Laser spectroscopy of the hyperfine splitting energy in the ground state of muonic hydrogen

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2014-04/67

A new measurement has been proposed to determine the proton Zemach radius from the ground-state hyperfine splitting energy of muonic hydrogen by mean of a laser spectroscopy. The resonance frequency corresponding to the hyperfine splitting energy difference is searched with a recently-developed mid-infrared laser. We have studied the experimental feasibility in the RIKEN-RAL muon facility.

1 Physics motivation

One of the recent hot topics in the present physics is *the proton radius puzzle*, which was stimulated by a measurement of the muonic hydrogen Lamb shift at Paul Scherrer Institute [1]. It is a discrepancy of the proton charge radius obtained by the muonic hydrogen Lamb shift from those by the ordinary methods such as electron-proton scattering and hydrogen spectroscopy [2]. The difference seems not to be attributed to the experimental uncertainty because it is more than 7σ by taking into account the new precise measurements in both sides [3, 4, 5]. To explain the discrepancy, there are several interpretations including hypotheses for physics beyond the standard model. However, none of them are still conclusive.

Meanwhile, the proton internal structure is not only related with the electric distribution, as defined as charge radius, but also with the magnetism distribution. It is a very interesting question how the magnetic distribution of the proton is determined by muons and it may give a definitive answer to understand proton radius puzzle. Therefore, we focus on the proton Zemach radius R_Z, which is defined as,

$$R_Z = \int d^3\mathbf{r}|\mathbf{r}| \int d^3\mathbf{r}' \rho_E(\mathbf{r}')\rho_M(\mathbf{r}-\mathbf{r}'), \tag{1}$$

where ρ_E and ρ_M denote the spatial distribution of the proton charge and the magnetism, respectively. To derive the proton Zemach radius, we measure the hyperfine splitting energy of

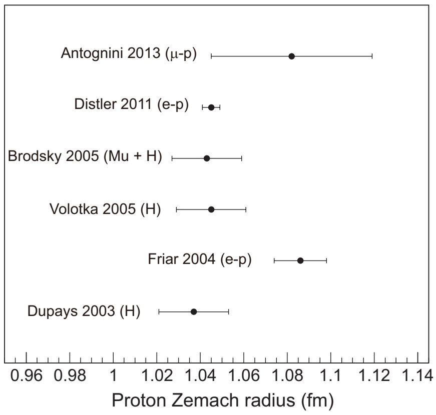

Figure 1: Summary of proton Zemach radius measurements.

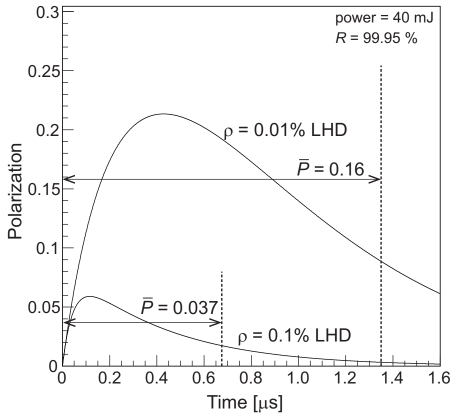

Figure 2: Time population of the muon spin polarization.

the muonic hydrogen. Theoretically, the hyperfine splitting energy is described as [6],

$$\Delta E_{HFS} = E_F(1 + \delta^{QED} + \delta^{FF} + \delta^{rec} + \delta^{pol} + \delta^{hvp}), \tag{2}$$

where E_F denotes the Fermi energy. The terms δ^{QED}, δ^{FF}, δ^{rec}, δ^{pol} and δ^{hvp} indicate the corrections related with higher order QED, proton electromagnetic form factor, recoil effect, proton polarizability and hadronic vacuum polarization, respectively. The dominant contribution is δ^{FF} and is as large as ∼7500 ppm [7]. Its leading contribution is expressed with the proton Zemach radius as, $\delta^{FF} = -2\alpha m_{\mu p} R_Z + O(\alpha^2)$, where α and $m_{\mu p}$ is the fine structure constant and the reduced mass of the muon and the proton. As same with the charge radius, the proton Zemach radius has been determined by $e - p$ scattering and the hydrogen spectroscopy [7, 8, 9, 10, 11]. Very recently, the PSI group has determined the Zemach radius from the two transitions in the 2S to 2P states of muonic hydrogen [5]. That is the first determination of the proton Zemach radius from the muonic system, however, the accuracy is still lower than the electronic determinations. A summary of the proton Zemach radius measurements is plotted in Fig. 1. Our goal is to determine proton Zemach radius from muonic hydrogen with much higher precision.

2 Principle

The experimental principle is as follows.

- *Formation of the muonic hydrogen*
  Negative muons are stopped in the hydrogen target. In the initial capture, an excited state of the muonic hydrogen is formed with a high principle quantum number of ~ 14, however, the state is quickly de-excited to the ground state. Since the nuclear capture rate in the muonic hydrogen is extremely small, muons in the atomic ground state decay with almost the same lifetime of free muons ($\tau = 2.197\ \mu$s).

