High precision measurement of muonium hyperfine structure

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PSAS2018@Vienna University
Outline

• Introduction
  - About muonium hyperfine structure
  - Related physics
  - Roadmap of MuSEUM experiment

• ZF Experiment
  - Experimental setup
  - Status of the ZF experiment

• Developments of HF experiment
  - R&D status of the superconducting magnet
  - R&D status of the NMR probe
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MuSEUM collaboration

Muonium Spectroscopy Experiment Using Microwave @ J-PARC MLF


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Goals of MuSEUM collaboration

• High precision measurement of muonium hyperfine structure (MuHFS) in Zero field & High field

• Stringent test of bound state QED by comparing to the theoretical calculation

\[ \Delta \nu_{\text{HFS}}(\text{theo}) = 4\,463\,302\,891(272)\text{Hz} \ (63\text{ppb}) \]


\[ \Delta \nu_{\text{HFS}}(\text{exp}) = 4\,463\,302\,765(53)\text{Hz} \ (12\text{ppb}) \]


• Relative uncertainty of 1.7 T measurement at LAMPF
  MuHFS (ZF) : 300ppb
  MuHFS (HF) : 12ppb, \( \mu_\mu / \mu_p \) and \( m_\mu / m_e \):120ppb


• MuSEUM's goal : Improve the precision by a factor of 10
**MuHFS measurement with HF**

- Hamiltonian describing energy splitting of the muonium $1^2S_{1/2}$ state
  \[
  \mathcal{H} = \hbar \Delta \nu_{\text{HFS}} \vec{I} \cdot \vec{J} + g_J \mu_B \vec{J} \cdot \vec{H} - g' \mu_B \vec{I} \cdot \vec{H}
  \]

- Spin states splits to substructure
  \[
  \nu_{12} = -\frac{\mu_B g'_\mu H}{\hbar} + \frac{\Delta \nu_{\text{HFS}}}{2} \left[ (1 + x) - \sqrt{1 + x^2} \right]
  \]
  \[
  \nu_{34} = +\frac{\mu_B g'_\mu H}{\hbar} + \frac{\Delta \nu_{\text{HFS}}}{2} \left[ (1 - x) + \sqrt{1 + x^2} \right]
  \]
  \[
  (x \propto H)
  \]

- In the limit of a strong magnetic field ($x >> 1$, $x \sim 10.7$ with 1.7 T)
  \[
  \nu_{12} + \nu_{34} = \Delta \nu_{\text{HFS}} \quad \frac{\mu_\mu}{\mu_p} = \frac{1}{2} \frac{(\nu_{34} - \nu_{12})}{\nu_p} \frac{g_\mu}{g'_\mu} \quad \frac{m_\mu}{m_e} = \frac{g_\mu}{2} \frac{\mu_p}{\mu_\mu} \frac{\mu_B}{\mu_P}
  \]
Related physics - muon magnetic moment

• \( \sim 3\sigma \) discrepancy between theory and experiment

\[
a_{\mu}(exp) - a_{\mu}(th) = 250(89) \times 10^{-11}
\]
(from CODATA 2014)

• \( \mu_\mu / \mu_p \): essential parameter for muon \( g-2 \) measurement

\[
a_{\mu}(exp) = \frac{(g-2)_\mu}{2} = \lambda - R
\]

\[
R = \frac{\omega_\mu}{\omega_p} \quad (540\text{ppb})
\]

\[
\lambda = \frac{\mu_\mu}{\mu_p} \quad (30\text{ppb})
\]

1. \( R \): Planning 140ppb measurement at J-PARC and Fermilab

J. Grange Fermilab \( g-2 \) experiment technical design report (2015).

2. \( \lambda \): 30ppb (HFS result + calculation) -> **direct** 10ppb measurement
Road map of Experiment

