Precise spectroscopy of muonium hyperfine structure at J-PARC

2018/06/15 SSP2018
Shun SEO (The University of Tokyo)
for MuSEUM collaboration
Outline

1. Introduction
   • About MuSEUM
   • Why do we use muonium?
   • Contribution to other physics topics

2. Experimental setup

3. Zero-field measurement

4. High-field measurement preparation
MuSEUM collaboration

Muonium Spectroscopy Experiment Using Microwave

Collaborators


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Goal of MuSEUM

- Precise spectroscopy of MuHFS (Muonium Hyperfine Splitting) in zero & high magnetic field
  - Zero field measurement - ongoing
  - High field measurement - in preparation

- World record @LAMPF
  - $\Delta v$ (ZF) = 4.463 3022 (14) GHz (300 ppb)  
  - $\Delta v$ (HF) = 4.463 302 765 (53) GHz (12 ppb)  
  - $\mu_\mu / \mu_p = 3.183 345 13 (39)$ (120 ppb)  

- MuSEUM’s Goal: ten-fold improvement for both experiments
Comparison among Hydrogen-like atoms

Hydrogen
- Proton consists of 3 quarks
- Difficult to calculate $\Delta \nu_{\text{th}}$
- $\Delta \nu_{\text{th}} = 1.420\,403\,1 (8) \text{ GHz}$ (560 ppb)
- $\Delta \nu_{\exp} = 1.420\,405\,751\,766\,7 (8) \text{ GHz}$ (0.6 ppt)

Muonium
- Purely-leptonic
- Long lifetime
- $\Delta \nu_{\text{th}} = 4.463\,302\,891 (272) \text{ GHz}$ (63 ppb)
- $\Delta \nu_{\exp} = 4.463\,302\,765 (53) \text{ GHz}$ (12 ppb)

Positronium
- Large recoil effect
- Short lifetime
- $\Delta \nu_{\text{th}} = 203.391\,69 (41) \text{ GHz}$ (2.0 ppm)
- $\Delta \nu_{\exp} = 203.388\,65 (67) \text{ GHz}$ (3.3 ppm)


Motivation:
The most rigorous validation of the bound-state QED

Comparison among Hydrogen-like atoms

<table>
<thead>
<tr>
<th>Hydrogen</th>
<th>Muonium</th>
<th>Positronium</th>
</tr>
</thead>
<tbody>
<tr>
<td>e− ↓ p</td>
<td>e− ↓ μ+</td>
<td>e− ↓ e+</td>
</tr>
</tbody>
</table>
| Proton consists of 3 quarks  
→ Difficult to calculate $\Delta\nu_{\text{th}}$  
$\Delta\nu_{\text{th}} = 1.420\,403\,1 \pm 8 \text{ GHz} \quad (560 \text{ ppb})$  
$\Delta\nu_{\exp} = 1.420\,405\,751\,7667 \pm 8 \text{ GHz} \quad (0.6 \text{ ppt})$ | Purely-leptonic  
• Long lifetime  
$\Delta\nu_{\text{th}} = 4.463\,302\,891 \pm 272 \text{ GHz} \quad (63 \text{ ppb})$  
$\Delta\nu_{\exp} = 4.463\,302\,765 \pm 53 \text{ GHz} \quad (12 \text{ ppb})$ | Large recoil effect  
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$\Delta\nu_{\text{th}} = 203.391\,69(41) \text{ GHz}$  
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muon anomalous magnetic moment (muon g–2) : $a_\mu$

- More than 3σ discrepancy between theory and experiment

\[ a_\mu(\text{exp}) - a_\mu(\text{theo}) = 268(63)(43) \times 10^{-11} \text{ (from PDG 2017)} \]

$\mu_\mu/\mu_p$: essential parameter for muon g-2 measurement

\[ a_\mu(\text{exp}) = \frac{(g - 2)_\mu}{2} = \frac{R}{\mu_\mu/\mu_p - R} \]

- $R$: Planning 140 ppb measurement at J-PARC and Fermilab
- $\mu_\mu/\mu_p$: 30 ppb ($\Delta\nu$ measurement + the SM calculation)

- 120 ppb in precursor exp. ($\mu_\mu/\mu_p$ measurement)

-> 20 ppb measurement without assuming the SM
Outline

1. Introduction

2. Experimental setup
   - Experiment procedure
   - Apparatus
     - Beamline, RF and gas system, detectors

3. Zero-field measurement

4. High-field measurement preparation
Experiment Procedure

- 100% polarized muon beam (~27 MeV/c)
- Fiber beam monitor
- Gas chamber
- Microwave cavity
- Kr gas
- Magnetic shield (ZF) / Superconducting magnet (HF)
- $\mu^+$
- $e^+$ counter
Experiment Procedure

