For example, visible and infrared laser spectroscopy of muonic hydrogen atoms, in which negative muons are trapped by hydrogen atoms in place of electrons, has shown that the values of proton charge radius derived from these measurements deviate significantly from the values obtained from high-energy proton–electron inelastic scattering and hydrogen atom spectroscopy. The large discrepancy has been noted as the proton radius puzzle [1, 2].

MuSEUM (Muonium Spectroscopy Experiment Using Microwave) Collaboration has been carrying out microwave spectroscopy experiments on the hyperfine structure (HFS) of the ground state of the muonium atom. In pursuit of high precision, we have developed an innovative method of atomic spectroscopy that does not require any frequency sweep and can achieve high precision without being affected by fluctuations in the applied microwave intensity. This new method, which we have named "Rabi-oscillation spectroscopy", can be used to precisely determine the magnetic moment and the mass of the muon, and is expected to test quantum electrodynamics (QED) and weak interactions, and to search for new physics beyond the Standard Model. This paper describes the principles and characteristics of Rabi-oscillation spectroscopy as a new tool of atomic spectroscopy, applied to the muonium atom.

2 Level structure of the muonium atom

The level structure of the muonium atom is basically the same as that of the hydrogen atom. The energy of the electronic state is proportional to the electron mass, with almost no difference between muonium and hydrogen. However, the hyperfine splitting (HFS) due to the spin–spin interaction is about three times higher in muonium (4.46 GHz) than in hydrogen (1.42 GHz) in the 1S ground state, reflecting the fact that the magnetic moment of the muon is larger than that of the proton. Figure 1 shows a level diagram of muonium.

Unlike the spectroscopy of hydrogen, where the comparison with theoretical calculations is limited by the uncertainty of the proton charge radius, muonium is an atom composed purely of leptons, making it a suitable system for test of QED. In fact, as early as the year after the experimental confirmation of the existence of muonium atoms by Hughes et al. [3] in 1960, a spectroscopic experiment of its HFS was already reported [4] and future verification of QED by precision spectroscopy was discussed. Although limited by the natural width of 140 kHz due to the 2.2 μs lifetime of the muonium, sufficient precision can be expected.

3 Experimental overview and apparatuses

The MuSEUM Collaboration has so far obtained results under zero magnetic field (or more precisely speaking, extremely small magnetic field), and we are about to start our measurements at high magnetic fields, aiming to obtain the magnetic moment and mass of the muon with an order of magnitude higher precision than before. Our goal is to test QED and weak interactions in atomic bound systems, and to explore new physics beyond the Standard Model.

The experiment was so far performed using the D line of the Materials and Life Science Experimental Facility (MLF) in the Japan Proton Accelerator Research Complex (J-PARC). This is one of the beamlines providing pulsed muons. The decay of a positive pion $\pi^+ \rightarrow$

