論文の内容の要旨

論文題目

Precision Spectroscopy of Muonium Ground-State Hyperfine Structure at Very Weak Magnetic Field

(極小磁場におけるミューオニウム超微細構造の精密分光)

氏名

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1 Introduction

Muonium is the bound state of a positively-charged muon and an electron, one of the hydrogen-like atoms. Unlike hydrogen atom, muonium is free from the internal structure of the proton, and it is one of the best probes to test the bound-state QED. The muonium ground-state hyperfine structure (MuHFS) has been studied extensively from the experimental side and theoretical side. There are two experimental ways of MuHFS, a measurement at very weak magnetic field and a measurement in a high field, as shown in Fig. **??**. The most recent experimental results of the two measurements are

$$\Delta\nu_{\mathrm{HF}} = 4.463\ 302\ 776(51)\ \mathrm{GHz}\ (12\ \mathrm{ppb}) \tag{1}$$

$$\Delta\nu_{\mathrm{WF}} = 4.463\ 3022(14)\ \mathrm{GHz}\ (300\ \mathrm{ppb}), \tag{2}$$

where $\Delta\nu_{\mathrm{HF}}$ is the result in high field published in 1999 [**?**] and $\Delta\nu_{\mathrm{WF}}$ is the result in very weak field published in 1975 [**?**], and ppb indicates part per billion (10^{-9}). The two experiments have been conducted at Los Alamos Meson Physics Facility (LAMPF). Historically, the experimental precision has been limited by the statistical uncertainty, i.e. more intense muon beam can realize improved measurements of MuHFS.

Theoretical value of the MuHFS has been calculated as

$$\Delta\nu_{\mathrm{th}} = 4.463\ 302\ 868(271)\ \mathrm{GHz}\ (61\ \mathrm{ppb}). \tag{3}$$

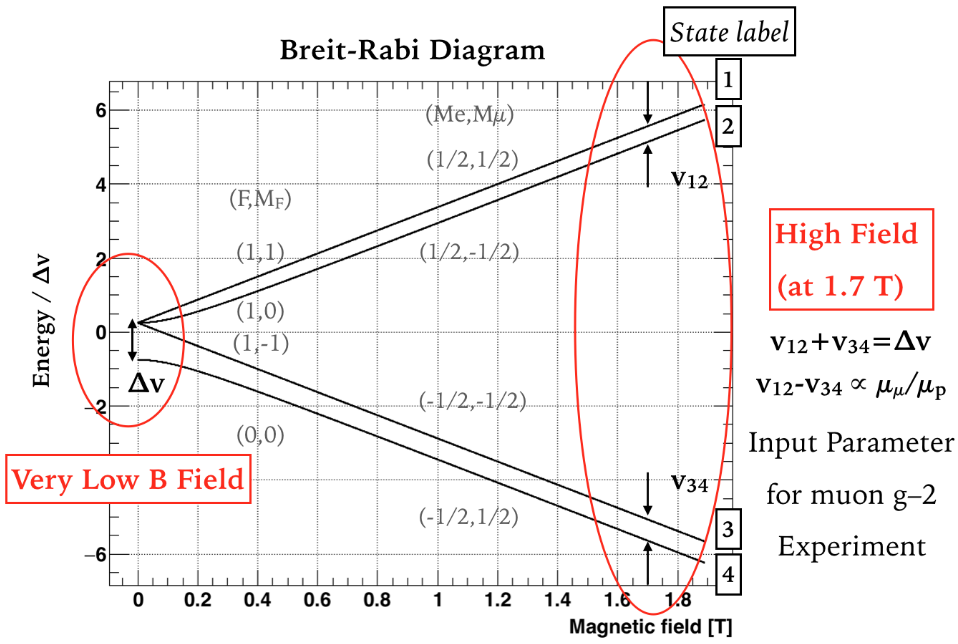

Figure 1: Breit-Rabi diagram of the ground-state muonium hyperfine structure. There are two measurement methods, high-field, and low-field, and we focus on the low-field measurement in this thesis.

The primary source of the uncertainty in the theoretical value is the uncertainty of the muon mass which need to be determined by other experiments. The advance of the techniques in continuous-wave laser and muonium production in vacuo can realize an improved measurement of muonium 1S-2S, which determines the muon mass precisely hence ameliorates the MuHFS theoretical value; indeed, a project on the muonium 1S-2S measurement was proposed recently [**?**].

In this thesis, we present a new precision measurement of the muonium hyperfine structure interval at the Japan Proton Accelerator Research Complex (J-PARC), Materials and Life science Facility (MLF). The new experiment is called Muonium Spectroscopy Experiment Using Microwave (MuSEUM). The intense pulsed muon beam at J-PARC improves the statistics. The thesis focuses on recent achievements in the measurement of MuHFS in very weak magnetic field.

2 Methods

Figure **??** shows the schematic drawing of the experimental procedure. Nearly 100% polarized muon beam is injected into krypton gas target, and muoniums are produced in the gas by electron capture from krypton atoms. Without MuHFS transition, muon spin is aligned anti-parallel to the initial beam direction (left-hand side in the Fig. **??**). The parity violating decay of the muon emits a positron, whose momentum is preferentially aligned to the muon spin; without the transition, more positrons are emitted to upstream. There is a microwave cavity in the gas chamber, and if the microwave with appropriate frequency is applied to the cavity, it induces the MuHFS transition, and flips the muon spin. Subsequently, more decay positrons are emitted in the downstream, where a positron counter is placed. By counting the number of the detected positrons while sweeping the microwave frequency, one can determines the MuHFS frequency.

