論文の内容の要旨

Direct measurement of muonium ground state hyperfine splitting with high-intensity pulsed muon beam

(大強度パルスミューオンビームによるミューオニウム基底状態超微細構造の直接測定)

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This thesis describes a new precision measurement of muonium ground state hyperfine splitting. The experiment was the first trial of muonium spectroscopy with high-intensity pulsed muon beam at J-PARC. In order to resolve the problems in precursor experiments and explore the precision frontier of muon physics, the world highest intensity pulsed muon beam, a high-rate capable positron detector, two-dimensional and three-dimensional muon beam profile monitors, and high performance magnetic shield were orchestrated. As a result of the experiment, muonium hyperfine structure interval $\Delta\nu$ = 4.463292(22) GHz was obtained with the relative precision of 4.9 ppm.

Muonium is the bound state of a positive muon and an electron. In the standard model of particle physics, muonium is a two-body system of structureless leptons. Therefore, a precision measurement of muonium ground state hyperfine splitting (HFS) is the most rigorous validation of bound-state quantum electrodynamics (QED) theory and the most precise method to determine the muon mass via the muon-to-electron mass ratio.

The precursor experiments of muonium HFS spectroscopy were performed at Los Alamos Meson Physics Facility (LAMPF) in Los Alamos National Laboratory (LANL). Direct measurement at zero magnetic field and indirect measurement in a high magnetic field were conducted with the continuous muon beam. The most precise value of directly-measured muonium HFS interval is 4.4633022(14) GHz.

This dissertation discusses a new direct measurement of the muonium HFS with high-intensity pulsed muon beam at Japan Proton Accelerator Research Complex (J-PARC). Figure 1 illustrates an experimental overview.

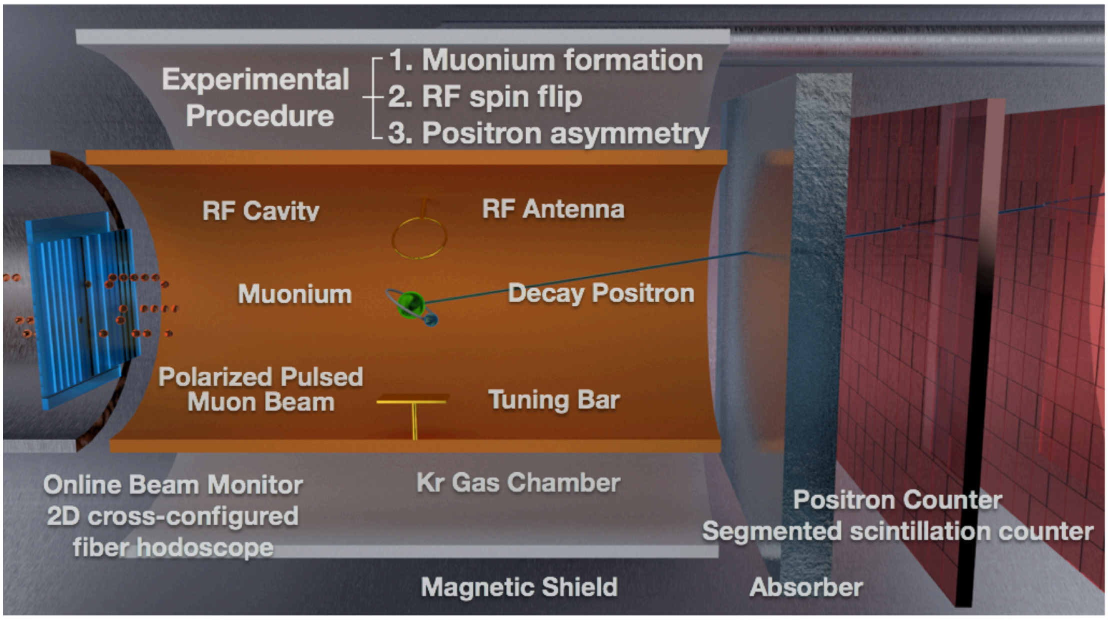

Figure 1: Experimental schematic of muonium HFS spectroscopy. Spin polarized pulsed muon beam is irradiated to Kr gas target. Muonium forms by an electron capture from Kr atom. The muonium HFS transition occurs due to the microwave resonance in the cylindrical cavity. Positrons from muonium decay are detected by the positron counter placed behind the gas chamber.