Magnetic shield (ZF) / Superconducting magnet (HF)

$e^+$ counter

gas chamber

microwave cavity

$e^-$ $\mu^+$

Kr gas

fiber beam monitor
Experiment Procedure

Magnetic shield (ZF) / Superconducting magnet (HF)

$e^+$ counter

gas chamber

microwave cavity

Kr gas

fiber beam monitor

$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

$e^+$

$e^-$
Experiment Procedure

Magnetic shield (ZF) / Superconducting magnet (HF)

gas chamber

microwave cavity

Kr gas

fiber beam monitor

e^+ counter

$e^-$

$\mu^+$

Kr gas
**Experiment Procedure**

- Magnetic shield (ZF) / Superconducting magnet (HF)
- Gas chamber
- Microwave cavity
- Fiber beam monitor
- $e^+ \text{ counter}$
- Kr gas
Experiment Procedure

- Magnetic shield (ZF) / Superconducting magnet (HF)
- Microwave cavity
- Gas chamber
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- $e^+$ counter
Experiment Procedure

Magnetic shield (ZF) / Superconducting magnet (HF)

gas chamber

microwave cavity

Kr gas

fiber beam monitor

$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

$e^+$ counter
Uncertainties of precursor measurements

- Statistical uncertainty was dominant in both Zero & High field measurements.
  - Zero field: Statistical uncertainty was 300 ppb.
    Systematic uncertainty was claimed to be negligible.
  - High field: Error budget is as below.
    **B-field uncertainty was large** in systematic uncertainties.

- Uncertainties in High field measurement (values from W. Liu et al., Phys. Rev. Lett. 82, 711 (1999).)
Beam line (J-PARC MLF)

- To obtain large statistics, we use the world highest intensity pulsed muon beam @J-PARC MLF MUSE.
Microwave cavity and RF system

- Make the MuHFS transition with a microwave cavity.
  - ± 1.5 MHz tuning with a piezo positioner
  - RF power in the cavity ~ 2 W
  - Q factor is about 10,000

Microwave cavity and RF system

- Microwave cavity and RF system
- High-field cavity (TM110, TM210)
- Zero-field cavity (TM110)

- length 230 mm
- diameter 81 mm
- piezo positioner

- length 304 mm
- diameter 187 mm
Gas handling system

- **Systematic uncertainty from Kr gas**
  - **Pressure shift** -> monitored by a capacitance gauge
    - Fluctuation \( \sim 0.002 \text{ Pa/min} \)
  - **Impurity effect** -> monitored by a Q-Mass spectrometer online
    - \( \text{O}_2 < 0.4 \text{ ppm} \)
Positron detector

- High rate capability is required (100 M muons/sec/ch at 1MW)
  - Detector property:
    - Segmented (10 mm×10 mm×3 mmt) Scintillator
    - Hamamatsu MPPC (Si photomultiplier)
    - 240 mm×240 mm area, 1152 ch in total

Outline

1. Introduction

2. Experimental setup

3. Zero-field measurement
   • Magnetic shield
   • Result of 1st measurement
   • The latest measurement

4. High-field measurement preparation
Magnetic shield

- Muon’s spin is depolarized by environmental B field
  - Typically 100 µT in the beam area
- **Magnetic shield** (three layers of permalloy): Suppress B-field
  - Measurement with a fluxgate probe
  - B-field < 350 nT

![Magnetic shield and gas chamber](image)

B-field with and without shield (Log Scale)

( ▲: without Shield, ●: with Shield)
1st Beam time: 2016 June

- The first muonium hyperfine resonance using pulsed beam was observed!
  - Beam power \( \sim 200 \text{ kW} \)
  - Result of measurement in 8 hours:
    \[
    4.463 \, 292 \, (22) \, \text{GHz} \, (4.9 \, \text{ppm})
    \]
    c.f.) Precursor exp. \( 4.663 \, 3022(14) \, \text{GHz} \, (300 \, \text{ppb}) \)
Uncertainty of 1st Beam time

- Statistical uncertainty: **22 kHz** (data taken for 8 hours)
- Systematic uncertainty: **123 Hz**