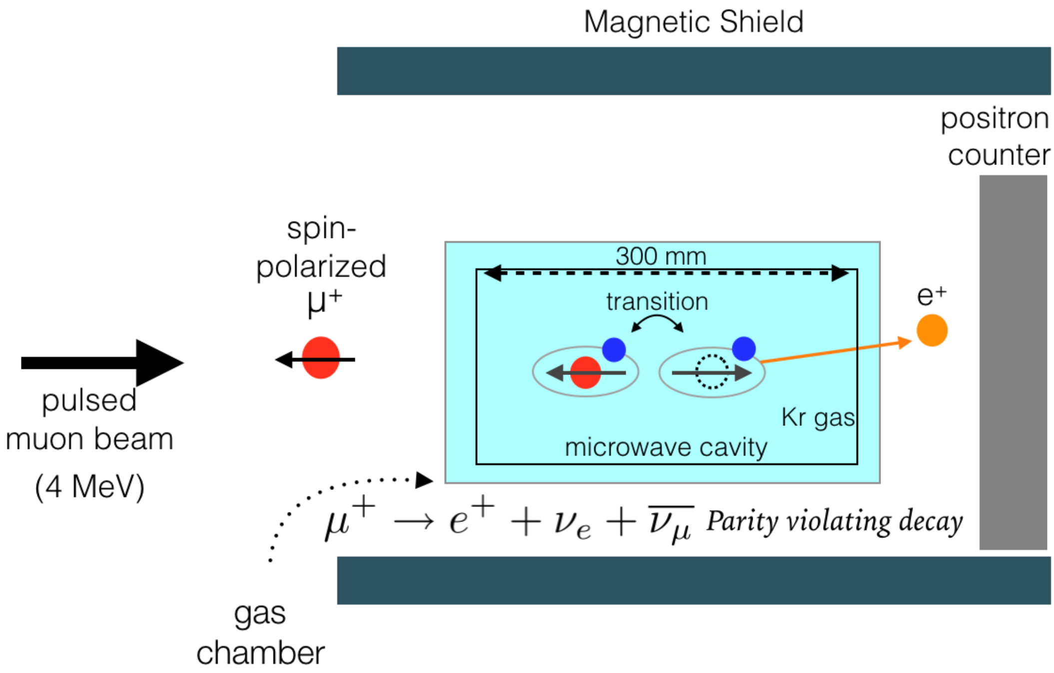

Figure 2: Schematic drawing of the experimental set up.

3 Achievements in the Thesis

The main achievements in this thesis are: development of a new cavity with a larger volume than the precursor measurement in J-PARC, suppression of the systematic uncertainty by the measurements in lower krypton gas pressures enabled by the new cavity, and application of so-called "old muonium" method to reduce the statistical uncertainty.

A new cavity with a large volume can improve the measurement in two aspects. First, it enables more muons to stop inside the cavity and more muoniums are available for the spectroscopy, thus it improves the statistics. Furthermore, it also enables the measurements with lower krypton gas pressure. In the precursor measurements in J-PARC, a cylindrical cavity using TM (Transverse Magnetic) 110 mode with a diameter of 81 mm and a length of 230 mm was used. We developed a new cavity using TM220 mode with a diameter of 181 mm and a length of 300 mm. In general, a cavity using higher mode and with larger volume should be carefully designed to avoid mode interferences. By using a numerical calculation before the production, we successfully designed the new cavity without any mode interference.

One of the most dominant systematic uncertainty in low-field measurement is the uncertainty related to the collision with muonium and krypton. To obtain the MuHFS value in vacuum, one need to measure the frequencies at two or more krypton pressures and extrapolate them. The precursor measurements [**?**, **?**] were conducted at pressures more than 0.8 atmosphere (atm). With lower krypton pressure, the muon stopping distribution in the microwave cavity become broader, and it reduces the statistics. By using the new cavity with large volume, we realized the low-pressure measurements without losing significant statistics.

One of the techniques in the MuHFS analysis is "old muonium" method, which is also applied in the precursor measurement at LAMPF [**?**]. The old muonium method narrows the resonance line width by counting positrons from long-lived muoniums, and improves the statistical sensitivity to the resonance line center. The LAMPF beam was DC beam, so they chopped the beam to make quasi-pulsed beam, and lost some of the statistics. Since our beam has pulse structure, there is no need to chop the beam and lose some muons. We successfully applied the method to our measurement, and fully exploits the pulse nature of the muon beam at J-PARC.

4 Outlook

In summary, we have successfully conducted measurements in low krypton gas pressures and used old muonium analysis method. These achievements are applicable to not only the measurement in weak magnetic field but also the measurement in high field. With a new beamline with ten times more intense muon beam which will be available in near future, it is feasible to realize the measurement of MuHFS with unprecedented precision.

References

[1] W. Liu, *et al.*, Phys. Rev. Lett., 82, 711(1999)

[2] D. E. Casperson, *et al.*, Phys. Lett. B59, 4 (1975)

[3] P. Crivelli, Hyperfine Interact., 239, 49 (2018)