Spin polarized pulsed muon beam is injected to a gas chamber filled with krypton gas. A two-dimensional fiber hodoscope for muon detection is placed in front of the gas chamber to measure the profile and the intensity of the incident muon beam. An injected muon loses its kinetic energy and forms a muonium via an electron capture from krypton atom. A cylindrical microwave cavity is placed inside of the gas chamber. It generates TM110 mode of microwave resonance at the frequency of 4.463 GHz and induces the muonium HFS transition. According to the state transition, muon spin flips as a function of time. A positron is emitted by parity violating decay of muon and its emission angle is correlated to the muon spin direction. Spectroscopy of the muonium HFS is performed by the measurement of microwave frequency dependence of the number of decay positron from muonium decay. Positron is detected by two layers of segmented scintillation counter. The detectors are placed in the downstream of the target chamber.

Figure 2 represents the time spectra of muon decay positron measured by using the positron detector. A histogram in blue line corresponds to all single hits, one in green line corresponds to cluster-analyzed hits to avoid an over counting due to the multiple hits caused by an identical origin. A histogram in black line corresponds to coincidence-analyzed hits to be utilized for signal evaluation of muonium spin flip.

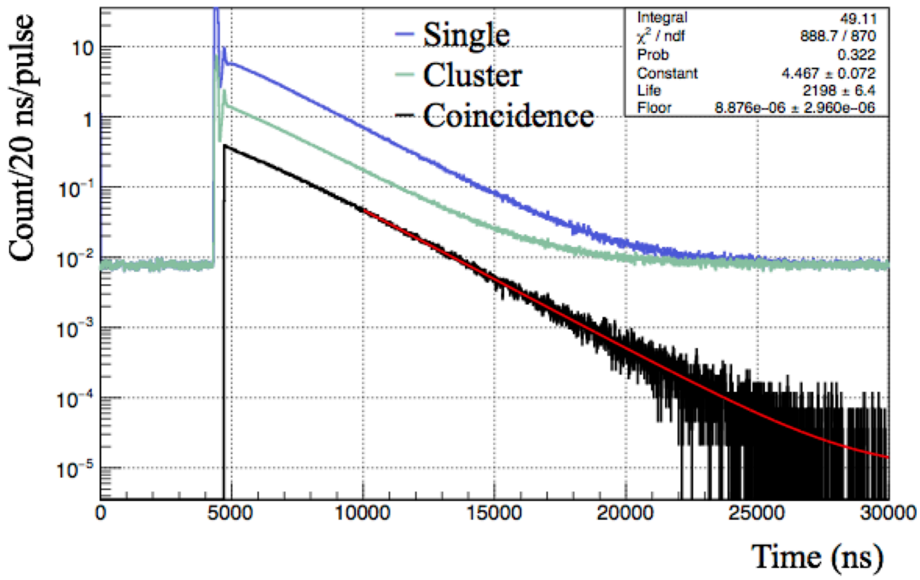

Figure 2: Time spectra of the detector hits. The histograms in blue, green, and black lines correspond to all single hits, cluster merged hits, and coincidence hits, respectively. Red line indicates the fitting result with an exponential function on a constant background.

By taking a difference between positron time spectra measured with and without microwave resonance, time dependent muonium spin flip signal was extracted. Figure 3 shows obtained spin flip signal. For a case of on-resonance, an oscillating spin flip signal was observed.