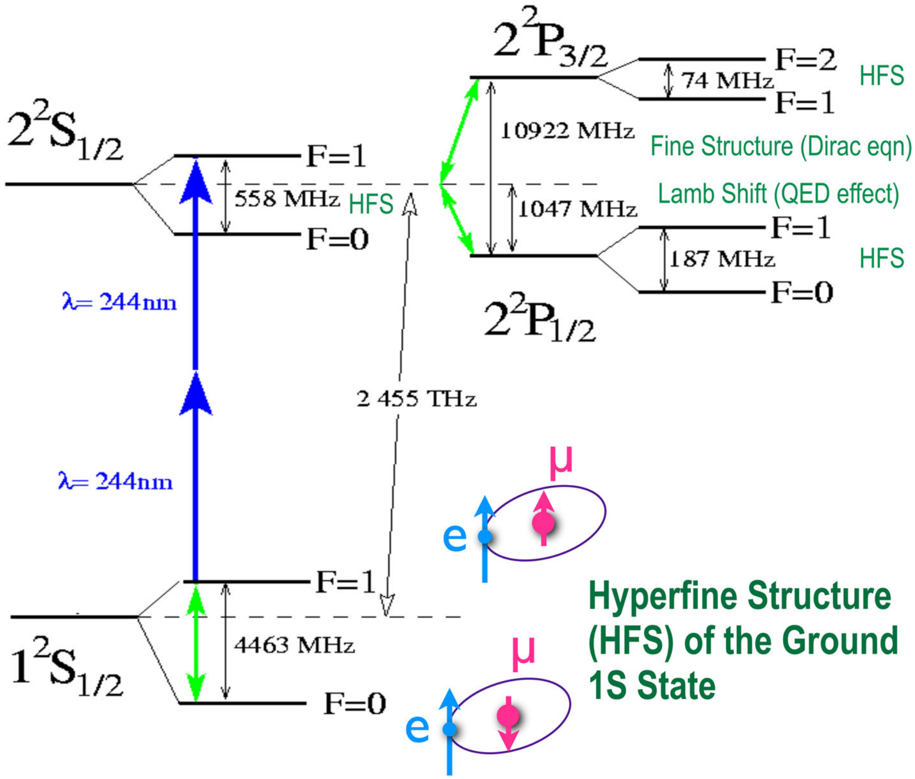

Fig. 1 Level diagram of the muonium atom

$\mu^+ + \nu_\mu$ produce a positive muon (μ^+) beam that is polarized 100% antiparallel to the beam direction. The beam was injected into a krypton (Kr) gas target and stopped inside. In the zero-field experiment, the entire experimental apparatus was surrounded by three layers of permalloy to shield the environmental magnetic field, keeping the internal residual magnetic field below 100 nT. As shown in Fig. 2, the gas chamber was equipped with a microwave cavity resonator in which μ^+ particles, decelerated to less than 10 eV, captured electrons from Kr atoms to produce muonium atoms. Kr shows a high efficiency for muonium production because of its similar ionization energy of 14.0 eV comparable to 13.5 eV for muonium.

When microwave-induced resonant transitions occur between hyperfine levels, the spin direction of μ^+ is flipped. When the positive muon decays, it emits a positron of up to 52 MeV through the reaction $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$. The direction of emission is anisotropic and the positron is more likely to be emitted in the μ^+ spin direction, the resonance transition can be observed as an increase in the number of positrons detected by a positron detector placed downstream. Therefore, subtraction of the number of detected positrons, normalized by the number of incident μ^+, between the cases for microwave ON and OFF, would give the resonance signal [5].

Since the muon beams are pulsed, the positron detection has a high instantaneous counting rate, and the detector must tolerate such a high counting rate; the counting loss due to pile-up must be sufficiently suppressed. We have developed a compact semiconductor photodetector (a silicon photomultiplier, SiPM) and two-dimensional arrays covered with tiles of 1 cm

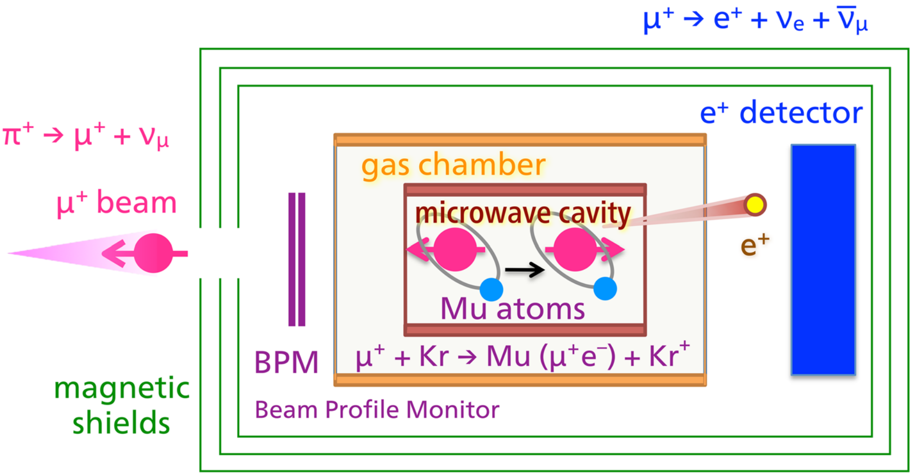

Fig. 2 Schematic of the apparatus for muonium atom spectroscopy experiment. The gas chamber is surrounded by three layers of magnetic shielding for the experiment at zero magnetic field as shown in the figure, while it will instead be enclosed in a superconducting magnet for experiments at high magnetic field

