Laser spectroscopy of the 1s hyperfine splitting energy of muonic hydrogen for the determination of proton Zemach radius

K. Ishida
RIKEN

Proton Radius Puzzle
Zemach radius and hyperfine splitting
Plan of our measurement
Status
Atomic binding energy $\sim (m_\mu/m_e)$
Energy shift by proton size $\sim (m_\mu/m_e)^2$
Relative sensitivity $\sim (m_\mu/m_e) \sim 200$
Proton radius puzzle?

Proton - major constituent of matters
charge, spin, mass - very well measured

Proton radius affects many precision measurements and should be known

Serious discrepancy was first found in 2010
in new proton radius measurement using muonic hydrogen

The radius was smaller by 4% (7σ) from the CODATA value
Proton Charge Radius Puzzle
PSI Measurement ($\mu p$ 2s-2p by CREMA collaboration)

Measurement of 2s-2p energy difference
Formation of $\mu p$ (1% feeds 2s)
  Laser resonant excitation of 2s-2p (Lamb Shift)
Observation: 2s metastable state -> 2p->1s
Proton Radius Puzzle

Further measurement and analysis did not ease the discrepancy.

Proton Radius Puzzle: Recent Update

Hydrogen atom
three new results - some closer, some not ...
and existence of many older values ...

Bezginov et al. (Toronto), Science 6.9.2019 measuring 2S-2P

Graph showing data points for proton radius measurements.
Proton Radius Puzzle: Recent Update

**ep scattering**
MAMI (Mainz) e- p high statistics data consistent with previous values, detail analysis continuing also, preparation of new better target, separation of $G_M$, ...

JRAD (Jefferson) e- p at high energy and low $Q_2$
new data indicates radius value consistent with $\mu p$ Lamb shift

ULQ2 (Tohoku) low energy e- p preparing

**$\mu p$ scattering**
MUSE (PSI) $\mu p$/ep scattering direct comparison - run nearly ready

COMPASS (CERN) 190GeV $\mu$ -low energy ($Q^2$) p recoil - in a few years
Where will we go?

2018 CODATA lists "both" values
0.8751(61) fm 2014 CODATA value
0.8414(19) fm $\mu p$ -atom Lamb shift

1. Need to be checked/confirmed
   new measurements/data are arriving
   still do not know how to understand new/old data ...

2. Checking theory/analysis
   Many refined analysis of scattering data,...
   Calculation of correction factors,...
   Beyond SM, lepton universality breaking,...

3. Zemach radius $r_Z$
   another proton radius accessible by spectroscopy
   includes magnetic structure
Zemach radius

How about magnetic radius of proton?

$=>$ Hyperfine splitting is related to the magnetic moment. 

$$R_Z = \int d^3 r \int d^3 r' \rho_E(r') \rho_M(r - r')$$

convolution of charge and magnetic moment distribution

Why not only magnetic but also charge distribution?

$=>$ Hyperfine coupling is affected with distributed magnetic moment

$=>$ Charge distribution reduces muon attraction and modify overlap

Through $R_Z$ measurement,

If the muon and electron determination are consistent

- $=>$ some problem in charge radius measurements?

If they are different

- $=>$ radius puzzle continues,
  
  size of discrepancies may give us hint
Zemach radius so far

2s HFS was indirectly determined in the same CREMA experiment at PSI (from two lines)

\[ R_z = 1.082(37) \text{ fm} \]  


from e-p: 1.086(12), 1.045(4) fm

from H spectroscopy: 1.047(16), 1.037(16) fm

No definitive interpretation with proton radius puzzle because of the large error bar

Need high precision values

Direct measurement of 1s HFS has chance to determine Rz to better than 1%
Formation of Muonic Hydrogen atom ($\mu^-p$)

Muon stops in hydrogen

Muon capture at high orbit and cascade to ground state

Rapid conversion to lower hyperfine state

$\Rightarrow$ no muon polarization left

All muons reach 1s ground state

vs. 1% only to 2S in PSI Lam Shift measurement

$\Delta E_{\mathrm{HFS}} \approx 0.183 \text{ eV}$

$1^3S_1$ (F=1) but $1^1S_0$ (F=0)
HFS splitting energy

How is the Zemach radius determined?