<table>
<thead>
<tr>
<th>Source</th>
<th>Contribution (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas pressure extrapolation</td>
<td>119</td>
</tr>
<tr>
<td>Gas pressure fluctuation</td>
<td>6</td>
</tr>
<tr>
<td>Microwave power drift</td>
<td>26</td>
</tr>
<tr>
<td>Gas impurity</td>
<td>12</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>0</td>
</tr>
<tr>
<td>Detector pileup</td>
<td>2</td>
</tr>
<tr>
<td>others</td>
<td>9.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>123</strong></td>
</tr>
</tbody>
</table>

by S. Kanda (RIKEN)
Gas pressure extrapolation

- Frequency shift due to an atomic collision between Mu and Kr
  \[ \Delta \nu(P) = (1 + aP + bP^2)\Delta \nu(P = 0) \]
  where \( P \): gas pressure,
  \( a, b \): parameters

- Precursor exp.: Measured with more than 0.8 atm gas

- In the 1st result,
  - Measured with 1 atm gas
  - Extrapolate with 0.8 atm of precursor exp.
Recent upgrades

- To obtain more statistics,
  - **New cavity (TM220 mode) was installed**
    - More muons stop in the cavity
    - Beam power is enhanced to about 400 kW (2018 March)

Upgraded in June 2017

- TM110 Cavity
  - Length: 230 mm
  - Diameter: 81 mm

- TM220 Cavity
  - Length: 300 mm
  - Diameter: 181 mm
The Latest Experiment (2018 Mar & June)

- 2018 March & June: Measured with 0.3, 0.4, 0.55 and 0.7 atm Kr gas
  - Reduce the uncertainty of extrapolation
  - The first time to measure with less than 0.8 atm gas

- Analysis is ongoing
  - We expect a smaller uncertainty than the precursor experiment.

![Image of experiment setup]

![Graph showing resonance with 0.4 atm gas]

Signal \( \frac{[\text{Non-Noff}]}{\text{Noff}} \)

Resonance with 0.4 atm gas - 4,463,302 kHz

Very Preliminary
Outline

1. Introduction

2. Experimental setup

3. Zero-field measurements

4. High-field measurement preparation
   • Shimming B-field
   • Development of NMR probe
Uncertainties of LAMPF experiment

In the precursor exp., **statistical** and **B-field uniformity** uncertainties were dominant.

- We reduce statistical uncertainty with the intense pulsed beam
- Need to improve B-field!

Uncertainties in High-field measurement

Reduction of the B-field uncertainty

- Stability and homogeneity of B-field
  - Stability ~ 3 ppb/h
  - Homogeneity: shimmed

- Precise field probes
  - Fixed probe for stability
  - Mapping probe for homogeneity
  - Absolute probe for calibration of other probes
Shimming B-field

- Shimming with iron plates (5 & 25 µm thickness) in 24 pockets × 24 trays = 576 pockets inside the magnet
- Position and volume of plates were determined by Singular Value Decomposition (SVD) method
- Improved **homogeneity to 0.80 ppm** of 1.7 T in target area (mapped with single NMR probe)
NMR probe

- **Nuclear Magnetic Resonance (NMR) probe**
  - The most precise method for $B > 1$ T
  - Determine B-field by observing RF absorption of the proton in pure water

- **Continuous Wave NMR (CW-NMR) probe**
  - Input constant RF
  - Sweep the B-field by using modulation coils

\[ \Delta E = \nu = \gamma B \]
Test of CW-NMR probe and Cross calibration

- Development of CW-NMR probe
  - Convert analog signal to digital (ppm -> ppb precision)
  - Select materials to cancel the susceptibility each other
  - $61,717,644.5 \pm 0.9$ Hz ($15$ ppb) @ $1.45$ T

- 1st Cross calibration with a NMR probe of Fermilab g-2 group (2017 Mar)
  - Fermilab probe: another NMR method (Pulse NMR)
  - 20 ppb agreement at blind analysis between two probes (preliminary)
### Systematic uncertainty (prospect)

