20th Particles & Nuclei International Conference @ Hamburg

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

RIKEN

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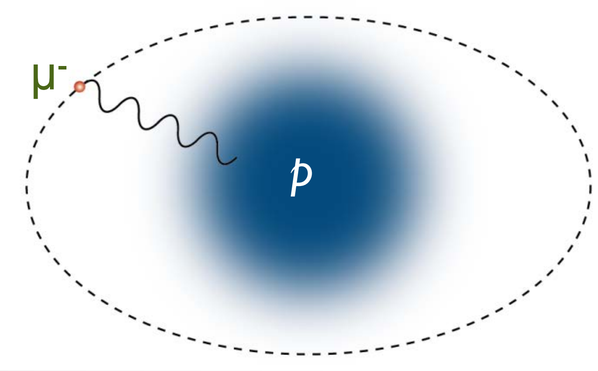
Introduction

- *structure of the proton is one of the most fundamental observables in the atomic and nuclear physics*

  (radius, form factor etc)

- *Muonic hydrogen atom*

  an exotic atom consisted with μ- and p



$m_\mu/m_e \sim 207$, $R \sim a_B/207$

probability within the proton :

$(r_p/a_B)^3 = (\alpha m_{\mu p}\, r_p\,)^3 \sim 8 \times 10^6$

bound μ feels the effect of the proton structure

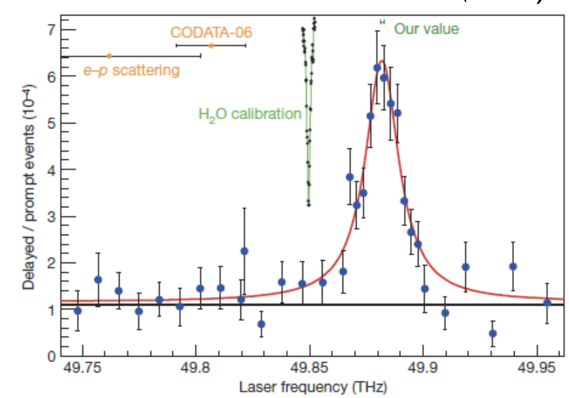
Study the internal structure of proton probed by muonic hydrogen

Proton radius puzzle

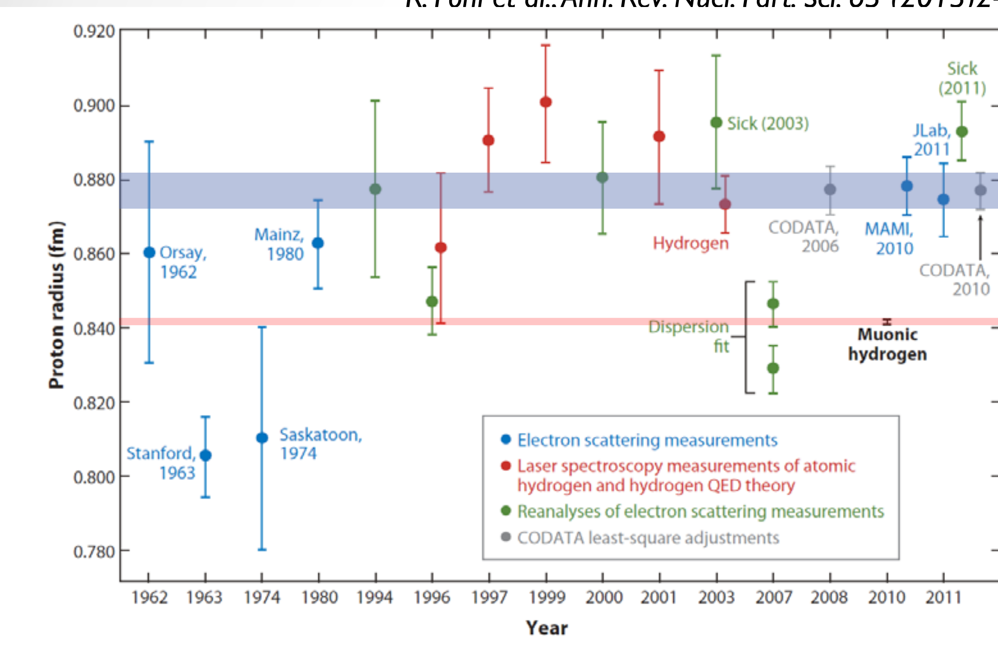
Discrepancy in proton charge radius determined by;

