Spectroscopy of Muonium Hyperfine Structure at J-PARC

Yasuhiro UENO, from RIKEN, for MuSEUM collaboration
Agenda

➤ Introduction
  - Motivation
  - Procedure
  - Apparatus

➤ Recent Measurements at low B field
  - Result with lower gas pressure

➤ R&D for future
  - Mixture gas
  - Magnet for high field measurement
  - Time differential method
Muonium Spectroscopy Experiment Using Microwave

- Muonium: $\mu^+&e^-$, no nuclear structure, calculation with high precision
- Two major motivations
  - Test of the bound-state QED
  - Most precise determination of the muon magnetic moment (synergy with the muon $g-2$ experiment)

Experiment: MuSEUM

<table>
<thead>
<tr>
<th>HFS</th>
<th>H</th>
<th>Mu</th>
</tr>
</thead>
<tbody>
<tr>
<td>relative uncertainty of theory</td>
<td>560 ppb</td>
<td>115 ppb</td>
</tr>
</tbody>
</table>
Test of the Bound-State QED

- $\nu_{\text{exp}} = 4\,463\,302\,765\,(53)\,\text{Hz}$
  - Experiment at LAMPF (1999)

- $\nu_{\text{th}} = 4\,463\,302\,891\,(511)(70)(2)\,\text{Hz}\ (m_\mu/m_e)(\text{QED})(\alpha)$
  - By Eides

- Effort in QED calculation for <10 Hz precision is in progress by Eides et al.

- Combined with independent muon mass determination
  - $\rightarrow$ test of the bound-state QED

- Muonium Laser Spectroscopy
  - planned at PSI (Paul Scherrer Institute)

- Improve Muonium 1s-2s by a factor of 1000

- Determine the muon mass with 1 ppb
  - (more than a factor of 100 improvement)

P. Crivelli, Hyperfine Interact., 239, 49 (2018)
Muon Magnetic Moment and Muon $g-2$

$\alpha_\mu = \frac{R}{\mu_\mu \mu_\nu - R}$

$a_\mu$: muon $g-2$
(anomalous magnetic moment)

26 ppb (QED assumed) or 120 ppb (direct determination)

MuSEUM aim: 10 ppb (direct)

Muon Ring Experiment at BNL
GW Bennett et al., PRD 73 072003 (2006)

SM Theory including QED, Weak, Hadronic contributions

$R$ determined by muon ring Experiment:
Current: 540 ppb
Future: <140 ppb

Talk by D. Nomura

GW Bennett et al., PRD 73 072003 (2006)


Talks by S. Corrodi, and S. Lee

new experiments by Fermilab and J-PARC
MuSEUM: Zeeman Splitting

“Zero” Field (very low B field)
4.463 3022 (14) GHz

High Field (at 1.7 T)

$\nu_{12} + \nu_{34} = \Delta \nu$
$\nu_{12} - \nu_{34} \propto \mu/\mu_p$

4.463 302 765 (53) GHz

Both world records at Los Alamos Meson Physics Facility (LAMPF)

Their precision are statistically limited, we need more muons!
The precision of the precursor experiments were limited by statistics.

We use the most intense pulsed muon beam at J-PARC MLF.

**Precursor Measurement at LAMPF**

- **LAMPF (DC beam)**
  - 10 ms
  - 0.65 ms

**Our Measurement at J-PARC MLF**

- **J-PARC/MLF (pulsed beam)**
  - 40 ms

Be careful when chopping the beam:

- **Beam is chopped**
  - 3.9 us
  - 9.9 us

After chop:
- **2 × 10^6 µ+/sec**

J-PARC/MLF beam has a double-pulse structure:
- **FWHM ~ 100 ns**
- **>10^8 µ+/sec (H-Line 1 MW)**
Procedure of Measurement

Magnetic Shield/Superconducting Magnet

- positron counter
- gas chamber
- microwave cavity
- spin-polarized $\mu^+$
- pulsed muon beam (4 MeV)
- Kr gas
- 300 mm
- 180 mm
Procedure of Measurement

- Pulsed muon beam (4 MeV)
- Gas chamber
- Microwave cavity
- Kr gas
- Magnetic shield/superconducting magnet
- Positron counter
Procedure of Measurement

