New Precise Measurements of Muonium Hyperfine Structure at J-PARC MUSE

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What is Muonium?

Muon:
- Elementary particle (lepton)
- 200 times heavier than an electron
- Lifetime of 2.2 microseconds.

Muonium:
- Bound state of a positive muon and an electron.
- Hydrogen-like atom free from the finite size of the nucleon.
- Most suitable for validation of bound state quantum electrodynamics (QED).
- Theoretical and experimental precision of the hyperfine structure comparable.

Precision of the hyperfine structure (HFS, $\Delta\nu$):

<table>
<thead>
<tr>
<th>Hydrogen-like atom</th>
<th>Experiment</th>
<th>Theory</th>
<th>$\frac{(\Delta\nu_{\text{theo}} - \Delta\nu_{\text{exp}})}{\Delta\nu_{\text{exp}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>0.2 ppt</td>
<td>1.2 ppm</td>
<td>$(-0.45 \pm 1.2)$ ppm</td>
</tr>
<tr>
<td>Positronium</td>
<td>3.3 ppm</td>
<td>2.0 ppm</td>
<td>$(15 \pm 4)$ ppm</td>
</tr>
<tr>
<td>Muonium (Zero-Field)</td>
<td>310 ppb</td>
<td>61 ppb</td>
<td>$(150 \pm 320)$ ppb</td>
</tr>
<tr>
<td>Muonium (High-Field)</td>
<td>12 ppb</td>
<td>61 ppb</td>
<td>$(23 \pm 62)$ ppb</td>
</tr>
</tbody>
</table>
Muonium Hyperfine Structure

\[ \mathcal{H} = \hbar \Delta \nu I_{\mu} \cdot J - \mu_B g'_{\mu} I_{\mu} \cdot H + \mu_B^e g_J J \cdot H \]

\( \Delta \nu_{\text{HFS}} \): Mu Hyperfine Structure

\[ \Delta \nu_{\text{HFS}} \approx 4463 \text{ MHz} \]

Pure lepton
= point particle

Zeeman Splitting

Breit-Rabi diagram

\( (F, M_F) \)

\( (1, 1) \)

\( (1, 0) \)

\( (1, -1) \)

\( (0, 0) \)

\[ \nu_{12} + \nu_{34} = \Delta \nu_{\text{HFS}} \]

\[ \nu_{12} - \nu_{34} \propto \frac{\mu_{\mu}}{\mu_p} \propto \frac{m_{\mu}}{m_p} \]

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Purpose of MuSEUM

• Measure the two RF resonances ($\nu_{12}$ and $\nu_{34}$) at high magnetic field (1.7 T), and $\Delta \nu$ directly at zero field.
  – Different systematics from the magnetic field (negligible at ZF)

• Muonium ground state HFS ($\Delta \nu_{\text{HFS}}$)
  – Precise test of bound-state QED
  – Current uncertainty: 12 ppb
  – Test of CPT and Lorentz Invariance

• Muon magnetic moment relative to that of the proton
  – Basic property of muon
  – Current uncertainty: 120 ppb
  – Basic input parameter for the muon g-2 experiment

We aim to improve the uncertainties of both quantities by a factor of 10, taking advantage of the high intensity beam at J-PARC/MUSE.
Most Precise Test of Bound State QED

**Experiment:**

$\nu_{\text{HFS}}(\text{exp})$ 4463.302 765 (53) MHz  [12 ppb]

$\mu_\mu/\mu_p = 3.18334524(37)$  [120 ppb]

$m_\mu/m_e = 206.768277(24)$  [120 ppb]

**Theory:**

$\nu_{\text{HFS}}(\text{theory})$ 4463.302 868 (271) MHz  [61 ppb]

$\nu_{\text{HFS}}(\text{QED})$ 4463.302 720 (253) (98) (3) MHz

$\nu_{\text{HFS}}(\text{weak})$ -65 Hz

$\nu_{\text{HFS}}(\text{had. v.p.})$ 232 (1) Hz

$\nu_{\text{HFS}}(\text{had. h.o.})$ 5 (2) Hz

QED calculation: **Effort for 10 Hz accuracy in progress (by Eides et al.)**

Determination of the Muon Mass

\[ \frac{\mu}{\mu_p}, a_\mu, \frac{\mu_p}{\mu_B} \rightarrow \frac{m_\mu}{m_e} \]

Muon mass (CODATA2016) determined by MuHFS (LAMPF 1999)
Why Mu HFS measurement is so important?