square plastic scintillators [6] as shown in Fig. 3. The signals were read out with KALLIOPE circuits [7] developed at the High Energy Accelerator Research Organization (KEK). Later, a silicon strip detector [8] (bottom of Fig. 3) with an even higher counting-rate tolerance was introduced, which was originally developed for the E34 experiment to measure the anomalous magnetic moment ($g - 2$) of the muon at J-PARC.

4 Rabi-oscillation spectroscopy

In standard spectroscopy, the resonance curve is drawn by varying the frequency of the electromagnetic wave and plotting the obtained signal intensity, which is then fitted with the Lorentz function or the Voigt function convoluted with the Gauss function to obtain the center frequency of resonance (Fig. 4 left). For precise measurement, it is essential to narrow the width of the resonance by introducing a constant low power of the electromagnetic wave.

However, exotic atoms such as muonium need to be observed with a high power of the electromagnetic wave in order to induce the transition within a short lifetime of microseconds, and not only does the resonance width increase due to collisional broadening and power broadening in addition to the natural width, but any factor that causes asymmetry in the resonance curve would significantly reduce the accuracy in determination of the resonance center. In fact, in our experiments, microwave power of around 1 W was injected, which was then amplified by the resonator with a Q-value of about 10 000 [9], so that the power had to vary to some extent depending on the frequency.

The "old muonium method" [10] has been known as a technique to narrow the line width. This is a method in which only long-lived muons (i.e., with positrons detected later than some microseconds after μ^+ beam injection) are selected for analysis, which guarantees a long interaction time with the microwave and thus narrows the energy width, or the resonance curve line width, according to the uncertainty principle. (Note that the central resonance peak narrows, but the side peaks rise, and the overall width of the envelope remains unchanged.) Although a certain degree of improvement in accuracy is possible by selecting a reasonable

