Measurement of the proton Zemach radius from the hyperfine splitting energy in ground-state muonic hydrogen

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Studies of the proton electromagnetic structure have recently attracted great interest stimulated by *the proton radius puzzle*, which is a 7σ discrepancy in the proton charge radius determined using two different methods. One is a traditional determination method using $e-p$ scattering and the atomic hydrogen spectroscopies as compiled in CODATA[1)]. The other is a method of laser spectroscopy of the Lamb shift in muonic hydrogen[2)]. To understand this inconsistency between "electronic" and "muonic" methods, there are several hypotheses including physics beyond the Standard Model. However, none of them are conclusive, and the puzzle is still an unsettled question.

Since the proton charge radius is defined only from the electric distribution in the proton, it is a curious question as to how we can determine the magnetic distribution of a proton probed with muons, which may become a clue to solve the puzzle. Therefore, we focus on the proton Zemach radius, which contains information on both the charge and magnetic-moment distributions in the proton. The proton Zemach radius, R_Z, is expressed as

$$R_Z = \int d^3\mathbf{r}|\mathbf{r}| \int d^3\mathbf{r}' \rho_E(\mathbf{r}')\rho_M(\mathbf{r}-\mathbf{r}'),$$

where ρ_E and ρ_M denote spatial distributions of the charge and magnetic moment of the proton, respectively. This Zemach radius can be determined from the hyperfine splitting energy of a hydrogen-like atom. Thus, we determine the proton Zemach radius from the laser spectroscopy of the hyperfine splitting energy of muonic hydrogen.

The experimental principle is as follows. When negative muons are stopped in hydrogen, they form muonic hydrogen atoms and are quickly deexcited to the ground state. Its energy level is split into hyperfine sublevels by the spin combination of the proton and muon: the spin singlet (F = 0) and the triplet (F = 1) states. The splitting energy is $\sim$0.183 eV, which corresponds to a mid-infrared frequency of 44.2 THz and wavelength of 6.78 μm. We will measure this energy through a laser spectroscopy. To search for the resonance frequency, the spatial asymmetry of spin-polarized muon decays is used. To populate the spin polarization in F = 1, we use a circularly polarized laser. A specific F = 1 state is selectively excited because of the conservation of the total angular momentum. The electrons from polarized muon decays are detected to find the decay asymmetry during the laser frequency scan.

A conceptual drawing of the experimental setup is shown in Fig. 1. Negative muons with momenta of 40 MeV/c are stopped in a gas hydrogen target. The density of the hydrogen gas is optimized to be 0.01% of LHD (liquid hydrogen density) to suppress the collisional quench process, which is a deexcitation from F = 1 to F = 0 through a collision with a neighboring atoms. The mid-infrared laser is injected from the side of the target $\sim$ 1 μs after the stopped μ^- timing. The laser power is a key issue to achieve sufficient polarization through a laser-induced excitation. The laser system is under development in RIKEN[3)], and the achievable laser performance is a power of 40 mJ and bandwidth of 50 MHz with a repetition rate of 50 Hz. For further enhancing the effective laser power by multiple reflection, a multi-pass cavity consisting of two mirrors facing each other is installed in the hydrogen target, as schematically illustrated in the figure. The mirror reflectivity is assumed to be 99.95% and the resulting polarization is $\sim$16%.

The yield estimation and a feasibility study of the present measurement are nearing completion. A beam study with negative muons in RIKEN-RAL is scheduled for the next fiscal year.

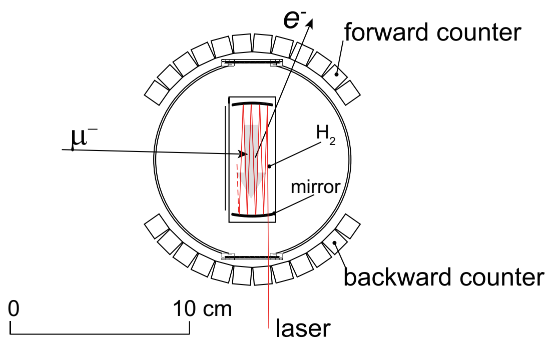

Fig. 1. Conceptual drawing of the experimental setup.

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References

1) P. J. Mohr, B. N. Taylor, D. B. Newell: Rev. Mod. Phys. **84**, 1527 (2012).
2) R. Pohl et al.: Nature **466**, 213 (2010).
3) N. Saito et al.: Proc. of SPIE, Vol. 8526, 852605 (2012).