Precision measurement of muonium hyperfine splitting at J-PARC

Sohtaro Kanda / the University of Tokyo / RIKEN Nishina Center

kanda@post.kek.jp
Overview

- Introduction of Muonium HyperFine Splitting (MuHFS)
- Measurement precision
- New Experiment at J-PARC
  - Muon beam at J-PARC, Superconducting magnet
  - Online/Offline beam profile monitors
  - Gas chamber and Cavity
  - High rate capable positron detector
    - Detector R&D
- Summary and prospects
Muonium Hyperfine Splitting

\[ \mathcal{H} = a \mathbf{I} \cdot \mathbf{J} + \mu^e_B g_J \mathbf{J} \cdot \mathbf{H} - \mu^\mu_B g\mu \mathbf{I} \cdot \mathbf{H} + \text{RF term} \]

Hamiltonian of Muonium  HFS  Zeeman Splitting

Muonium:
- Bound state of \( \mu^+ \) and e- (Less affected by recoil than Ps)
- Pure leptonic system (Composite particle free)

Objectives:
- Precision test of bound state QED
- Muon mass determination
- Test of Lorentz invariance
- Muon g-2
Precision of measurement

\[ \Delta E_{\text{HFS}} = 4463302765(53) \text{ Hz (12ppb)} \]

\[ \mu_\mu / \mu_p = 3.18334513(39) (120 \text{ppb}) \]

Liu et al., PRL. 82, 711 (1999)

92% of uncertainty is statistical error

Understanding of systematics is limited by measurement time

Our goal: 200 times of statistics and minimization of systematic uncertainty
How to improvement

Error Budget (frequency sweep, $\mu_\mu/\mu_p$) and our approach to improvement

- Microwave Power
- Gas Density Extrapolation
- Muon Stopping Distribution
- Field Measurement
- Statistical Error

The Keys:
- Highest intensity pulsed muon beam at J-PARC
- Various calibration runs and well understanding in systematic errors

Requirement:
- High rate capable positron counter
Experimental Setup

1. RF freq. scan
2. Positron asymmetry
3. Resonance curve

Experimental procedure

Microwave Cavity
Kr Gas Chamber
1.7 T SC Magnet

Forward positron detector
Backward positron detector

Muonium
Formation, Transition, and Decay

Decay positron

Beam Profile Monitor
Tuning Bar
Absorber
Muon beam and Magnet

- H-Line: The highest intensity pulsed muon beam at J-PARC (Under construction)

Simulation Result:
- Profile at final focus
  - $\sigma_x = 13$ mm, $\sigma_y = 13$ mm
  - $\theta_p = 161.5$ mrad, $\phi_p = 137.4$ mrad
- 93.6% transmission efficiency
- Leakage field 0.5 Gauss
  (Requirement < 1.7 Gauss)


- Magnet: 1.7 T high precision superconducting magnet (Installed at J-PARC)

Requirement to the magnet:
- 1ppm homogeneity in z300 mm, r100 mm region

Specification of the magnet:
- Field strength 1.7 T
- Bore diameter 925 mm

Field correction is performed by main coil, iron shim, and shim coil
Field strength is monitored by NMR probes

Beam Profile Monitors

- **Online beam profile monitor**: 2D non-destructive muon monitor
  
  Non-destructive 2D Beam profile monitor
  
  **Beam stability measurement**
  
  150 μm plastic scint. + clear fiber + MAPMT (or SiPM)
  
  16 ch. × 2 Layers
  
  Prototype is developed and beam test is performed


- **Offline beam profile monitor**: 3D monitor for muon stopping distribution measurement
  
  3D Beam profile monitor
  
  **Muon stopping distribution in the cavity**
  
  Image intensifier + CCD
  
  Prototype is developed and beam test is performed

Chamber and Cavity

- **Kr Gas Chamber**
  - Prototype of the gas chamber

- **Microwave Cavity**
  - Prototype of the cavity

Extrapolation to lower gas density
- Long cavity is required for muon stop

Two transition frequencies
- Two modes should be tuned by tuning bars

Prototype development
- Pressure test and RF test is performed

Requirement: Suitable for high intensity pulsed beam
Highly segmented positron counter
-> 2~4 layers of scintillating fiber hodoscope
Expected event rate ~ 3 MHz/cm²
Scintillation fiber+MPPC+ASIC based ASD+FPGA MHTDC

Prototype is developed and beam test is performed

Summary and Prospects

- MuHFS measurement is a good test of bound system QED
- New Experiment at J-PARC can improve the measurement precision
  - The keys are intense muon beam and high rate capable detector
- R&D in progress
  - Profile monitor -> Prototype development, beam test
  - Chamber, cavity-> Prototype development, pressure and RF test
  - Detector -> Simulation, prototype development and beam test
- The experiment will start in FY2014
- We are looking for new collaborators!
Additional Materials
Profile monitor R&D

Online beam profile monitor

M. Tajima et al,

Prototype

Obtained beam profile
at J-PARC

σ: 33.8 ± 0.1

Offline beam profile monitor

T. U. Ito et al,
USM2013 (2013)

Prototype

Obtained beam profile
at J-PARC
Simulation geometry

Muon stopping distribution

Simulation Study

2013. 09.10 at PSI2013
Extrapolation to Gas pressure=0

Los Alamos Experiment
only 2 pressure data points
->Extrapolation uncertainty

More data points is important for the improvement of precision
(Especially lower gas density)

->J-PARC new experiment uses longer cavity (lower gas density is achievable)

Resonance Line Shape

Calculation procedure

1. Hamiltonian of muonium
2. Wave function of muonium
3. State amplitude/probability
4. Muon stopping distribution
5. Muon polarization
6. Decay positron asymmetry
7. Positron detection
8. Frequency sweep
9. Difference between RF on/off
Readout Electronics

32ch MPPC input  FPGA  Ethernet  Trigger input

ASIC  PROM  +5V(A), +1.8V

(to be published)
Detector Options

2D Tiled Pixel

1D Fiber Array

and hybrid of them