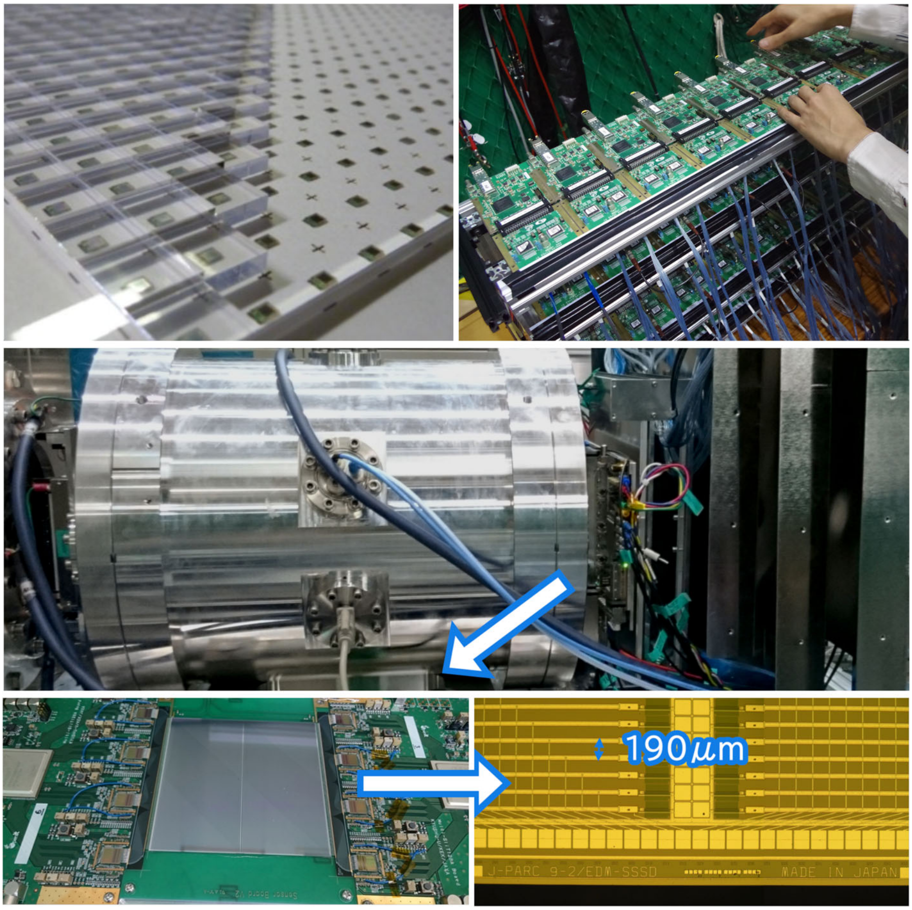

Fig. 3 Photograph of the positron detector. Top: Detector with an array of semiconductor photodetectors and plastic scintillators (upper left: detector in the process of assembly, upper right: KALLIOPE circuit board for readout). Middle: Photograph showing the vacuum chamber, the positron detector and three layers of magnetic shielding. Bottom: Silicon strip detector (the bottom right picture is a magnified view of the central part of the silicon sensor shown in the bottom left picture)

time-cut threshold, a severer selection of long-lived atoms may result in a dramatic decrease in the number of events, which in turn may worsen the accuracy.

Since all signals are accompanied by temporal information, the authors focused on the time evolution of signals to be directly connected to Rabi oscillations obtained from the Bloch equation for transitions between levels [11]. An example of a theoretical simulation is shown in Fig. 4 (right). If the frequency of the electromagnetic wave matches or is close to the resonance frequency, the signal oscillates slowly with a large amplitude, but if the detuning i.e. the gap between the two frequencies is large, the oscillation repeats quickly with a small amplitude. As for the intensity dependence, the stronger the microwave intensity, the larger the amplitude and the faster the oscillation. Using these relationships, the time evolution data of a signal obtained at a fixed microwave frequency can be compared to the calculated Rabi oscillations to determine the detuning without being affected by the frequency dependence of microwave intensity as a result of parameter fitting.

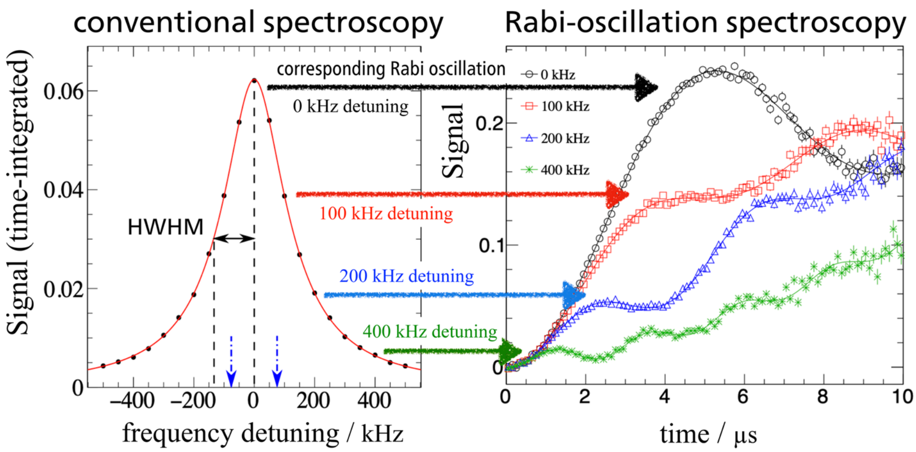

Fig. 4 Comparison between standard spectroscopy and Rabi-oscillation spectroscopy. Left: In standard spectroscopy, signal intensity is plotted as a function of frequency, and the resonance center frequency is obtained by fitting a mountain-shaped resonance curve. Right: A theoretical simulation of Rabi-oscillation spectroscopy. The speed and the amplitude of the oscillations differ depending on the frequency detuning

Simulation and experimental data were analyzed at different frequencies of electromagnetic waves, and it was confirmed that the same resonance frequencies were correctly obtained no matter which fixed frequency of the microwave was used in the experiment. In addition, since this method does not draw resonance curves, it does not require data at frequencies corresponding to the feet of the mountain where the signal strength is weak, and thus enables efficient data acquisition. We found that fixing the frequency near the center of the resonance (shown as blue dash-dotted arrows on the left side of Fig. 4) can improve the accuracy by factor 2 with the same statistics compared to the standard spectroscopy. As a result, the accuracy of our experiment surpassed that of the past experiments performed under zero magnetic field conditions, despite the short time spent for our measurement [11].