Magnetic Shield/Superconducting Magnet

Microwave OFF resonance

Pulsed muon beam (4 MeV)

\[ \mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu \]  Parity violating decay
Procedure of Measurement

- Pulsed muon beam (4 MeV)
- Microwave cavity
- Transition
- Microwave ON resonance
- Magnetic Shield/Superconducting Magnet
- Positron counter
- Kr gas
Procedure of Measurement

Magnetic Shield/Superconducting Magnet

Microwave ON resonance

Microwave cavity

Kr gas

transition

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

positron counter

pulsed muon beam (4 MeV)
Shield for Magnetic Field

➤ Geomagnetic field and stray field from the beam line magnets

➤ **Three-layer permalloy shields** suppress the magnetic field (1/1000 suppression)

➤ Field measurement by flux-gate probe

Comparison of field with and without the shield

- **Without shield**
  - Max 108 μT
  - Min 82 μT

- **With shield**
  - Max 71 nT
  - Min 33 nT
Gas Chamber and Microwave Cavity

- Gas pressure monitored by a capacitance gauge
- Impurity measured by Q-MASS spectrometer
- Cavity Q factor ~10000, Input power ~1 W
- Cavity resonance frequency is tunable: 4463 ± 1 MHz
Positron Detector

Plastic Scintillator + MPPC(SiPM) + Kalliope read out board

- Unit cell: 10 mm × 10 mm
- Covers 240 mm × 240 mm
- Two layers, 1152 ch in total

Work by S. Kanda (RIKEN)
Agenda

➤ Introduction
  - Motivation
  - Procedure
  - Apparatus

➤ Recent Measurements at low B field
  - Result with lower gas pressure

➤ R&D for future
  - Mixture gas
  - Magnet for high field measurement
  - Time differential method
First Result in 2016

- Measurement in 2016 at zero field at D-Line (Beam Power 200 kW) at Kr pressure = 1.0 atm
- First result: 4.463 292(22) GHz
  precision: 22 kHz, statistically limited (world record: 1.4 kHz)
- First measurement of MuHFS using a pulsed muon beam
MuHFS shifts in Kr, we need a value in vacuo to compare with theory

Measurement at lower Kr pressure points (0.3-1.0 atm) in 2018, 2019 (D-Line, with improved beam power ~500 kW)

(Measurement at less than 0.8 atm has not been done before)
Extrapolated the results to obtain the MuHFS in vacuo

The uncertainty is comparable to the world record (1.4 kHz)

Our result is consistent with the theory and the precursor experiment
Uncertainty in Weak Field Measurement

- Current statistical uncertainty: 1400 Hz in 3 days
  With new beamline and 100-days run: 40 Hz is expected
  Further improvement is achievable

- Systematic uncertainty: currently 112 Hz, <10 Hz in future

Systematic uncertainty table

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Uncertainty [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Gauge</td>
<td>79</td>
</tr>
<tr>
<td>Pressure Fluctuation</td>
<td>24</td>
</tr>
<tr>
<td>Quadratic Term</td>
<td>(2)</td>
</tr>
<tr>
<td>Frequency Reference</td>
<td>45</td>
</tr>
<tr>
<td>Power Drift</td>
<td>60</td>
</tr>
<tr>
<td>Muon Beam</td>
<td>6</td>
</tr>
<tr>
<td>Others</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Total</td>
<td>112</td>
</tr>
</tbody>
</table>
Agenda

➤ Introduction
  - Motivation
  - Procedure
  - Apparatus

➤ Recent Measurements at low B field
  - Result with lower gas pressure

➤ R&D for future
  - Mixture gas
  - Magnet for high field measurement
  - Time differential method
## Systematic Uncertainties for High Field