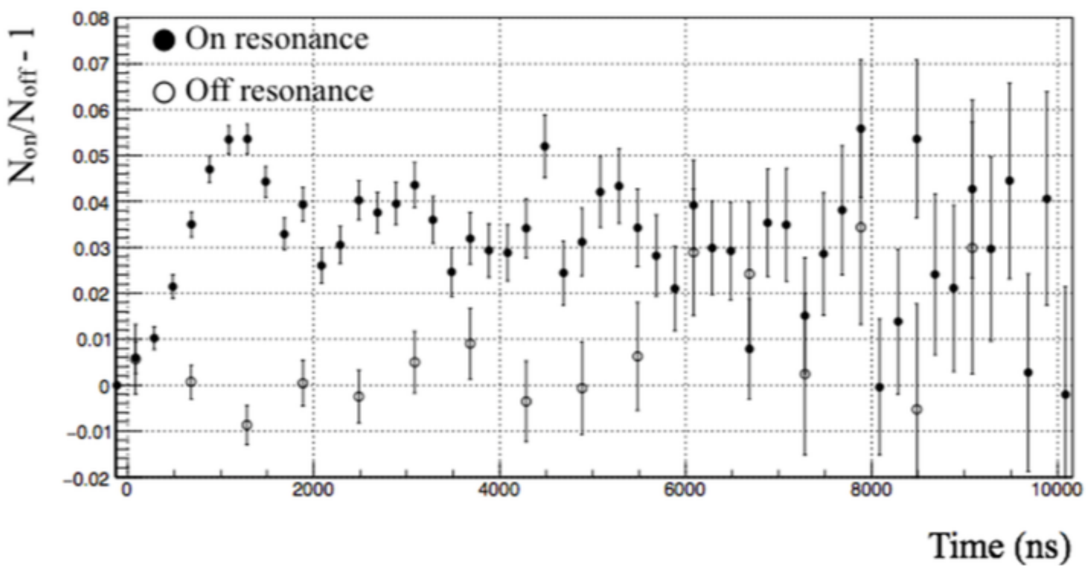

Figure 3: Time dependent muonium spin flip signal at on-resonance and off-resonance. Black circles indicate the result with the microwave frequency of 4463.3 MHz which correspond to muonium HFS resonance. Outlined circles correspond to one with off-tuned microwave frequency from the resonance.

To obtain a resonance lineshape of muonium HFS, muonium spin flip signal was time-integrated at several values of the microwave frequency. Figure 4 shows a result of the microwave frequency scan. This result is the world first observation of the muonium HFS resonance with the pulsed muon beam.

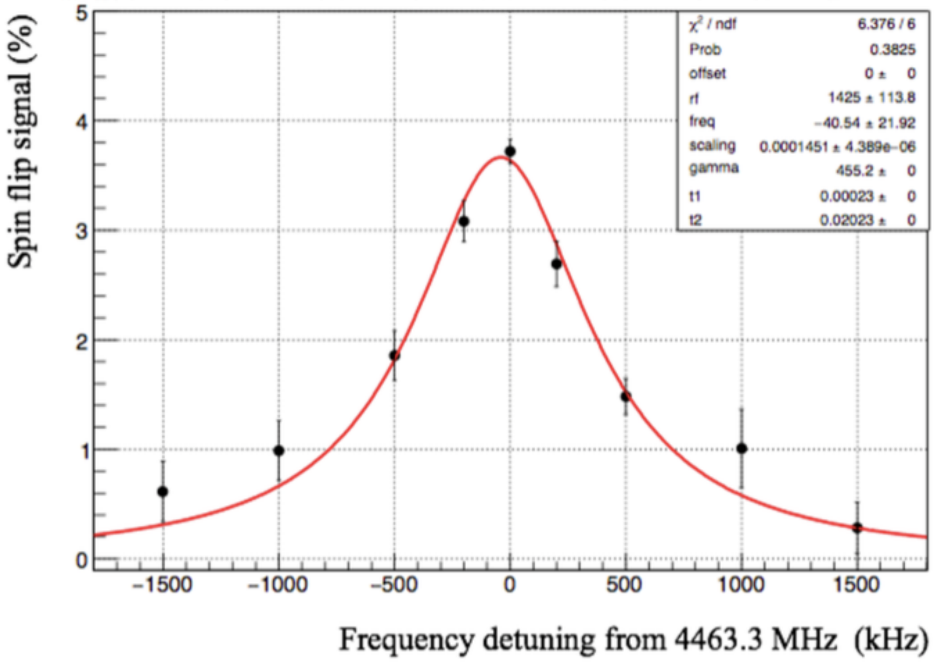

Figure 4: Measured resonance lineshape of muonium HFS. Red line indicates a fitting curve in theoretical expression of the resonance. Obtained frequency center was −41 ± 22 kHz.

This result corresponds to a relative uncertainty of 4.9 perts per million. An expected resonance frequency was -33 kHz. There was a good agreement with the experimental result and expectation.

The development of the high-rate capable positron detector enabled to handle the high-intensity pulsed muon beam without increase of systematic uncertainties. Both experimental and computational approaches to the systematic uncertainty provided an understanding of the uncertainties and a suitable means to control the systematics.

Due to a limited muon beam deliverance and a reduction of signal-to-noise ratio caused by background positrons, a sixteen-fold of improvement is necessary to exceed the highest precision in direct determination of the muonium HFS. However, as a result of studies for background sources and their suppression, major objects to be improved were revealed.

Estimated systematic uncertainty in the measurement was 73 Hz. This value is sufficiently smaller than statistical errors in both this experiment case and the precursor experiment case. However, it is nearly equivalent to the order of total uncertainty in the most precise result obtained by an indirect measurement at high magnetic field. Therefore, improvements in major sources of the systematic uncertainty were studied. An order of magnitude improvement is expected by adaptation of the microwave power feedback and a precise silicon pressure gauge.

In conclusion, the experiment succeeded in the world’s first demonstration of muonium HFS spectroscopy by using the high-intensity pulsed muon beam.