\( g-2 \) E821(BNL) 0.5ppm 3\( \sigma \) deviation

- Measurement of the deviation of muon spin direction (\( \omega_s \)) and muon momentum direction (\( \omega_c \)) \( \omega_a \propto (g-2)/2 = a_\mu \)

\[ \Rightarrow \tilde{\omega}_a = \frac{e}{mc} \left[ a_\mu \vec{B} - \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \beta \times \vec{E} \right] \]

\( a_\mu \) an independent precise muon mass measurement is required!

- The ratio to the proton NMR frequency is important!

\[ \Rightarrow \frac{a_\mu}{\lambda - R} = \frac{\omega_a}{\omega_p} \]

From g-2 storage ring

From Muonium HFS

\[ \frac{\omega_a}{\omega_L(\mu)} = \frac{a_\mu \frac{eB}{mc}}{g_\mu \left( \frac{eB}{2mc} \right) \left( \frac{g_\mu}{2} \right)} = \frac{a_\mu}{1 + a_\mu} \]

\[ \frac{\omega_a}{\omega_L(p)} \frac{\omega_L(\mu)}{\omega_L(p)} = \frac{\omega_a}{\omega_p} \frac{\mu_p}{\mu_\mu} = R/\lambda \]

\( \frac{\mu_\mu}{\mu_p} \) accuracy from direct measurement of 120 ppb.

Experimental Layout

1. Muonium formation
2. RF spin flip
3. Positron asymmetry

Upstream Counter

Experimental Procedure

Online Beam Monitor
2D cross-configured fiber hodoscope

Kr Gas Chamber

Polarized muon beam 100% →

Muonium

decay e+

1.7 T Magnet

RF Cavity

RF Tuning Bar

Positron Counter
Segmented scintillation counter
Improvement of statistics

LAMPF Experiment

<table>
<thead>
<tr>
<th>Statistics</th>
<th>$\delta(\Delta\nu)$</th>
<th>$\delta(\mu_\mu/\mu_p)$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kr Density/Pressure</strong></td>
<td>10.9 ppb</td>
<td>107 ppb</td>
</tr>
<tr>
<td>Muon stopping</td>
<td>4.4 ppb</td>
<td>56 ppb</td>
</tr>
<tr>
<td>RF power</td>
<td>1.0 ppb</td>
<td>13 ppb</td>
</tr>
<tr>
<td></td>
<td>0.96 ppb</td>
<td>11 ppb</td>
</tr>
</tbody>
</table>

MuSEUM Improvements:

- **Statistics:**
  - LAMPF: DC $10^7$/s
  - total $10^{13}$
  - J-PARC/MUSE: **Pulsed $1 \times 10^8$/s**
  - H-Line
  - total $2 \times 10^{15}$

- **Systematics:**
  - magnetic field accuracy & uniformity
  - pressure dependence (longer cavity lower pressure)
  - muon stopping distribution measurement
  - RF power stability

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J-PARC Muon Science Facility (MUSE)

**H-Line**: for particle and atomic physics large scale experiments, “precision frontier”.

Higher intensity tunable (4 – 50 MeV) $\mu^+$ & $\mu^-$ beam. 
(Exp.: MuSEUM, Deeme, g-2, ...)