<table>
<thead>
<tr>
<th>Source</th>
<th>Specification</th>
<th>$\Delta v$</th>
<th>$\mu_\mu/\mu_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>B field</strong></td>
<td></td>
<td>0</td>
<td>26 ppb</td>
</tr>
<tr>
<td>RF stability</td>
<td>0.02%</td>
<td>0.8 ppb</td>
<td>8 ppb</td>
</tr>
<tr>
<td>Collision with Kr</td>
<td></td>
<td>1.0 ppb</td>
<td>5 ppb</td>
</tr>
<tr>
<td>Kr Temperature</td>
<td>0.2 K</td>
<td>0.4 ppb</td>
<td>4 ppb</td>
</tr>
<tr>
<td>Detector pile up</td>
<td>&lt; 0.5 ppb</td>
<td></td>
<td>3 ppb</td>
</tr>
<tr>
<td>Others</td>
<td>&lt; 0.8 ppb</td>
<td></td>
<td>7 ppb</td>
</tr>
<tr>
<td><strong>Overall</strong></td>
<td>&lt; 1.6 ppb (8 Hz)</td>
<td></td>
<td>29 ppb</td>
</tr>
</tbody>
</table>
Systematic uncertainty from the collisional shift is dominant

- There are two major effects from the collision

- Pauli exclusion effect (Short-range) -> positive shift

- Van der Waals interaction effect (Long-range) -> negative shift dominant for large Z atom


- He-Kr mixture gas can reduce the collisional shift

- From Hydrogen HFS, Kr:He=4.8:10.4=Kr32% is ideal

H-HFS pressure dependence in noble gas


<table>
<thead>
<tr>
<th>System</th>
<th>Short-range</th>
<th>Long-range</th>
<th>Total</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-He</td>
<td>2.130</td>
<td>-0.952</td>
<td>1.178</td>
<td>4.80</td>
</tr>
<tr>
<td>H-He</td>
<td>2.679</td>
<td>-0.950</td>
<td>1.729</td>
<td>4.80</td>
</tr>
<tr>
<td>H-Ne</td>
<td>2.059</td>
<td>-1.952</td>
<td>0.107</td>
<td>2.88</td>
</tr>
<tr>
<td>H-Ar</td>
<td>4.556</td>
<td>-7.827</td>
<td>-3.081</td>
<td>-4.77</td>
</tr>
<tr>
<td>H-Kr</td>
<td>7.525</td>
<td>-11.842</td>
<td>-4.317</td>
<td>-10.40</td>
</tr>
<tr>
<td>H-Xe</td>
<td>10.922</td>
<td>-17.560</td>
<td>-6.638</td>
<td>-20.00</td>
</tr>
</tbody>
</table>
• Used mixture gas Kr-He to suppress the extrapolation uncertainty
• Confirmed Mu formation in Kr-He gas, and observed MuHFS resonance

resonance with Kr 20% gas at 1.0 atm

Work by S. Seo (Univ. of Tokyo)
## Systematic Uncertainties for High Field

<table>
<thead>
<tr>
<th>Source</th>
<th>Specification</th>
<th>$\Delta v$</th>
<th>$\mu_\mu/\mu_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B field</td>
<td>0</td>
<td>26 ppb</td>
<td></td>
</tr>
<tr>
<td>RF stability</td>
<td>0.02%</td>
<td>0.8 ppb</td>
<td>8 ppb</td>
</tr>
<tr>
<td>Collision with Kr</td>
<td>1.0 ppb</td>
<td></td>
<td>5 ppb</td>
</tr>
<tr>
<td>Kr Temperature</td>
<td>0.2 K</td>
<td>0.4 ppb</td>
<td>4 ppb</td>
</tr>
<tr>
<td>Detector pile up</td>
<td>&lt; 0.5 ppb</td>
<td></td>
<td>3 ppb</td>
</tr>
<tr>
<td>Others</td>
<td>&lt; 0.8 ppb</td>
<td></td>
<td>7 ppb</td>
</tr>
<tr>
<td>Overall</td>
<td>&lt; 1.6 ppb (8 Hz)</td>
<td></td>
<td>29 ppb</td>
</tr>
</tbody>
</table>
Superconducting Magnet for 1.7 T Field

- Time stability: \textbf{3 ppb/hour} over 10 days period (required stability 100 ppb/h) \hspace{1cm} By K. Sasaki and M. Abe (KEK)

- Required uniformity is 1 ppm in a rugby-ball sized volume by shimming we achieved \textbf{0.3 ppm}
NMR Magnetometer

➤ Proton NMR (Nuclear Magnetic Resonance) in pure water

➤ Cross-check measurement at 1.45 and 1.7 T with NMR probes used in Fermilab muon $g-2$ experiment


Work by K. Sasaki, H. Yamaguchi (KEK) and T. Tanaka (Univ. of Tokyo)
MuHFS determined by fitting the time-dependent signal of muon spin flip (Rabi oscillation)