<table>
<thead>
<tr>
<th>Source</th>
<th>Accuracy</th>
<th>v12,v34</th>
<th>HFS</th>
<th>$\mu_\mu/\mu_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnetic Field</strong></td>
<td>20 ppb</td>
<td></td>
<td>0.0 ppb</td>
<td>10 ppb</td>
</tr>
<tr>
<td>RF power</td>
<td>0.2%</td>
<td>4Hz</td>
<td>0.8 ppb</td>
<td>8 ppb</td>
</tr>
<tr>
<td>Kr gas temp.</td>
<td>0.2 K</td>
<td>&lt; 2Hz</td>
<td>0.4 ppb</td>
<td>4 ppb</td>
</tr>
<tr>
<td>Kr gas pressure</td>
<td>0.01 hPa</td>
<td>1Hz</td>
<td>0.2 ppb</td>
<td>0 ppb</td>
</tr>
<tr>
<td>H impurity</td>
<td>&lt;50 ppm</td>
<td>1Hz</td>
<td>0.5 ppb</td>
<td>0 ppb</td>
</tr>
<tr>
<td>Quadratic pressure dependence</td>
<td></td>
<td>5Hz</td>
<td>1.0 ppb</td>
<td>5 ppb</td>
</tr>
<tr>
<td>Muonium Position (x,y)</td>
<td>1mm</td>
<td>3 Hz</td>
<td>0.6 ppb</td>
<td>6 ppb</td>
</tr>
<tr>
<td>Muonium position (z)</td>
<td>1mm</td>
<td>&lt; 1 Hz</td>
<td>0.2 ppb</td>
<td>2 ppb</td>
</tr>
<tr>
<td>Beam intensity</td>
<td>1e-4</td>
<td>&lt; 1 Hz</td>
<td>0.2 ppb</td>
<td>2 ppb</td>
</tr>
<tr>
<td>Detector pile up</td>
<td></td>
<td>2.8 Hz</td>
<td>0.5 ppb</td>
<td>3 ppb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.3 Hz</td>
<td>&lt;0.1 ppb</td>
<td>1 ppb</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Without ab.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>With ab.</td>
</tr>
</tbody>
</table>

**Total systematic uncertainty:** MuHFS ~2 ppb, $\mu_\mu/\mu_p$ ~20 ppb

**We hope this experiment will be held in 2019**
Summary

• Precise measurement for muonium HFS is the most rigorous validation of the bound-state QED.

• MuSEUM group measured MuHFS at zero magnetic field.
  • For the 1st measurement, we obtained the value of MuHFS and its uncertainty. **4.463 292 (22) GHz (4.9 ppm)**
  • We measured MuHFS with the larger cavity and lower gas pressures to reduce the uncertainties.

• For high-field measurement, R&D is ongoing.
  • Shimming B-field in the magnet
  • Development of precise magnetic probes

Thank you for listening!
Backup slides
Breit-rabi diagram

- Hamiltonian describing energy splitting of the muonium $1^2S_{1/2}$ state

$$\mathcal{H} = \hbar \Delta \nu_{\text{HFS}} \vec{I} \cdot \vec{J} + g_J \mu_B \vec{J} \cdot \vec{H} - g'_\mu \mu_B^e \vec{I} \cdot \vec{H}$$

- Spin states splits to substructure

$$\nu_{12} = -\frac{\mu_B^\mu g'_\mu H}{\hbar} + \frac{\Delta \nu_{\text{HFS}}}{2} \left[ (1 + x) - \sqrt{1 + x^2} \right]$$

$$\nu_{34} = \frac{\mu_B^\mu g'_\mu H}{\hbar} + \frac{\Delta \nu_{\text{HFS}}}{2} \left[ (1 - x) + \sqrt{1 + x^2} \right]$$

$$\left( x \propto H \right)$$

- In the limit of a strong magnetic field ($x \gg 1, x \sim 10.7$ with $1.7$ T)

$$\nu_{12} + \nu_{34} = \Delta \nu_{\text{HFS}}$$

$$\frac{\mu_\mu}{\mu_p} = \frac{1}{2} \left( \frac{\nu_{34} - \nu_{12}}{\nu_p} \right) \frac{g_\mu}{g'_\mu}$$

$$\frac{m_\mu}{m_e} = \frac{g_\mu}{2} \frac{\mu_p}{\mu_\mu} \frac{\mu_B^e}{\mu_p}$$

$1.7$ T Measurement

Direct MuHFS measurement

$\Delta \nu_{\text{HFS}} = \nu_{34} + \nu_{12}$

$\mu_\mu/\mu_p \propto \nu_{34} - \nu_{12}$
Why 1.7 T?

