# Background study with negative muons in RIKEN-RAL for the laser spectroscopy of hyperfine splitting energy in muonic hydrogen

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We are planning a new measurement of the hyperfine splitting energy in ground-state muonic hydrogen in the RIKEN-RAL muon facility. This project was motivated by *the proton radius puzzle*, which is an unsettled problem on the root-mean-square charge radius of protons. Conventionally, the charge radius has been determined by electron-proton scattering and atomic hydrogen spectroscopy as compiled in CODATA.[1)] However, the charge radius determined from the Lamb shift in muonic hydrogen has a value smaller by 4 %, which corresponds to 7 times the standard deviation.[2,3)] Thus far, there has been no definitive explanation for this puzzling discrepancy.

In our proposed experiment, we will determine the proton Zemach radius, which is a convolution of the proton charge and magnetic moment distributions. Since the Zemach radius can be determined from the hyperfine splitting energy in hydrogen-like atoms, we derive it from muonic hydrogen which is a Coulomb bound system consisting of a negative muon and a proton. Then, we can obtain information on the magnetic structure inside the proton by probing with muons.

For laser spectroscopy, muon spin is re-polarized by a circularly polarized laser in the laser-induced transition between hyperfine sub-levels. The polarized muons have a spatial asymmetry in the electron emission from the muon decay ($\mu^- \to e^- + \overline{\nu_e} + \nu_\mu$). The resonance can be identified by detecting the spatial distribution of electrons.

In the experiment, pulsed negative-muons are stopped in a hydrogen target to form muonic hydrogen. The pulsed laser used to induce the transition between hyperfine sublevels is irradiated with a delay of 1 $\mu$s from muon stoppage to suppress background events caused by muon stoppage due to materials in other than the hydrogen target. Since the negative muon capture rate is proportional to $Z^4$, muons stopped in high-$Z$ materials around the target are quickly captured. In this manner, we aim to achieve a reduction factor greater than $10^{-4}$ at 1 $\mu$s compared to the prompt timing events at the time of muon stoppage.

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For the study of the background level, the timing spectrum after muon stoppage was measured in the RIKEN-RAL PORT-4 beam line. In the beam time in March 2016, we acquired data using an existing $\mu$SR spectrometer in PORT-4 (CHRONUS), which consists of segmented plastic scintillation counters. Each segment was viewed using a photomultiplier tube with wavelength shifting fiber.[4)] The timing spectrum obtained by CHRONUS is shown by the red line in Fig. 1. The inset shows a close-up of the prompt timing which shows peaks caused by electrons and muons in a double pulse. In the spectrum, there is an unknown long-tail component which is the severe background of the measurement. To suppress this background, we prepared another type of counters in the successive beam time in May 2016. It has two-layered plastic scintillation counters with photomultiplier tubes on both sides. We acquired the timing spectrum with the coincidence of the two counters. As shown by the blue line in Fig. 1, the long-tail component was drastically suppressed. The reduction factor is greater than $10^{-4}$, which is sufficient for the measurement. The origin of the component is still not understood, but it may be caused by neutral particles coming along with a negative muon pulse. Further investigation will be conducted in RIKEN-RAL, and the design of the electron counter will be finalized based on these studies.

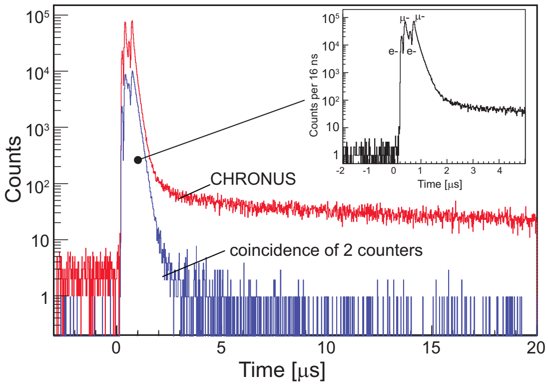


Fig. 1. Time spectra with negative muons obtained by CHRONUS (red) and coincidence counters (blue).

References

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