No need to take data at many microwave frequency points a method immune to the systematic uncertainty from the microwave power dependence on frequency

Mu HFS is obtained by only one detuning frequency data
First result obtained by time differential method

Promising method to improve the precision

By S. Nishimura (KEK)
Summary and Prospect

- MuSEUM
  Test of the bound-state QED
  Determination of muon magnetic moment
  -synergy with muon g-2

- Recent measurement with lower Kr gas pressures at low B field consistent with theory and the precursor experiment

- R&D for future experiment
  First measurement using Kr-He mixture gas
  Magnet and magnetometer development for high field measurement
  First analysis using time differential method

- MuHFS 2 ppb, $\mu_\mu/\mu_p$ 30 ppb is achievable
  (a factor of 10 improvements from the precursor experiment)
  Further improvement is in progress
Thank you!
Silicon Strip Sensor

- Developed for muon $g$-2 J-PARC experiment
- Capable of high-rate counting; R&D for H-Line measurement in future
- There was stray magnetic field from the detector board; made a permalloy shield for the detector
- Performed satisfactory in beam time on June 2019
### Uncertainty in Weak Field Measurement

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Uncertainty [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Gauge</td>
<td>79</td>
</tr>
<tr>
<td>Pressure Fluctuation</td>
<td>24</td>
</tr>
<tr>
<td>Quadratic Term</td>
<td>(2)</td>
</tr>
<tr>
<td>Frequency Reference</td>
<td>45</td>
</tr>
<tr>
<td>Power Drift</td>
<td>60</td>
</tr>
<tr>
<td>Muon Beam</td>
<td>6</td>
</tr>
<tr>
<td>Others</td>
<td>&lt; 1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>112</strong></td>
</tr>
</tbody>
</table>

**in future [Hz]**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>&lt;1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>&lt;1</strong></td>
<td><strong>&lt;1</strong></td>
</tr>
</tbody>
</table>

10
## Silicon Strip Detector

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor type</td>
<td>single-sided, p+ on n</td>
</tr>
<tr>
<td>Size</td>
<td>98.77 mm × 98.77 mm</td>
</tr>
<tr>
<td>Active area</td>
<td>97.28 mm × 97.28 mm</td>
</tr>
<tr>
<td>Strip pitch</td>
<td>0.19 mm</td>
</tr>
<tr>
<td>Strip length</td>
<td>48.575 mm</td>
</tr>
<tr>
<td># of strips</td>
<td>512 × 2 blocks</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.32 mm</td>
</tr>
</tbody>
</table>

- Silicon strip detector
- Readout chips (SLiT128A, 128 ch/chip)
- Developed for J-PARC g-2/EDM experiment
- Highly-segmented
- Greater high rate capability
- S/N ∼ 21
Microwave Cavity and System

- TM220 mode cavity, $Q = 10000$
- Typical input power: 1 W
- Power stability is monitored

Signal Generator → Amplifier → cables & feedthrough → Power monitor 1

Cavity: pick up

Power monitor 2
Lorentz (CPT) Invariance

➤ Lorentz (CPT) violating background field can be detected as **sidereal** (or annual) oscillation of the hyperfine frequency

➤ Constraint on Standard Model Extension (SME) parameters

A. H. Gomes, V. A. Kostelecky and A. J. Vargas, PRD 90 076009 (2014)
Conventional Method

➤ Integrate all the signal

(number of detected positrons $\propto$ time integral of state amplitude)

![Graph showing the relationship between RF frequency and count](image)
Old Muonium Method

- Line narrowing technique by the analysis using signals from a delayed time window; Long life time hence narrow natural width.
Passive Shimming Technique

- Required field uniformity: 1 ppm
- In addition to shimming coil, shimming by small iron plates is important
- The positions of the iron plates can be calculated by the Singular Value Decomposition Method

Plate Volume:
Thick: 0.325 cc
Thin: 0.065 cc
Shimming

Field uniformity is improved by shimming using iron-plate. We have succeeded in obtaining required uniformity < 1 ppm.

Peak-to-peak: 1000 ppm

Peak-to-peak: 0.80 ppm
By iron-plate shimming, uniformity 1000 ppm → 0.8 ppm
(required uniformity: 1 ppm)