This new spectroscopy, named "Rabi-oscillation spectroscopy", does not require frequency sweep or drawing of any resonance curves in the frequency domain as a result of Fourier transformation, but makes direct use of time-domain information. Rabi-oscillation spectroscopy can be applied not only to muonium, but also to the spectroscopy of other general atoms and molecules. In particular, it may be advantageous for exotic atoms and radioisotopes, i.e., atoms containing short-lived elementary particles and radionuclides produced at accelerator facilities. Rabi oscillations are noticeably fast with periods of hundreds of nanoseconds and easily observed under experimental conditions where the power must be high enough to obtain the maximum signal from a limited amount of observation time and number of atoms. We expect that this revolutionary spectroscopic method will be applied in a variety of fields of research.

5 Precision experiment at high magnetic field

In pursuit of higher accuracy in muonium spectroscopy, it is advantageous to make measurements at high magnetic fields, and we have been preparing a superconducting magnet [12], with field uniformity rigorously required.

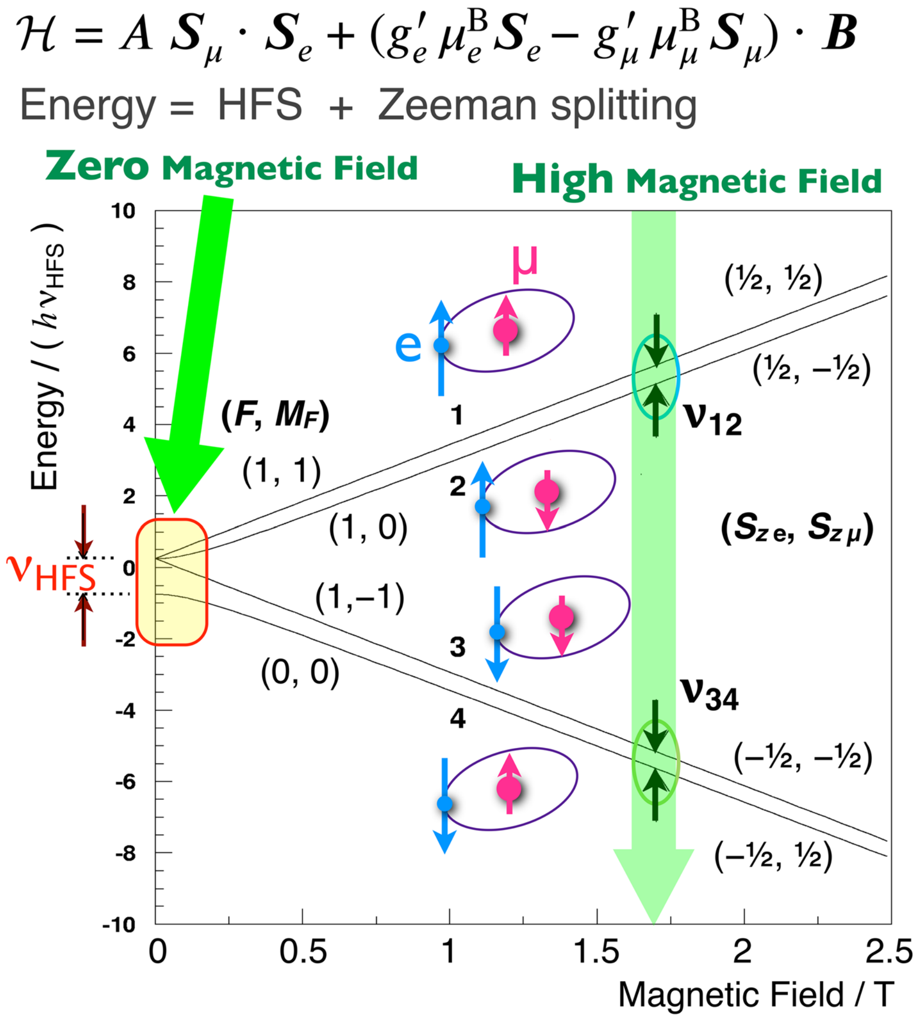

Fig. 5 Breit-Rabi diagram of the hyperfine structure of the muonium atom in the ground state, showing the change in level energy due to the Zeeman effect in a magnetic field