• **Zero field measurement @MLF D2-line - ongoing**
  • 2016 Jun. - 1st measurement
  • 2017 Feb. - 2nd measurement
  • 2017 Jun. - 3rd measurement
  • 2017 Dec. - Beam monitor test
  • 2018 Mar. - 4th measurement
  • 2018 Jun. - planning 5th measurement

• **High field measurement @MLF H-line**
  • Will be ready with H-line construction (2019~)
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RF cavity resonant to $v_{12}$ with TM110 mode & $v_{34}$ with TM210 mode
Fiber Beam Profile Monitor

Positron Counter w/ Al Absorber

Muon Beam

Kr Gas Chamber (RF Cavity inside)

Three layers of magnetic shield

200 mm
Time dependent spin flip signal

- Counting the numbers of the decay positron when RF ON/OFF
- Near at HFS resonance (~4.463 302GHz) -> red
- RF frequency far detuned -> blue

![Graph showing the signal over time with red and blue dots indicating on and off resonance respectively.]

Red: on resonance
Blue: off resonance

Signal = \( \frac{N_{\text{on}}}{N_{\text{off}}} - 1 \)

preliminary

Time (ns)
Previous ZF experiments

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016 June</td>
<td>1st observation 22 kHz precision</td>
</tr>
<tr>
<td>2017 Feb</td>
<td>BG surpression RF optimization 4 kHz precision</td>
</tr>
<tr>
<td>2017 June</td>
<td>New Cavity (TM110 -&gt; TM220 mode) upgrade</td>
</tr>
</tbody>
</table>

ZF’s world record 1.4kHz

Preliminary

Spin flip signal (%)

Frequency detuning (kHz)

81 mm

Upgrade

181 mm
**Latest Experiment**

- 2018 Mar 9th - 16th @ J-PARC D2-Line
- Purpose: Measure the HFS value in vacuum by extrapolation
- Measured with 0.4, 0.55 and 0.7 atm Kr gas pressure
Latest Experiment

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• Purpose: Measure the HFS value in vacuum by extrapolation
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Data analysis is ongoing
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### Uncertainties of LAMPF experiment

<table>
<thead>
<tr>
<th>Component</th>
<th>MuHFS (ppb)</th>
<th>$\mu_\mu / \mu_p$ (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics</td>
<td>10.9</td>
<td>107</td>
</tr>
<tr>
<td>B field</td>
<td>0</td>
<td>56</td>
</tr>
<tr>
<td>Kr Gas</td>
<td>4.4</td>
<td>11</td>
</tr>
<tr>
<td>Muon stopping</td>
<td>1.0</td>
<td>13</td>
</tr>
<tr>
<td>RF power</td>
<td>0.96</td>
<td>9.6</td>
</tr>
</tbody>
</table>

- Mainly limited by statistics - installation of H-Line @ J-PARC MLF
- Magnetic field inhomogeneity causes next

Required B-field at MuSEUM

Superconducting magnet (1.7 T)

- Required ~0.1ppm homogeneity of 1.7 T in the spheroid muonium formed area (z= 300 mm, r=100 mm)
MRI magnet status

- Solenoid MRI magnet for MuSEUM @ J-PARC (max 2.9 T, used in 1.7 T)

- B-field drifted 64Hz per 9 days (2015/3/30 - 2015/4/9)
  - 3ppb/h stability

- B-field homogeneity suppressed to 0.8ppm by shimming the MRI magnet with shim trays
- 576 points measured by single NMR probe (including B-field drift, alignment error etc.)
B-field improvement - shimming

- Shimming by placing iron plates (5 & 25μm thickness) in 24 pockets* 24 trays = 576 pockets inside the magnet
- Optimized homogeneity to 0.80ppm of 1.7 T in target area (mapped by single NMR probe)

Thin and thick iron plates for shimming (W 40 mm, D 30 mm, t 5 or 25μm)
CW-NMR probe

- NMR (Nuclear Magnetic Resonance)
  \[ 2\pi \nu_0 = \gamma_p B \ (\gamma_p = 267.52219 \times 10^6 \text{ [rad s}^{-1}\text{t}^{-1}] \]

