Precise Measurement of Muonium Hyperfine Structure in J-PARC -MuSEUM-

K. Shimomura (KEK)
on behalf of the MuSEUM Collaboration
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, Δν):**

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

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

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

Zeeman Splitting

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

Pure lepton = point particle

Breit-Rabi diagram

\[ (F, M_F) \]

\[ (1, 1) \]

\[ (1, 0) \]

\[ (1, -1) \]

\[ (0, 0) \]

\[ \nu_{12} \]

\[ \nu_{34} \]

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

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

2018/9/26
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]
- $\mu_\mu/\mu_p = 3.18334524(37)$ [120ppb]
- $m_\mu/m_e = 206.768277(24)$ [120ppb]

**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 $(m_\mu/m_e) (\text{QED}) (\alpha)$
- $\nu_{\text{HFS}}(\text{weak})$ 232 (1) Hz
- $\nu_{\text{HFS}}(\text{had. v.p.})$ 5 (2) Hz
- $\nu_{\text{HFS}}(\text{had. h.o.})$ -65 Hz

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

Determination of the Muon Mass

Muon mass (CODATA2016) determined by MuHFS (LAMPF 1999)

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

\[
206.768 \pm 0.000282 \pm 0.00006 (46) [22 \text{ ppb}]
\]

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

$g$-2 E821(BNL) 0.5ppm 3.6σ deviation

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

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

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

- The ratio to the proton NMR frequency is important!

$$\Rightarrow a_\mu = \frac{R}{\lambda - R}$$

$$R \equiv \frac{\omega_a}{\omega_p}$$

$$\lambda \equiv \frac{\mu_\mu}{\mu_p}$$

$$\frac{\omega_a}{\omega_L(\mu)} = \frac{a_\mu \left( \frac{eB}{mc} \right)}{g_\mu \left( \frac{eB}{2mc} \right) \left( \frac{g_\mu}{2} \right)} = \frac{a_\mu}{1 + a_\mu} = \frac{\omega_a}{\omega_L(\mu)} = \frac{\omega_a}{\omega_L(p)} \frac{\omega_L(p)}{\omega_L(\mu)} \frac{\mu_p}{\mu_\mu} = \frac{R}{\lambda}$$

$\mu_\mu/\mu_p$ accuracy from direct measurement of 120 ppb.

Experimental Layout

- **Experimental Procedure**
  1. Muonium formation
  2. RF spin flip
  3. Positron asymmetry

- **Upstream Counter**
- **Muonium**
  - decay e+
- **Online Beam Monitor**
  - 2D cross-configured fiber hodoscope
- **Kr Gas Chamber**
- **RF Tuning Bar**
- **RF Cavity**
- **Positron Counter**
  - Segmented scintillation counter
- **1.7 T Magnet**

2018/9/26
### Improvement of statistics

#### LAMPF Experiment

<table>
<thead>
<tr>
<th>Systematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\delta(\Delta \nu))</td>
</tr>
<tr>
<td><strong>Statistics</strong></td>
</tr>
<tr>
<td><strong>Kr Density/Pressure</strong></td>
</tr>
<tr>
<td>Muon stopping</td>
</tr>
<tr>
<td>RF power</td>
</tr>
</tbody>
</table>

#### MuSEUM Improvements:

**Statistics:**
- LAMPF: DC \(10^7/s\) total \(10^{13}\)
- J-PARC/MUSE: Pulsed \(1x10^8/s\) total \(2x10^{15}\)

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

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2018/9/26
H1 Area

Phase 2 (g-2/EDM, TμS)

Under construction

**H-Line:** for particle and atomic physics large scale experiments, “precision frontier”.
Higher intensity tunable (4 – 50 MeV) \( μ^+ \) & \( μ^- \) beam.
(Exp.: MuSEUM, Deeme, g-2, ...)