In a magnetic field, the muonium atom is subject to Zeeman splitting, as drawn in the Breit-Rabi diagram shown in Fig. 5. The triplet state splits into three levels at low magnetic fields, two of which shift to the high-energy side in high magnetic fields, while the other one and the singlet state shift to the low-energy (stable) side. Let the frequency corresponding to the transition energy between the top two levels 1 and 2 be denoted by ν_{12}, and the frequency between the bottom two levels 3 and 4 by ν_{34}, we obtain

$$\nu_{\mathrm{HFS}} = \nu_{12} + \nu_{34} \tag{1}$$

and

$$\mu_\mu / \mu_{\mathrm{p}} \propto (m_\mu / m_{\mathrm{p}})^{-1} \propto \nu_{34} - \nu_{12}. \tag{2}$$

It can be mathematically shown that the sum of the two transition frequencies is always constant regardless of the magnetic field strength, and is equal to the hyperfine structure splitting ν_{HFS} at zero magnetic field. The difference between the two frequencies is proportional to the magnetic moment μ_μ of the muon, and under the experimental conditions where the magnetic field is determined using the NMR signal of hydrogen, the ratio μ_μ/μ_{p} between the magnetic moment of the muon and that of the proton, and thus the mass ratio m_μ/m_{p}, can be derived. For this purpose, two resonance frequencies ν_{12} and ν_{34} are measured in the experiment. We can use two different modes of a cylindrical cavity to measure both frequencies when the magnetic field strength is set to a 'magic' field of 1.7 T: $\nu_{12} = 1.95$ GHz for TM110 mode and $\nu_{34} = 2.65$ GHz for TM210 mode [9].

A previous study was conducted in the 1990s at the Los Alamos National Laboratory in a high magnetic field [13], already a quarter of a century ago. At that time, the hyperfine splitting ν_{HFS} was measured with an experimental precision of 12 ppb (this is a test of QED), and the ratio μ_μ/μ_{p} of the magnetic moment was determined at 120 ppb (or indirectly with a precision of 20–30 ppb by comparison with theoretical calculations, assuming the correctness of QED). We aim to eventually determine ν_{HFS} to an accuracy of 2 ppb (with uncertainty within 10 Hz of frequency) and μ_μ/μ_{p} directly to an accuracy of 15 ppb. If the above accuracy is achieved experimentally, we expect to be able to reliably observe effects by electroweak interactions [14] and by hadron vacuum polarization [15, 16] beyond the test of QED through comparison between experiments and the calculations.

A new muon beamline, the world's most intense H-line, has now been completed at the J-PARC MLF, making even higher intensity beams of 1×10^8 muons per second available soon. This beamline will enable us to achieve a statistical precision of 2 ppb, a new world record, within a few months of beamtime.

Recent experiments on the anomalous magnetic moment $(g-2)$ [17] have shown a discrepancy between the measured results and the Standard Model, suggesting the existence of a new particle or new physics. The value of μ_μ/μ_{p} to be determined by our experiment is a prerequisite for deriving the value of $g-2$ from these experiments. Experiments are also planned to precisely measure the 1S–2S electronic transitions of the muonium atom using two-photon laser spectroscopy [18, 19], and are expected to improve the accuracy by two orders of magnitude over the previous experiment. Our microwave spectroscopy of muonium atoms is not only important by itself but also in the complementary relationship with these experiments, and further progress is awaited.

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Author Contributions H.A.T wrote the manuscript and reviewed it on behalf of the MuSEUM Collaboration.

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Data Availability The data will be available upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Ethical Approval Not applicable.

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