Possibility of precise measurements of muonium HFS at J-PARC MUSE

K.Shimomura

High Energy Accelerator Research Organization (KEK), Oho 1-1,Tsukuba, Ibaraki Japan

Abstract. Intense pulsed muon beam will be available at J-PARC MUSE up to 4×10^8/s within a few years. We propose the next generation of the precise measurements of muonium hyperfine structure and the ratio of muon to proton magnetic moments by using the muonium spin resonance method at high magnetic field.

Keywords: Muonim, Hyperfine Structure
PACS: 36.10.Ee, 32.10.Fn

INTRODUCTION

Muonium is the bound system of a positive muon and an electron. It provides the simplest two-body bound system in which the interaction between the muon and the electron can be studied and the behavior of the muon as a heavy electron can be tested. In the standard model of modem particle physics the electron and the muon are treated as structureless point leptons with the same electromagnetic and weak interactions but essentially free from strong interactions.

Muonium is quite simpler system for testing bound-state QED than other simple atoms, like hydrogen and positronium. For muonium the theoretical value of the hyperfine structure (HFS) interval $\Delta\nu$ in the ground state has been calculated to about 0.05 ppm Error is mainly due to uncertainties of the muon mass. The theory for hydrogen is limited by our knowledge of the internal structure of the proton arising from the strong interactions. For positronium, the theory is more difficult because of the annihilation effect and the strong recoil effect.

The muon mass m_μ and the muon magnetic moment μ_μ are fundamental constants of the muon. The most precise value for μ_μ is determined from the previous muonium hfs experiment [1]. A precise value of m_μ is determined from μ_μ and the muon g value, and a more precise value of m_μ can be determined by equating the experimental value of $\Delta\nu$ to its theoretical expression. Knowledge of the muon mass is important for the spectra of muonic atoms, such as muonium, muonic helium, the theoretical evaluation of muon g-2, and the determination of the muon neutrino mass. A precise value for the Fenni constant of the weak interaction can be obtained from the muon mass together with the muon lifetime. The precise values for μ_μ and m_μ are required to determine the magnetic moment anomaly of the muon in the BNL E821 experiment [2] and the new muon g-2 experiment in progress at the J-PARC MUSE and FNAL.

A value for the fine structure constant α can be determined from our knowledge of $\Delta\nu$. The QED calculation of the hfs interval is expressed in terms of the electron to muon mass ratio m_e/m_μ and the fine structure constant α. A value for α may be evaluated by equating the experimental value of $\Delta\nu$ to its theoretical expression.

In precise muonium hfs experiments, muonium is formed in a pure gas target, such as krypton, when a muon is slowed down by collisions with krypton atoms and captures an electron from a krypton atom. Muons are obtained from parity-violating pion decays and are polarized in a direction opposite to their momentum, Hence polarized muonium is formed because the electron capture reaction is dominated by the Coulomb interaction, which does not change the muon spin direction. The transition frequencies between Zeeman energy levels of the n= 1 state of muonium at weak or strong magnetic fields are measured by microwave resonance spectroscopy. An applied microwave magnetic field induces transitions between Zeeman levels. The parity-violating muon decay determines the muon spin direction at the instant of the decay because of the correlation of the direction of the positron emission and the direction of the muon spin. The transition frequencies are determined from resonance lines observed by scanning the microwave.

The latest experiment at Los Alamos obtained the remarkable precision value of

$$\Delta\nu=4463302776(51)\mathrm{Hz}\ \ (12\mathrm{ppb}),$$
$$m_\mathrm{m}/m_\mathrm{p}=3.18334524(37)\ \ (120\mathrm{ppb}).$$

However, the main uncertainty came from the lack of statistics. In this measurement, quasi DC muon beam was adopted.