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

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

**U-Line:** Ultra-slow muon (\( μ^+ \))
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

Field Homogeneity (after shimming)
- Spheroid: $r=100 \text{ mm}, z=300 \text{ mm}$
- 18 ppb
- 1.4 ppm p-p

Long Term Stability
- 64 Hz / 9.7 days
- 0.003 ppm /h
RF Cavity for High Field Experiment

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

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

- Energy vs. \( B(T) \)
- Two transitions
- Two resonance modes
- MWS simulation
- 3D CAD

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>

Q Value
**Positron Counter (1):**

Scintillation Position Detector

Kanda, Kojima

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**Plastic scintillator + MPPC + Kaliope readout circuit**

- 32ch MPPC input
- FPGA
- Ethernet
- Trigger input

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**Segmented scintillation detector**

- Scintillation counter with SiPM readout
- Unit cell: 10 mm × 10 mm × 3 mm³
- Area: 240 mm × 240 mm
- 24x24 segments x 2 layers = 1152 ch
- High-rate capability required
- Pileup loss at 3 MHz/ch ~ 2%
Positron Counter (2): Silicon Strip Detector

Nishimura

<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 $\Delta \nu_{\text{HFS}} \sim 2$ ppb, and $\mu_\mu/\mu_p \sim 20$ ppb
Zero Field Measurements at D-Line

Experimental Setup

Online Beam Profile Monitor
Magnetic Shield
Positron Counters
Readout Electronics
Kr Gas Chamber
Muon Beam

New RF Cavity for Zero Field

Residual Magnetic Field

~ 80nT

Upstream Window
Downstream Window

RF Intensity

\[ \Delta \nu = 4.463 \text{ GHz} \]

TM220 mode
Larger cavity
More muon stop
Q-Value: 20,000 (calc.)
Results (1): Time Integral Method

- Scintillation Position Detector Data -

Off Resonance

On Resonance

Statistical uncertainty:
2016 Feb.  ~ 20 kHz (5ppm)
2017 Feb.  ~ 4 kHz (1ppm)
2017 June  ~ 2 kHz (0.5ppm)
2018 March ~ 1kHz, measured at 0.4, 0.55, 0.7 atm.
2018 June  ~ 1kHz, measured at 0.3 atm Kr gas pressure.

Systematic uncertainty: Estimation in progress

Previous ZF Experiment at LAMPF:
\[ \Delta \nu_{\text{HFS}} = 4463\,302.2 \pm 1.4 \text{ kHz (0.3 ppm)} \]

New world record at ZF ???
Data analysis on going
Results (2): **Time Differential Method**

– Silicon Strip Detector Data –

**Nishimura thesis**

**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 \( \sim 60 \text{ kHz} \).
- 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.
## Possible Accuracy

<table>
<thead>
<tr>
<th>Item</th>
<th>2016 June</th>
<th>2017 June</th>
<th>Prospects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis method</td>
<td>Time integral</td>
<td>Time differential</td>
<td>Time differential</td>
</tr>
<tr>
<td>Beam line</td>
<td>D line</td>
<td>D line</td>
<td>H line (D line × 10)</td>
</tr>
<tr>
<td>Beam power</td>
<td>200 kW</td>
<td>150 kW</td>
<td>1 MW</td>
</tr>
<tr>
<td>Measurement period</td>
<td>8 hours</td>
<td>31 hours</td>
<td>80 days</td>
</tr>
<tr>
<td>Microwave cavity</td>
<td>TM110</td>
<td>TM220</td>
<td>TM220</td>
</tr>
<tr>
<td>Detector area</td>
<td>240 × 240 mm²</td>
<td>98.77 × 98.77 mm²</td>
<td>98.77 × 98.77 mm² × 4</td>
</tr>
<tr>
<td>Statistic Uncertainty</td>
<td>22,000 Hz</td>
<td>3,100 Hz</td>
<td>690 ppb</td>
</tr>
</tbody>
</table>
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

\[
\begin{align*}
\text{HFS} & \sim 2 \text{ ppb} \ (\sim 8\text{Hz}) \\
\text{Magnetic moment } (\mu_{\mu}/\mu_p) & \sim 20 \text{ ppb}
\end{align*}
\]

• 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 !
MuSEUM Collaborators
(Muonion Spectroscopy Experiment Using Microwave)

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H. Iinuma

Tohoku University
K. S. Tanaka

Seoul National Univ.
S. Choi

Triumf
H. M. Shimizu, M. Kitaguchi
Thank You For Your Attention
Backup Slides
$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

Muons g-2

FNAL

→ hadronic contribution
→ hadronic IIB contribution
→ New Physics

$$a_\mu = \frac{\omega_a}{\omega_p} \frac{m_\mu}{m_e} \frac{\mu_p}{\mu_B}$$

QED

$$\mu_\mu = g_\mu \frac{e\hbar}{2m_\mu}$$

MUSEUM - HFS

$$\Delta\nu_{\text{HFS}, n=1}$$
→ \(\mu_\mu\)
→ \(\alpha\)
→ QED corrections
→ weak contribution

Mu-MASS

$$\Delta\nu_{1S-2S}$$
→ \(m_\mu\)
→ QED corrections
→ Rydberg

From K. Jungmann
How to improve the accuracy of $m_\mu/m_e$?