**Beamlines in Operation**

**S-Line**: Surface muon ($\mu^+$)
Slow (4 MeV) beam for condensed matter physics.

**D-Line**: Decay muon ($\mu^+$ & $\mu^-$)
Slow (50 keV) – fast (50 MeV) beam, general purpose.

**U-Line**: Ultra-slow muon ($\mu^+$)
Ultra-slow (0.1 – 30 keV) beam for near-surface condensed matter physics, chemistry, etc.
MRI Magnet for High-Field Experiment

Second-hand 2.9 T MRI magnet

CW-NMR Field Monitoring System

Field Homogeneity (after shimming)

Spheroid:
- r=100 mm, z=300 mm

1.4 ppm p-p

18 ppb

Long Term Stability

64 Hz / 9.7 days

0.003 ppm /h

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RF Cavity for High Field Experiment

\[ \nu_{12} = 1.906 \text{ GHz} \]
\[ \nu_{34} = 2.556 \text{ GHz} \]

**Test Cavity**

<table>
<thead>
<tr>
<th>Modes</th>
<th>Q (measured)</th>
<th>Q (simulation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM110</td>
<td>11,300</td>
<td>29,700</td>
</tr>
<tr>
<td>TM210</td>
<td>8,050</td>
<td>28,900</td>
</tr>
</tbody>
</table>

MWS simulation

3D CAD

Q Value
Positron Counter (1): Scintillation Position Detector

Kanda, Kojima

MPPC (Multi-Pixel Photon Counter)
1.3 mm x 1.3 mm active area
(Hamamatsu)

Plastic scintillator + MPPC + Kaliope readout circuit

Segmented scintillation detector

- Scintillation counter with SiPM readout
- Unit cell: 10 mm x 10 mm x 3 mm
- Area: 240 mm x 240 mm
- 24x24 segments x 2 layers = 1152 ch
- High-rate capability required
- Pileup loss at 3 MHz/ch ~ 2%

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### Positron Counter (2): 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>No. of strips</td>
<td>512 x 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
- High-rate capability
- S/N ~ 21
## Preliminary Systematic Error (HF)

<table>
<thead>
<tr>
<th></th>
<th>Accuracy</th>
<th>$\nu_{12}$ and $\nu_{34}$</th>
<th>$\delta(\Delta \nu_{\text{HFS}})$</th>
<th>$\delta(\mu_{\mu}/\mu_p)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Field*</td>
<td>30 ppb</td>
<td></td>
<td>0.0 ppb</td>
<td>15 ppb</td>
</tr>
<tr>
<td>RF power</td>
<td>0.2 %</td>
<td>4 Hz</td>
<td>0.8 ppb</td>
<td>8 ppb</td>
</tr>
<tr>
<td>Kr gas temperature</td>
<td>0.2 deg.</td>
<td>&lt; 2 Hz</td>
<td>0.4 ppb</td>
<td>4 ppb</td>
</tr>
<tr>
<td>Kr gas pressure</td>
<td>1 Pa</td>
<td>1 Hz</td>
<td>0.2 ppb</td>
<td>0 ppb</td>
</tr>
<tr>
<td>H impurity</td>
<td>&lt;50 ppm</td>
<td>1 Hz</td>
<td>0.5 ppb</td>
<td>0 ppb</td>
</tr>
<tr>
<td>Quadratic dependence</td>
<td></td>
<td>5 Hz</td>
<td>1.0 ppb</td>
<td>5 ppb</td>
</tr>
<tr>
<td>Muonium position (x,y)</td>
<td>1 mm</td>
<td>3 Hz</td>
<td>0.6 ppb</td>
<td>6 ppb</td>
</tr>
<tr>
<td>Muonium position (z)</td>
<td>1 mm</td>
<td>&lt; 1 Hz</td>
<td>0.2 ppb</td>
<td>2 ppb</td>
</tr>
<tr>
<td>Beamline</td>
<td>10(e-4)</td>
<td>&lt; 1 Hz</td>
<td>0.2 ppb</td>
<td>2 ppb</td>
</tr>
<tr>
<td>Detector pile-up</td>
<td>w/o absorber</td>
<td>2.8 Hz</td>
<td>0.5 ppb</td>
<td>3 ppb</td>
</tr>
<tr>
<td></td>
<td>w/ absorber</td>
<td>0.3 Hz</td>
<td>&lt; 0.1 ppb</td>
<td>&lt; 1 ppb</td>
</tr>
</tbody>
</table>

*should be re-estimated by latest progress and further MC simulation.