In the first order, proportional to muon and proton magnetic moments \(1/m_\mu \) and \(\mu_p\) and to \(1/R_{\mu p}^3\) but with correction terms, some are structure dependent

\[
\Delta E_{HFS}^{exp} = E_F \left(1 + \delta_{QED} + \delta_{Zemach} + \delta_{recoil} + \delta_{pol} + \delta_{hvp}\right)
\]

Fermi term:

\[
E_F = \frac{8}{3} \alpha^4 \frac{m_{\mu(e)}^2 m_p^2}{(m_{\mu(e)} + m_p)^3} \mu_p
\]

\(\delta_{QED}\): higher order QED correction (well known)

\(\delta_{Zemach} = -2\alpha m_\mu R_z + O(\alpha^2)\)

\(\delta_{recoil}\): recoil (well known)

\(\delta_{pol}\): proton polarizability (internal dynamics of protons)

\(\delta_{hvp}\): hadron vacuum polarization (small)

\[
R_Z = \left\{ \left(E_F \left(1 + \delta_{QED} + \delta_{recoil} + \delta_{pol} + \delta_{hvp}\right) - \Delta E_{HFS}^{exp}\right)/1.281 \right\} = 1.0XX(13) \text{ fm}
\]

1130(1) ppm 1700(1) ppm 20(2) ppm
460(80) ppm (2) ppm
proton polarizability

\(R_Z\) will be improved to 1 \(\%\) (with present limitation by \(\delta_{pol}\) precision).

or even better with improvement of \(\delta_{pol}\) (dispersion relation, QCD, ...),
Zemach radius measurement with muons

There are three proposals
This will make independent measurements possible

Two groups use increased kinetic energy after back decay
1) CREMA-3 at PSI
Faster $\mu p$ diffusion to wall

2) FAMU proposal to RIKEN-RAL
energy dependent muon transfer rate to admixture oxygen

$\mu p + O \rightarrow \mu O + p$

3) RIKEN group propose spin polarization measurement at RIKEN-RAL and J-PARC
simple & straightforward
Zemach radius measurement with muons

3) RIKEN group propose spin polarization measurement at RAL and J-PARC (idea started in discussion in RIKEN including M. Iwasaki and Ishida in 2013)

- (1) resonant excitation by circularly polarized laser
- (2) formation of triplet state with muon spin polarized
- (3) asymmetric emission of electron from muon decay

(0) ground state unpolarized

All based only on well known processes! No need of phenomenological simulation
RIKEN MuP Collaboration

K. Ishida, S. Kanda, M. Iwasaki, M. Sato*, Y. Ma,
S. Okada, S. Aikawa, H. Ueno, A. Takamine,
K. Midorikawa, N. Saito, S. Wada, M. Yumoto

RIKEN
Y. Matsuda, K. Tanaka**

Graduate of School of Arts and Science, The University of Tokyo
Y. Oishi

KEK

* Present address: KEK

** Present address: CYRIC, Tohoku Univ.

New collaborators are welcome
Key for the measurement

1. Increase **excitation** rate (M1 transition) and polarization

   **Intense mid infrared laser** developed at RIKEN + multi-pass cavity

2. Many muonic hydrogen atoms

   **Intense pulsed muon beam** at RIKEN-RAL and J-PARC

   Optimum gas condition, gas container,

   muon stopping simulation/measurement (test at RIKEN-RAL)

3. Optimization of **polarization detection**

   Detectors, Filtering by lifetime, Background reduction
Plan: Laser excitation

Laser requirement for $\mu p\ 1S$ HFS

$0.183\ eV = 6.8\ \mu m = 44\ THz$

Excitation rate

$$P = 2 \times 10^{-5} \frac{E}{S\sqrt{T}}$$

$E/S$: laser power density [$J/m^2$], $T$: temperature [K]

Doppler broadening (cooling to ~20 K helps => 63 MHz)
(A. Adamczak et al., NIM B 281 (2012) 72,
with correction by 1/4 , private communication)

ex. $E = 40\ mJ$, $S = 4\ cm^2$, $T = 20\ K$, then $P = 4.5 \times 10^{-4}$

by using multi-pass cavity (like PSI)

high reflective mirror 99.95%

$P=45\%$ after 1000 pass

However, ...
Experimental challenge: loss of polarization

Muon may lose polarization before decay by external collision:

\[ \mu \rho(\uparrow\uparrow) + p \rightarrow \mu \rho(\uparrow\downarrow) + p \]

Theoretical calculations (no measured rate)

Solution:
Use low density hydrogen to keep polarization
50 ns at 0.001 LHD (Liquid Hydrogen Density)
500 ns at 0.0001 LHD