Comparison between theoretical and experimental value of $\Delta \nu$

$$\Delta \nu (\text{Fermi}) = \frac{16}{3} \alpha^2 c R_\infty \frac{m_e}{m_\mu} \left[ 1 + \frac{m_e}{m_\mu} \right]^{-3}.$$  + higher order

where recoil term 800kHz (120ppm) and so on are included.

$R_\infty = 10973731.568639(91) \text{m}^{-1}(0.09\text{ppt})$

(Cs atomic beam interferometry)

$\alpha^{-1} = 137.03599958(52) \ (3.8 \text{ppb})$

(from electron $g$-2)

$m_\mu/m_e = 206.7682670(55) \ (27\text{ppb}), \ \mu_\mu/\mu_p = 3.183345396(94) \ (30\text{ppb})$

This value is used for the determination of $g$-2.
Test of CPT and Lorentz Invariance

CPT broken Theory $\Rightarrow$ Lorentz symmetry is broken

O.W. Greenberg, PRL 89 (2002) 231602
R. Blihm, V.A. Kosteleky, C.D. Lane, PRL 84 (2000) 1098
V.W. Hughes et al., PRL 87(2002) 111804

CPT violation search

Ex: Muon difference $g_{\mu^+}/g_{\mu^-} \sim 10^{-8}$

$g_{\mu^-}/$MuHFS precise measurement

Lorentz symmetry violating term in STE Lagrangian $b$

Corresponding MuHFS $\Delta \nu_{12/34}$

These value might change in sidereal time (23h56m)

$LAMPF$ Exp. Figure of Merit

$$2\sqrt{(b_{\mu^+ x})^2 + (b_{\mu^+ y})^2} / m_{\mu} < 5 \times 10^{-22}$$

$$m_{\mu}/M_p \sim 10^{-20}$$

Plank scale sensitivity

V.A. Kostelecky, A.J. Vargas, PRD 92 (2015) 056002
Key Components

• Intense Muon Beamline
• Superconducting Magnet (HF)
• Permalloy magnetic shield (ZF)
• RF Cavity
• Kr Chamber & Gas Handling
• Positron Detector
• Beam Profile Monitors
• Systematic Error Study

Kawamura, Toyoda
Sasaki, Mizutani, Higashi, Ueno
Tanaka, Kanda, Ueno
Tanaka, Matsuda, Yoshida
Tanaka, Torii, Strasser
Kanda, Fukao, Mibe, Kojima
Ueno, Kanda, Toyoda, Ito
Tanaka, Kanda, Ishida
The transition frequency of muonium in gas vary with the gas pressure due to atomic collision between Mu and Kr.

⇒ Fitting 0.8 and 1.5 atm data, old quadratic dependence parameter was used (Los Alamos).
⇒ We need data at lower pressure for improved fitting.
RF Cavity & Gas Chamber

- Pressure: 0.5 – 1.5 atm
- Readout precision: several ppm (crystal gauge: 0.008% of full range)
- Contamination: below 1ppm.
- gas sampling before, during and after the experiment (several weeks).
Systematic Error

Calculate transition probability.

RF field map
fluctuation of RF power
effect of tuning bar

B field map
fluctuation of B homogeneity

detection efficiency map

muonium distribution map
fluctuation of beam intensity
statistical uncertainty

signal or no signal

Repeat calculation for every muonium.

Center of the resonance line
determined by fitting.

plotting

fitting
Muon Beam Profile Monitor

- Two layers of 100-µm fiber hodoscope (2x16ch).
- 3 x 3mm² active area MPPC with 15-µm pixel pitch.
- EASIROC readout

Kanda, Ueno, Toyoda

\[ \sigma = 20.8 \pm 1.5 \text{ mm} \]

Horizontal position (mm)

\[ \sigma = 26.5 \pm 2.8 \text{ mm} \]

Vertical position (mm)
Offline 3D Beam Profile Monitor

μ⁺ → light

Scintillator + CCD camera

Actuator
Screw
Kr Gas Chamber
Scintillator

Muon beam width

± 2 mm

Muon beam center

± 2 mm

Ueno, Kanda, Toyoda, Ito

2018/9/26