MUON SOURCE AT J-PARC MUSE

To overcome above statistics limit, use of the intense pulsed muon beam is ideal. MUSE (Muon Science Establishment) is located at Materials and Life Science Facility (MLF) in J-PARC, where 1 MW (3 GeV, 333 μA) pulsed beam (25Hz 2 bunch) from a 3 GeV rapid synchrotron will be available within a few years, and. A carbon target of 2 cm thickness planed to be installed for the production of intense pulsed pion and muon beams. To achieve the best performance of this facility, four dedicated muon channels are planned to be installed.

The experimental area is divided east and west parts. In this condition, we arranged the superconducting muon channel and the large acceptance surface muon channel at the west area, and the surface muon channel and the high momentum muon channel at east area. Except surface muon channel, all are candidates for the muonium HFS measurement.

A conventional superconducting muon channel was installed at first phase [3], which can extract surface (positive) muon and decay positive/negative muon up to 120 MeV/c. It consists of three parts; 1) a pion injector, 2) a decay solenoid, 3) a muon extraction. Two experimental ports were constructed for simultaneous use. This channel is now used for various kinds of μSR and nondestructive elements analysis, however, if surface muon beam channel will be installed, this channel will be used for the long term experiments. The expected surface muon at 1MW is 3×10^7/s. By using this channel, about 10 times statistics will be obtained with 10 weeks run.

The second candidate is the large acceptance surface muon channel, so called Super Omega. Recently, inspired by the progress of muon science (like ultra slow muon generation/muon catalyzed fusion/muon rare decay etc.) and the design study of the muon collider /neutrino factory, several new concepts of the intense muon beam channel are extensively studied.

In KEK-MSL, a large solid angle axial focusing surface muon channel (Dai Omega) was successfully constructed. This channel consists of four sets of superconducting coil and transports the surface muon with an acceptance of more than 1000 msr. In PSI, to provide the highest intensity of the surface muon beam for the generation of the low energy muon, the new μE4 beam line is now under construction by using two normal solenoids as the first focusing elements. The residual magnetic field at the production target is less than 10G in this case. And also in BNL, for the search of the rare process μ^-N to e^-N, the new muon beam line is now under development. As the major part of this system, the transport solenoid (a set of solenoids and sections of toroidal) is designed to transport low energy negative muon with helical trajectories to the stopping target.

By combining the merits of these muon beam lines, we propose the world's highest intensity surface nuon channel called; Super-Omega. Axial focusing optics can achieve a significant acceptance and the bending solenoid and Dai Omega are very helpful to reduce neutron background. Super-Omega consists of three parts; 1) a double normal conducting solenoid lens, 2) a curved superconducting solenoid and 3) axially symmetric superconducting coils, the detailed design is shown in ref. [4]. In this case the expected surface muon yield is 4×10^8/s, therefore, about 100 times larger statistics within 10 weeks.

The last candidate is the high momentum muon beam line, the concept of which is now drastically changing. Some estimation shows 1×10^8/s surface muon will be provided to the several ports. This feature is very helpful to perform a long term experiment like 1 years run, therefore, 100 time statistics is also expected.

Reduction of systematic error

There are also many rooms for the improvement to reduce the systematic error in Los Alamos measurements. For example their length of homogeneous magnetic field was rather limited and their cavity length, therefore, was not long enough for the surface muon stopping at low density Kr gas [5]. And also by the nature of quasi AC muon beam structure, they could not use the time differential analysis in muonium spin resonance method [6], which is principally better than time integral analysis. The detailed design for the next generation of muonium HFS is now rapidly progressing.

REFERENCES

1. W. Liu *et al., Phys. Rev. Lett. 82, 711 (1999).*
2. G.W. Bennett, *Phys. Rev. D. 73, 072003 (2006)*
3. K. Shimomura *et al., Nucl. Inst. Meth. A 600 (2009)* 192
3. Y.Ikedo in these proceedings..
5. K. Jungmann private communication.
6. K. Nishiyama *et al., Hyperfine Interactions 32(1986)887* R. Sheuermann *et al*. Applied Magnetic Resonance 13(1997)195