Muon Polarization Calculation: build up and decay
0.001 HD target
Excitation by 40 mJ
Multi-pass laser cavity
Polarization of 0.037 in a time gate 0.7 μs (0.001 LHD)
Detection of Polarization

Circularly polarized laser select of one the excited sub-state
=> complete muon spin polarization
Muon decays with 2.2 $\mu$s lifetime and emits electrons asymmetrically to the spin. $\mu^- \rightarrow e^- \nu \nu$

Muon stopping simulation and background

Condition:
H2 target cell 0.0001 LHD and 4 cm^2 x 6 cm 20 K
40 MeV/c pulsed muon beam at RIKEN-RAL

Geant Simulation Result:
0.1% of incoming mons stops in 0.0001 LHD hydrogen gas
(or 1% at 0.001 LHD)

Using high-Z materials as the target cell,
muons in those materials disappear quickly
by nuclear capture (90ns in silver)

Laser injection after 1 µs
when backgrounds died away
Yield estimation (statistics)

Observe forward/backward ratio for the polarization effect

\[ \frac{N_F - N_B}{N_F + N_B} = A_0 \, P \]

Beam condition
- Intensity \(2.2 \times 10^4\)/s @40 MeV/c (RIKEN-RAL)
- Momentum width \(\sigma_p/p_0 = 2\%\)

Target condition
- H2 gas 0.001 LHD, Volume 4cm\(^2\) x 6 cm

Laser
- 40 mJ, 99.95% reflectivity, cavity length

Detector (solid angle 28% each, polarization sensitivity factor 0.23)

Time gate: laser at 1.0 \(\mu\)s after muon + 1.33 \(\mu\)s detection gate

Statistics in 5 hours

\(\Rightarrow\) signal \(N_F - N_B\), \(\sim 240\)

fluctuation \(\Delta N_F + \Delta N_B \sim \sqrt{(N_F + N_B)} \sim 80\)

significance = \(\frac{(N_F - N_B)}{\sqrt{(N_F + N_B)}} \sim 3\sigma\)

Time is doubled (~10 hour) for accumulating laser on and off
Scan of 100 laser wave length points = 1000 hours \(\Rightarrow\) 40~50 days
Fine scan near resonance takes another +30 days.
Beam test of background level

Beam test at RIKEN-RAL
Muons stopped in Cu target
We confirmed

Fast decay out of muons in high-Z materials like Cu
Low background level (< $10^{-4}$) at $\sim 1 \mu$s

Beam time in May (5/11-13): CHRONUS $\rightarrow$ coincidence counters

Also, studies on muon stopping in thin H2 target

Design the prototype of electron counters
beam test with dilute gas
R&D study: Measurement of muon polarization in hydrogen and quench rate of triplet state

"Measurement" of triplet $\mu_p$ quench rate (S. Kanda) by muon spin rotation method
$\mu_p(F=1)$ 3.1 MHz@0.067T, $\mu_d(F=3/2)$ 3.1 MHz @0.057T

Challenge: Stopping S/N of muons in thin H2 gas (0.1~1 atm) and rejection of wall stop muons

Measurement done at RIKEN-RAL with D2 in September 2018,

H2 planned in Nov, use of 20 MeV/c muons (good S/N)
RIKEN laser group's experience on 6 μm laser + frequency stabilization with QCL
Achieve10mJ+10mJ with best matching component and multi-source injection
Optimizations of laser components are in progress.

2.09 μm output

6 μm output
Beam time estimate: at J-PARC

If the laser power is half (~20 mJ), measurement at RIKEN-RAL is not practical (>1 year).
At J-PARC, with quicker data accumulation (x20?) Same statistics could be obtained in ~20 days.
Alternative idea (S. Kanda)

µp atomic beam from H2 film
No collisional quench! - much higher polarization
Emission efficiency ~0.5% at 0.2 eV (calc.)
Velocity ~6 mm/µs
Separation from decay in target by electron tracking

Using our expertise
1) Solid hydrogen film target
   µA* by P. Strasser
2) Detection of muon decay in vacu
   thermal Mu for g-2
Summary

Large discrepancy in proton radius values between measurements "Proton radius puzzle"
New measurements and more data are arriving but the puzzle has not been solved yet.

How about Zemach radius from \( \mu p \) HFS?
Preparing laser excitation and detection with muon spin polarization

Status for the measurement
Instruments design, simulation for RIKEN-RAL/J-PARC
Test of mid-infrared laser components at RIKEN
Beam and \( \mu p \) polarization studies have started at RIKEN-RAL