- Continuous wave NMR probe (CW-NMR)
  - Sweep the B-field mandatory by the modulation coil
  - Detect the envelope signal of proton NMR

![Diagram of CW-NMR probe](image)
NMR probes for MuSEUM experiment

- Stability per time - Online monitoring by fixed standard probes
- Homogeneity in Muonium formed area
  - Measurement by the multi channel field mapping probe
Probes used for the experiment

- Fixed standard probe: placing single-ch NMR probes for monitoring the stability of the B-field drift
- Motivation: Decrease the systematic shift caused by the material of the NMR probe

\[ \nu_p = (1 - (\sigma(\text{H}_2\text{O}) + \delta_b + \delta_p + \delta_s)) \nu_0 \]

- Field mapping probe: Fast field mapping enables B-field measurement with low drift
- Design: 24ch NMR probes on half-oval plate to scan the surface
NMR probe cross calibration

- Mar 2017: cross calibration with FermiLab g-2 group @ANL, B=1.45 T
- 20ppb agreement at blind analysis with CW and pulse NMR probe (preliminary)

- Found uncertainties caused by the material of the NMR probe itself, especially the circuit board - replace with non-magnetic materials
- Mar 2018: 2nd cross calibration of the new NMR probe @ANL, B=1.45 T
Summary

- MuHFS measurement is a good probe to test the bound state QED and also $\mu_\mu / \mu_p$ and $m_\mu / m_e$ can be measured. For improvement, more statistics and high homogeneity of magnetic field are required.

- MuHFS measurements with extremely low magnetic field is in progress and we are close to the world record.

- The spec of the magnet fulfills the requirement of the MuSEUM experiment. We are now doing the R&D of the NMR probes.
Appendix
Magnetic moment ratio values used at BNL (Brookhaven National Laboratory) result was derived from $\Delta\nu_{\text{HFS}}$ results by LAMPF (12 ppb) applying to

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

and the magnetic moment was calculated by the mass ratio as

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

which is called the indirect determination. This calculation assumes the SM of the correction terms.

(partially taken from D. Nomura’s slide)
old muonium method

conventional method

- Using all muons

old muonium method

- Observe from t1 to t2

FWHM is wide.
The number of observed muons is large.

FWHM is narrow.
The number of observed muons is small.

(from K.S. Tanaka-san’s slide)
Related physics: Exotic particle search

A pseudo vector boson

\[ -\frac{\alpha}{r} \rightarrow -\frac{\alpha + \alpha''(s_1 \cdot s_2)e^{-\lambda r}}{r} \]

A massive vector boson

\[ \frac{\Delta E_{\text{hfs}}}{E_{\text{hfs}}} = \frac{8\alpha' m_e}{m_V} = \frac{8\alpha\kappa (\kappa + g_V/e) m_e}{m_V} \]

Fig. 2 on PRL 104, 220406 (2010)


Fig. 6 on PRD90, 073004(2014).

(from K. Simomura-san’s slide)
Related physics: Test of Lorentz symmetry

CPT broken Theory $\Rightarrow$ Lorentz symmetry is broken

R. Blihm, V. A. Kosteleky and C. D. Lane, PRL 84, 1098 (2000)
V. W. Hughes et al., PRL 87, 111804 (2000)

CPT violation search

Ex., Muon difference $g_{\mu}^+/g_{\mu}^-$ $10^{-8}$

$g_{\mu}$ - 2/MuHFS precise measurement

Lorentz symmetry violating term in SME 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

Laboratory tests of Lorentz and CPT symmetry w/ muons

(from K. Simomura-san’s slide)
cavity design for HF measurement

two transitions

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

‘magic’ magnetic field = 1.7 T

two resonance modes

TM110

Input → Monitor

TM210

Input → Monitor

(from K.S. Tanaka-san’s slide)