High precision measurement of muonium hyperfine structure

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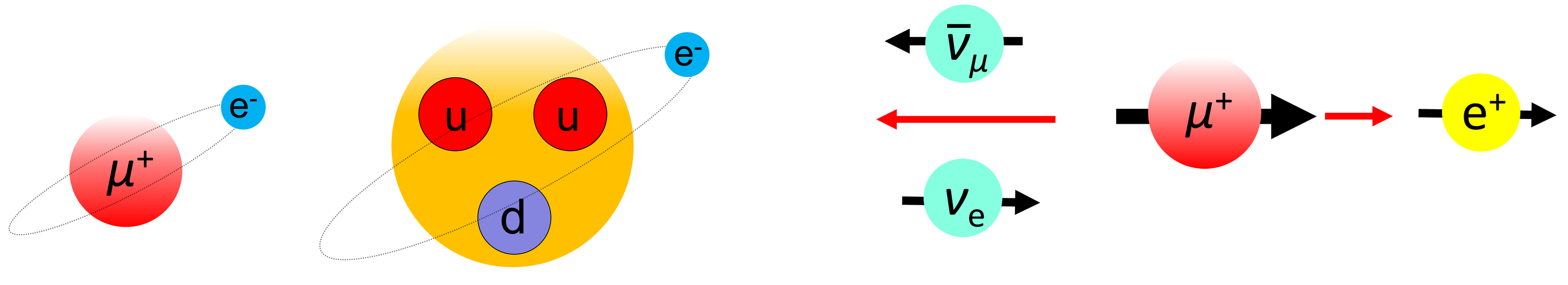
Muonium and hyperfine structure

- Muonium is the bound state of muon (μ+) and electron, which is the most simple model in Hydrogen-like atom.
- Muon decays to positron in 2.2 × 10^{-6} s to positron (e+) with parity violation, which enables a precise spectroscopy in muon spin state level by tracking positrons.



Muonium   Hydrogen (¹H)   Muon decays to positron and neutrinos

- Muonium hyperfine structure (MuHFS) is determined in high precision as…
  - Theory : 4 463 302 868 (271) Hz [61 ppb] [1]
  - Experiment : 4 463 302 765 (53) Hz [12 ppb] [2]
- *MuSEUM (Muonium Spectroscopy Experiment Using Microwave)* collaboration aims to improve the MuHFS experimental precision by a factor of 10 by…
  - Utilizing the high intense muon beamline at J-PARC, MLF
  - Upgrading the positron detection system
  - Improvement of the analysis technique
  - Improving and elaborating the systematic uncertainties

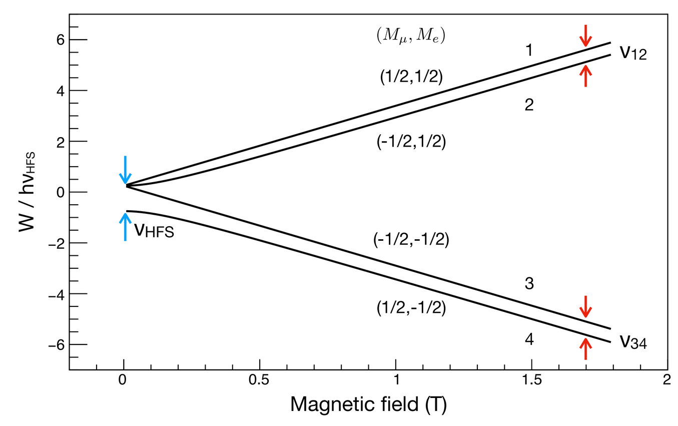
Spectroscopy of MuHFS

Muonium hyperfine structure is measured in two ways

- With extremely low magnetic field
  - Direct ν_{HFS} measurement
- With high magnetic field, Zeeman splitting
  - Measurement of sublevels ν_{12} and ν_{34}
  - MuHFS, muon magnetic moment (μ_μ) and muon mass are derived from ν_{12} and ν_{34}

$$\nu_{12} + \nu_{34} = \nu_{HFS}$$
$$\nu_{34} - \nu_{12} \propto \mu_\mu/\mu_p\,,\ m_\mu/m_e$$

μ_μ/μ_p : 3.183 345 13 (39) (120 ppb) [2]
m_μ/m_e : 206.768 277 (24) (120 ppb) [2]