- *Laser-induced hyperfine sublevel transition*
  We irradiate a laser before muon decays to induce a transition from $^1S_0$ to $^3S_1$. The ground state hyperfine splitting energy is 0.183 eV, which corresponds to the mid-infrared wavelength of 6.78 μm. A selective excitation in a specific $^3S_1$ state ($m_Z = +1$ or -1) is realized by using a circularly-polarized laser due to the conservation rule of total angular momentum. Then the muon spin in $^3S_1$ is polarized.

- *Detection of the muon decay asymmetry*
  If polarized muons in the $^3S_1$ state decay, the emission of electrons has an asymmetry in the spatial distribution by V-A theory. Therefore, the electron emission asymmetry will be a signal to search for the resonance during the frequency scan. We detect asymmetry in the number of decay electrons in the forward and backward directions along with the laser direction.

These are the brief principle of the proposed measurement. The feasibility with the above procedure is discussed in the next section.

3 Feasibility

To accomplish the measurement, we study the two key issues; the laser-induced transition probability from $^1S_0$ to $^3S_1$ and the collisional quench rate in the $^3S_1$ state.

To detect muon decay asymmetry in the $^3S_1$ state with a limited beam time, the transition probability has to be sufficiently high to scan over a wide range of the frequency. The laser-induced transition probability P is evaluated with the laser power E [J], the cross sectional area S [m^2] and the temperature T [K] as, $P = 2{\times}10^{-5} E/S/\sqrt{T}$ [12]. The probability is proportional to the laser power, thus the intense mid-infrared laser is important for this measurement. Very recently mid-infrared laser system with intense and narrow band-width has been developed in RIKEN [13]. The precision of the hyperfine splitting energy is expected to be $\sim$2 ppm due to the narrow band-width. With realistic parameters of $E = 40$ mJ, $S = 4$ cm^2 and $T = 20$ K, the probability is calculated to be 4.4×10^{-4}. Since this probability is too small to perform the measurement, we adopt a multi-pass cavity installed in the hydrogen target to enhance the effective laser power by a reflection with mirrors facing each other. We assume the reflectivity of the mirror to be 99.95%. Then achievable polarization is estimated with the effect of the collisional quench rate discussed below.

The second issue is the collisional quench rate. It is known that the muon in the $^3S_1$ state is quickly de-excited to the $^1S_0$ state by a collision with a neighboring hydrogen atom and lose the polarization. If the collisional quench rate is much larger than that of the muon decay, the muon polarization made by the laser excitation is mostly lost before muon decays. Therefore, this quench rate is essential and should be comparable with the muon decay rate. Theoretically, this quench rate is calculated in Ref. [14], and it is proportional to the hydrogen density. A typical quench rate is 20 MHz with the density (ρ) of 0.1% of the liquid hydrogen density (LHD), which corresponds to the $^3S_1$ lifetime of 50 ns.

With the discussion above, we estimate the muon spin polarization taking into account the transition and quench rates. Figure 2 shows the time population of the muon spin polarization. After laser injection, the polarization increases slowly due to the small transition probability caused by each laser pass, but eventually decreases with the attenuation of the laser after the multiple reflection. The averaged polarization during the optimized time gate is 3.7 % with

$\rho = 0.1\%$ LHD. If we decease the hydrogen density to be 0.01% LHD, the polarization is increased to be 16% due to the longer lifetime of the $^3S_1$ state as shown in the figure.

Finally, we estimate the beam time for the measurement in the RIKEN-RAL muon facility. A typical intensity of 40 MeV/c negative muon beam is 2×10^4 s^{-1} with double pulse operation [15]. With the density of $\rho = 0.1\%$ LHD, about 0.1% of muons stop in the hydrogen target. For the electron counter, the acceptance and the sensitivity of spin polarization are 28% and 23%, respectively. Then the time to find the resonance with the significance of 3σ is 25 hours, where the standard deviation is defined by the statistical fluctuation in the electron counts.

We simply set the range of the scan region to be ± 5.7 GHz, taken from a convolution of theoretical uncertainty of δ^{FF} and δ^{pol} in Ref. [7]. The scan interval is assumed to be 100 MHz which is comparable with the resonance width of $\sim$80 MHz. We follow the three-stage scan over the frequency range above. The first and second scans are devoted to finding the resonance frequency with 3σ and 5σ significance, respectively. In the third scan, we determine the resonance frequency with fine step of 50 MHz. In total, we need 220 days for the scan sequence. With lower hydrogen density of 0.01% LHD, the time is reduced to 26 days because of the higher spin polarization. However it is very challenging to perform with such a low-density gas target against the background. We plan to follow stepwise beam studies to optimize the experimental condition in RIKEN-RAL.

4 Summary

We propose a new measurement of the hypdrefine splitting energy in the ground-state muonic hydrogen. A newly-developed intense mid-infrared laser enables us to measure it with an unprecedented accuracy of $\sim$ 2 ppm. The spin polarization in the spin triplet state is populated by a circularly-polarized laser. We search for the resonance frequency by detecting the spatial asymmetry in the polarized muon decay. From the measurement of the hyperfine splitting energy, we can derive the proton Zemach radius. The measurement is feasible at the RIKEN-RAL pulsed-muon facility.

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