Total systematic error of $\Delta \nu_{\text{HFS}}$~2 ppb, and $\mu_{\mu}/\mu_p$~ 20 ppb
Zero Field Measurements at D-Line

Experimental Setup

Muon Beam

Online Beam Profile Monitor

Magnetic Shield

Positron Counters

Readout Electronics

Kr Gas Chamber

New RF Cavity for Zero Field

180 mm

RF Intensity

Δν = 4.463 GHz

TM220 mode
Larger cavity
More muon stop
Q-Value: 20,000 (calc.)

Residual Magnetic Field

~ 80nT

Upstream Window

Downstream Window

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B-Field Norm (nT)

0 10 20 30 40 50 60 70 80 90 100

Position (mm)

0 50 100 150 200 250

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Systematic Error in ZF Measurements

Expected accuracy ~10 ppb (or 40 Hz), if we have enough muons!
Results (1): **Time Integral Method**

- Scintillation Position Detector Data –

![Graph showing Off Resonance and On Resonance](image)

**Statistical uncertainty:**

- 2016 Feb. $\sim$ 20 kHz (5ppm)
- 2017 Feb. $\sim$ 4 kHz (1ppm)
- 2017 June $\sim$ 2 kHz (0.5ppm)
- 2018 March $\sim$ 1kHz, measured at 0.4, 0.55, 0.7 atm.
- 2018 June $\sim$ 1kHz, measured at 0.3 atm Kr gas pressure.

**Systematic uncertainty:** Estimation in progress

**Previous ZF Experiment at LAMPF:**

$\Delta v_{HFS} = 4\,463\,302.2 \pm 1.4$ kHz (0.3 ppm)

**New world record at ZF ??**

Data analysis on going
Results (2): **Time Differential Method**

– Silicon Strip Detector Data –

**Simulation:**

![Simulation graph showing signal over time for different frequencies.](image)

**Experiment (2017 June):**

![Experiment graphs showing signal over time.](image)

**Preliminary**

\[ \Delta \nu_{\text{HFS}} = 4 \, 463 \, 302.2 \text{ kHz} \pm 3.1 \pm 0.2 \text{ kHz} \]

**Statistics:**

- less data (smaller detector area)

**Systematics (main):**

- RF power drift (200 Hz)
- gas pressure extrapolation (66 Hz)
  (only one pressure data !)

**Possible advantages of this method:**

- Each detuning frequency data fitted individually.
- Can determine \( \Delta \nu_{\text{HFS}} \) with only one frequency data.
- Most sensitive detuning frequency is \(~60 \text{ kHz}.\)
- Can improve statistical uncertainty by 3.2 times compared to the conventional method.
- Can reduce systematics of RF power variation (free fitting parameter).
- Need high-statistics data.
Summary and Next Step

• New Precise muonium HFS measurements at high magnetic field will be carried out in a few years (H-Line).

• Present expected systematic error estimated as
  
  HFS Magnetic moment $(\mu_\mu/\mu_p)$
  
  $\sim 2$ ppb ($\sim 8$Hz) \textit{preliminary}
  
  $\sim 20$ ppb

• Zero-field measurements at existing beamline (D-Line) in progress for engineering run of the apparatus.

  ✓ Muonium HFS resonance clearly observed!
  ✓ Soon new world record at zero field! (data analysis in progress)
  ✓ Time-Differential Method promising to improve statistics and reduce RF power fluctuation systematics.
  ✓ Need improvement of the RF power stability (systematics) !!!

Stay tuned!
Thank You
For
Your Attention