Negative muon spin rotation with low-density gas target under transverse magnetic field to solve the proton radius puzzle

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When a negative muon is captured by a nuclear Coulomb potential, an electron around the nuclei is kicked out and the muon forms an exotic bound state called muonic atom. Muonic atom provides a unique opportunity to study the nuclear structure such as the charge radius of the nuclei. In particular, the proton charge radius attracts renewed interest since the measurement of the Lamb shift in muonic hydrogen.[1)] The experiment derived a significantly discrepant result compared to the results of electron-proton scattering and hydrogen spectroscopy. This discrepancy has been an important unsolved problem in sub-atomic physics.

To obtain a new insight into the puzzle, a new measurement of the ground-state hyperfine splitting (HFS) in muonic hydrogen is planned. The experiment aims to determine the proton Zemach radius, which is defined as a convolution of the electric charge and magnetic moment distributions. As a preliminary experiment toward the spectroscopy of HFS, a muon spin rotation (μSR) measurement with a gaseous hydrogen target was proposed.[2)] The objective of the experiment was to understand the spin depolarization process involving the muonic hydrogen atom.

In a magnetic field, muon spin rotates with the Larmor frequency, which depends on the hyperfine state of muonic atom. Therefore, we can quantify the population of the hyperfine states and the depolarization effect by measuring the angular asymmetry of decay electrons.

Figure 1 illustrates the experimental setup at Port4

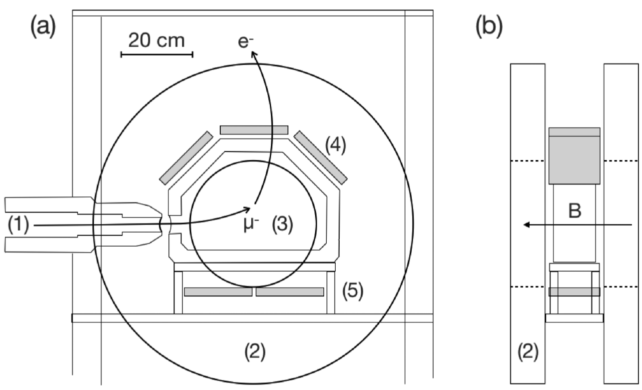

Fig. 1. Experimental setup: (a) cross-sectional view; (b) view from downstream. The numbers in the parentheses denote: (1) negative pulsed muon beam, (2) Helmholtz coils, (3) aluminium gas chamber, (4) top electron detectors, and (5) bottom electron detectors.

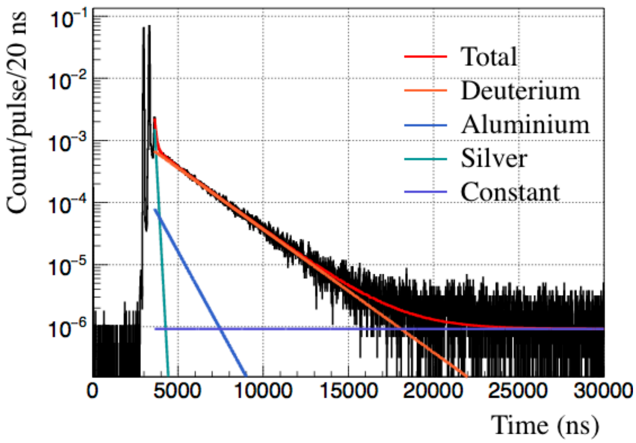

Fig. 2. Decay electron time spectrum with deuterium gas target at 1 atm. No magnetic field was applied. Each line corresponds to the respective fitting result.

in RIKEN-RAL muon facility. A transverse magnetic field was applied using the coils, which are parts of the CHRONUS spectrometer. Decay electrons from the muonic atoms were detected by the segmented scintillation counters with silicon photomultiplier (SiPM) readout. The detectors were originally developed for the muonium production experiment at Port3.[3)] A study conducted in 2016[4)] revealed that a countermeasure for the background arising from the duct-streaming neutrons is essential for sufficient signal-to-noise ratio. Accordingly, the detectors were placed away from the beam axis. The inner walls of the target chamber were covered with silver plates to reduce the lifetime of wall-stopped muons via nuclear capture.

The experiment was conducted in 2018 with a gaseous deuterium target to establish the measurement procedure. Deuterium was selected owing to its longer-lifetime of polarization instead of protium. Figure 2 shows a measured time spectrum of electrons from the muon decays. The spectrum was analyzed using a fitting function containing three exponential components and a constant background. Each exponential component corresponded to the muon lifetime in silver (87 ns), aluminium (864 ns), and deuterium (2195 ns). The beam momentum was optimized at several target densities considering the muonic hydrogen yield. The analysis for the μSR measurement under the transverse magnetic field is in progress.

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References

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