- For TM_{mn0} mode, the resonance frequency of a cavity is in inverse proportion to its radius.
- To measure both $\nu_{12}$ and $\nu_{34}$, require that $\nu_{12}/\nu_{34} = f_{110}/f_{210}$. $\Rightarrow B=1.55$ T.
- Considering cavity perturbations by tuning bars, optimum $B$ is 1.7 T.
**μ_μ/μ_p uncertainty for muon g-2**

- **μ_μ/μ_p : essential parameter for muon g-2 measurement**

\[ a_\mu(\text{exp}) = \frac{(g - 2)_\mu}{2} = \frac{R}{\mu_\mu/\mu_p - R} \]

- **R**: Planning 140 ppb measurement at J-PARC and Fermilab
- **μ_μ/μ_p**: 30 ppb (HFS result + the SM calculation)
  - \( \rightarrow 10 \text{ ppb measurement without assuming the SM} \)

In the BNL experiment, \( \Delta \nu_{\text{HFS}} \) and calculation assuming the SM is used

\[ \Delta \nu_{\text{HFS}} = \frac{16}{3} \alpha^2 c R_\infty \frac{m_e}{m_\mu} \left[ 1 + \frac{m_e}{m_\mu} \right]^{-3} + \text{corrections} \]

extract \( m_e/m_\mu \)

\[ \frac{\mu_\mu}{\mu_p} = \left( \frac{g_\mu}{2} \right) \left( \frac{m_e}{m_\mu} \right) \left( \frac{\mu_B^e}{\mu_p} \right) \]
Contribution to other physics topics

- Lorentz violating background field can be detected as sidereal oscillation of MuHFS

- Constraint on Standard Model Extention (SME) parameters
  
  A. H. Gomes, V. A. Kostelecky and A. J. Vargas, PRD 90 076009 (2014)
Methods of Mu production for MuHFS exp.

- Beam foil
  - cannot apply to ours
  - appliable to the measurement of lamb shift transition \((2S_{1/2} \rightarrow 2P_{1/2})\)
- SiO\(_2\) powder
  - formed in vacuum (unlike gas target)
  - both the production rate and the polarization are insufficient
  - cannot distinguish between signals of muon decay in vacuum and in a powder target.

![Diagram showing beam foil, SiO\(_2\) powder, and gas target with their respective yields and polarizations](image)
Why Kr gas?

- Noble gases are suitable to avoid chemical reactions and depolarizing collisions.

\[ \text{Ionization E of Kr} = 14.00 \text{ eV} \]

\[ \text{Threshold energy} = 0.46 \text{ eV} \rightarrow \text{low energy Mu} \]

- Kr -> Mu fraction \( f_{\text{Mu}} \sim 100 \% \rightarrow \text{ideal} \)

### Table: Comparison of atoms or molecules

<table>
<thead>
<tr>
<th>atom or molecule</th>
<th>threshold energy (eV)</th>
<th>pressure (atm)</th>
<th>( f_{\text{Mu}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>+11.04</td>
<td>1.2–3.1</td>
<td>0(1)</td>
</tr>
<tr>
<td>Ne</td>
<td>+8.02</td>
<td>1.2</td>
<td>7(5)</td>
</tr>
<tr>
<td>Ar</td>
<td>+2.22</td>
<td>1.0–2.8</td>
<td>74(4)</td>
</tr>
<tr>
<td>Kr</td>
<td>+0.46</td>
<td>0.4–0.95</td>
<td>100(5)</td>
</tr>
<tr>
<td>Xe</td>
<td>-1.41</td>
<td>0.4–0.65</td>
<td>100(4)</td>
</tr>
<tr>
<td>( \text{N}_2 )</td>
<td>+2.0</td>
<td>1.0–2.4</td>
<td>84(4)</td>
</tr>
<tr>
<td>( \text{CH}_4 )</td>
<td>-0.6</td>
<td>1.2–3.0</td>
<td>87(4)</td>
</tr>
</tbody>
</table>
Muon decay

- Angular distribution of decay $e^+$ is

$$N(y, \theta) = \frac{\gamma}{2\pi} y^2 \{(3 - 2y) + (2y - 1)\cos \theta\}$$

where

- $y$ : $e^+$ momentum in units of $\frac{1}{2}m_\mu c$
- $\theta$ : angle between $\mu$ spin direction and $e^+$ momentum

- maximum momentum of decay $e^+$ is 52.83 MeV/c
**TM_{nm0} mode of cavity**

- Along z axis: $E_z$ is constant, and $B_z=0$
- A cross-sectional view of cavity
  - Red: electric field
  - Green: B-field
Power measured by a monitoring antenna

by S. Kanda (RIKEN)
Other B-field effect in zero field exp.

- Only the transitions between 1-4 and 3-4 contribute to the signal
- $\nu_{14}$ and $\nu_{34}$ shift by 14 Hz/nT in opposite directions

$\rightarrow$ Broadening effect on the signal

B~100 nT $\rightarrow$ this effect is negligible

Energy-diagram of muonium in ground state in very small B-field
Fluxgate probe

- Triaxial fluxgate magnetic probe (made by MTI Corp., FM-3500)
- 0.5 nT resolution for each axis, linearity 5 nT