Breit-Rabi diagram of muonium $1S_{1/2}$ state

The HFS spectroscopy contributes to other physical properties

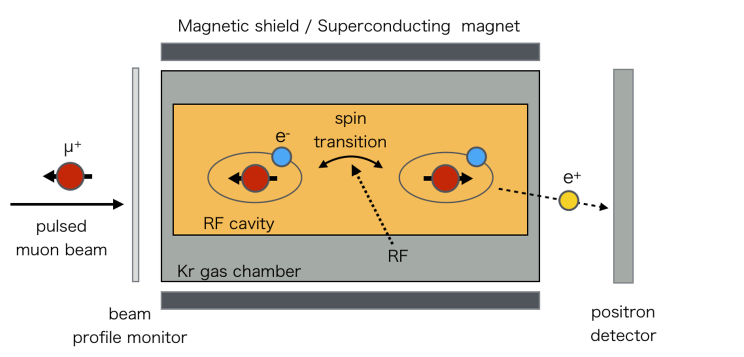
- μ_μ/μ_p is an important outer parameter for the muon anomalous magnetic moment (muon *g-2*) which has 3.7σ discrepancy between the theoretical prediction and the experimental result [3][4]. To solve this problem, we need the μ_μ/μ_p result based on only measurement.
- The experimental value of m_μ/m_e is the dominant contribution of the uncertainty of the MuHFS theoretical prediction.

Measurement status

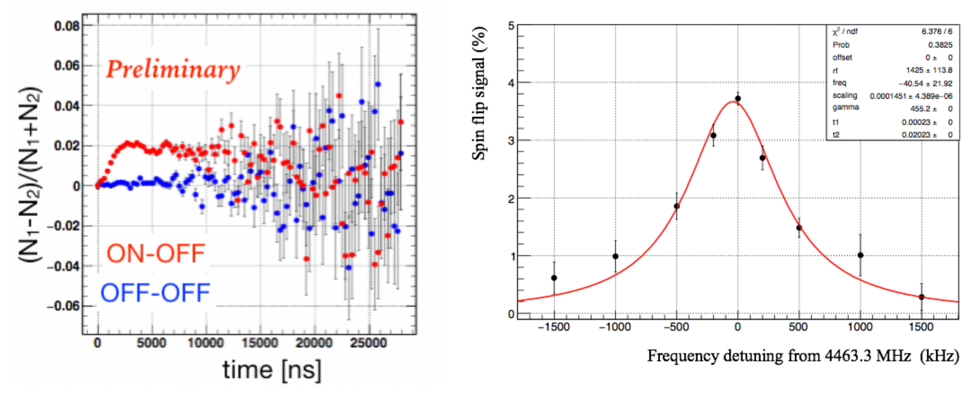
- Muons are formed to muoniums by the interaction with Krypton gas and capturing the electron with a low threshold energy.

$$\mu^+ + \mathrm{Kr} \rightarrow \mathrm{Mu} + \mathrm{Kr}^+ \ (0.46\mathrm{eV})$$

- The MuHFS spectroscopy is performed by applying the microwave and counting the numbers of the decay positrons by the positron counters.

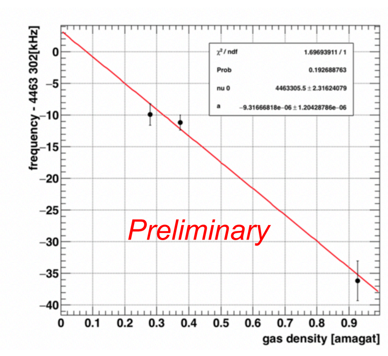


Setup of the muonium HFS measurement

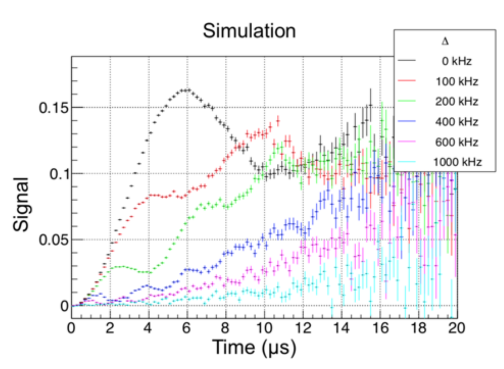


Resonance signal and the resonance line shape of the frequency in muonium hyperfine structure [5]