- *hydrogen spectroscopy / e-p scattering*
- *muonic hydrogen Lamb shift (PSI)*

R. Pahl et al., Nature 466 (2010)



R. Pohl et al.. Ann. Rev. Nucl. Part. Sci. 63 (2013)242001



e-p & H

7 σ deviation

μ-p

"Proton radius puzzle"

Still unsettled question:

- *errors in the measurements?*
- *structure-dependent corrections are wrong?*
- *QED needs modification (in μ- p interaction)?*
- *new physics beyond the standard model?*

How is the radius by magnetic moment distribution?

(Zemach radius, magnetic radius)

Physics motivation

proton Zemach radius

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

convolution of charge and magnetic moment distribution(ρ_E, ρ_M)

good physics quantities for studying proton electronic & magnetic structure

- *determined from Hyperfine splitting energy of H-like atom*

$$\Delta E^{th}_{HFS} = E_F(1 + \delta_{QED} + \delta_{str})$$

➢ E_F *:Fermi term* $E_F = \frac{8}{3}\alpha^4 \frac{m^2_{\mu(e)} m^2_p}{(m_{\mu(e)} + m_p)^3} \mu_p$

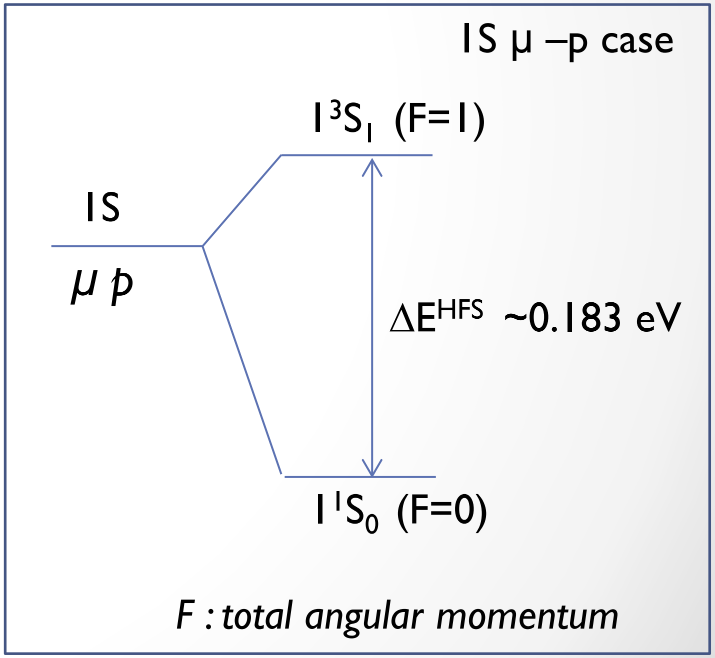
➢ δ_{QED} *:higher order QED correction*

➢ δ_{str} *:proton structure correction*

$$\delta_{\mathrm{str}} = \delta_{Zemach} + \delta_{recoil} + \delta_{pol} + \delta_{hVP}$$