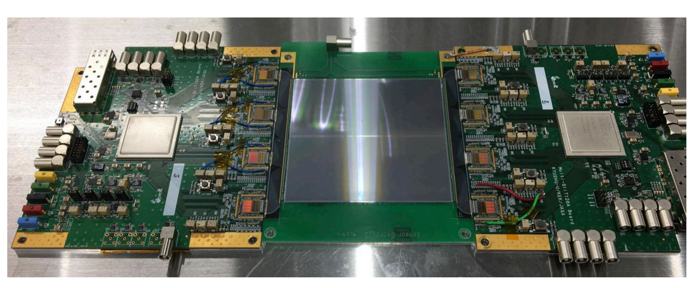
The measurement with extremely low magnetic field (<100 nT) is started form 2016 and we are continuing the measurement with upgrades of gas system, analysis method and the new silicon detection system.



Pressure extrapolation from several MuHFS results (from Y. Ueno's doctoral thesis)



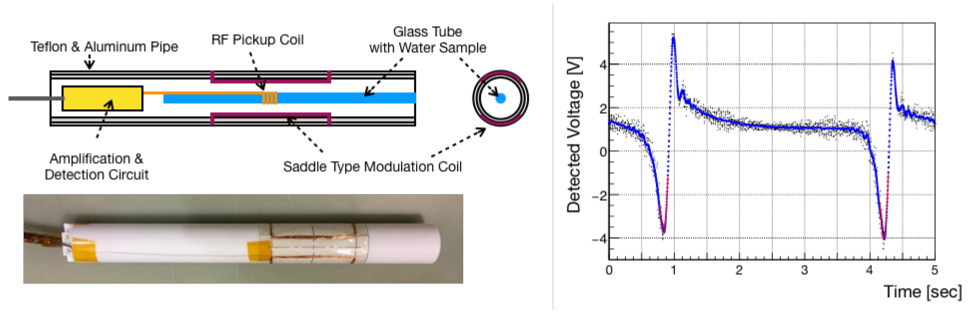
Simulation of resonance signal (from S. Nishimura's doctoral thesis)



Silicon stripe detector for the positron counting system

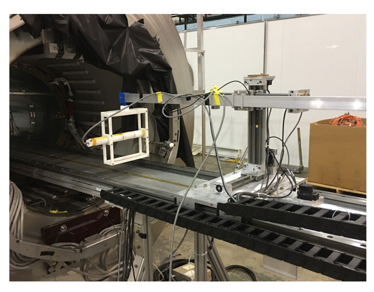
Preparations for high field MuHFS

We are planning to perform a HFS measurement with the 1.7 T magnetic field. In this measurement, the systematic uncertainty due to the magnetic field inhomogeneity is unique to this measurement and crutial. To evaluate this precision, developments of the high precision CW-NMR probes are ongoing.

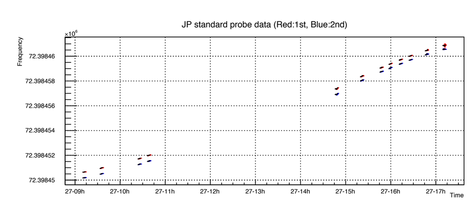


CW-NMR probe and the detected signal at NMR resonance [6]

To evaluate the accuracy of our probe, we are calibrating our probes with pulse NMR probes used at Fermilab muon g-2 experiment.



NMR probe test



Magnetic field measured by the CW-NMR probe

Summary

- Muonium HFS is a suitable probe to test the bound state QED ,and by measuring the hyperfine structure with a strong magnetic field, the muon magnetic moment and mass are also provided.
- The direct HFS measurement with an extremely low magnetic field is taken place at J-PARC. We are now continuing our measurement with upgrades.
- The measurement with a high magnetic field is under preparation. For this measurement, the precise measurement of the magnetic field is required.

References

[1] P. J. Mohr, D. B. Newell, and B. N. Taylor, Rev. Mod. Phys. **88**, 035009 (2016). [2] W. Liu *et al*., Phys. Rev. Lett. **82** 4 (1999)
[3] A. Keshavarzi, D. Nomura and T. Teubner, Phys. Rev. D **97** 114025 (2018) [4] G.W. Bennett *et al*., Phys. Rev. D **73** 072003 (2006)
[5] S. Kanda *et al.,* Proceedings of Science (INPC2016) **170** 1-6 (2017) [6] T. Tanaka *et al.,* J. Phys.: Conf. Ser. 1138 012008 (2018)