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

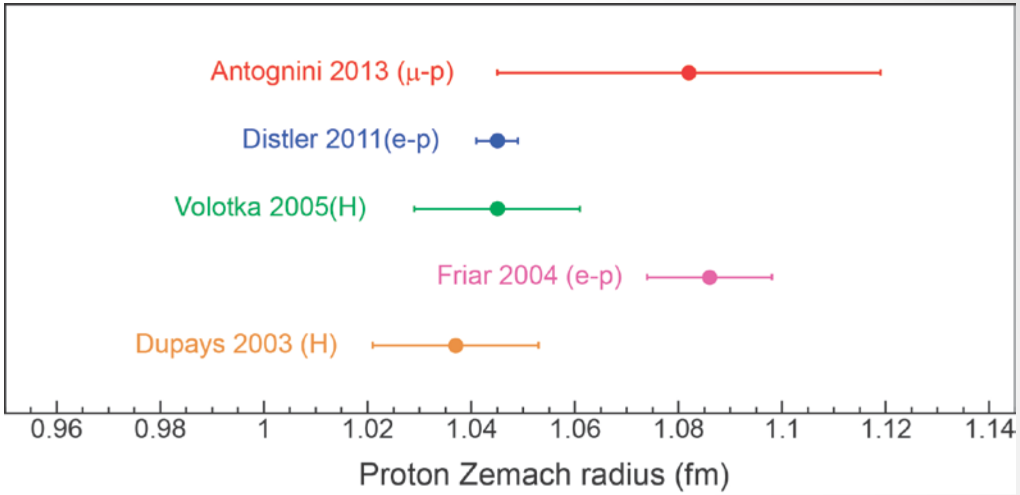
directly connected with Rz



Past measurements on Zmeach radius

- *hydrogen spectroscopy*

R_z =1.037(16) fm *Dupays et al., PRA(2003)*
=1.047(19) fm *Volotka et al., EPJ(2005)*

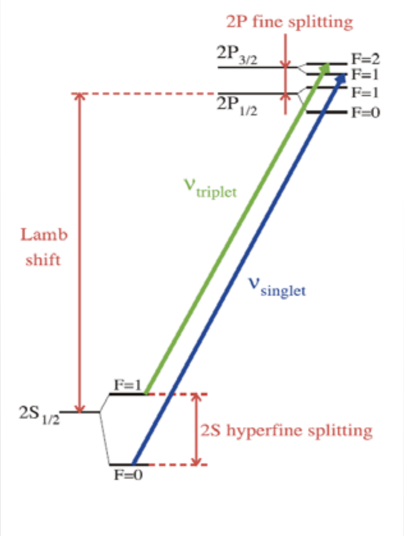


- *e-p scattering*

R_z =1.086(12) fm *Friar & Sick, PLB(2004)*
=1.045(4) fm *Distler et al., PLB(2011)*

- *muonic hydrogen 2S HFS*

R_z = 1.082(37) fm



- *latest value of e-p and H spectroscopy are consistent within their errors*
- *μ-p value differs? But accuracy is insufficient to verify.*

New measurement of μp 1S ΔE_{HFS}

- *muonic hydrogen 1S HFS energy* ← *not measured precisely before*

  laser spectroscopy : 0.183 eV = ~6.8 μm (=~44 THz)

  mid infrared laser is needed

Our goals :

- *determine 1S ΔE_{HFS} with an accuracy of ~* 100 MHz (~ 2 ppm)

  due to accuracy of frequency

  the 1st precise measurement of g.s. ΔE_{HFS} of μ-p

  fundamental quantity of μ-p system

  (can determine proton structure correction (δ^{str}) with ~ppm accuracy)

- *derive Zemach radius from ΔE_{HFS}*

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

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

$$R_Z = \left\{\left(E_F\,(1 + \delta_{QED} + \delta_{recoil} + \delta_{pol} + \delta_{hvp}\right) - \Delta E_{HFS}^{exp}\right\}/1.281$$

as same with hydrogen spectroscopy

Expected precision of Zemach radius

$$R_Z = \{(E_F\,(1+\delta_{QED}+\delta_{recoil}+\delta_{pol}+\delta_{hvp}) - \Delta E^{exp}_{HFS}\}/1.281(<10?)$$

(need radiative correction)

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

Dupays et al., PRA 2003

	Hydrogen		Muonic hydrogen	
	Magnitude	Uncertainty	Magnitude	Uncertainty
E^F	1418.84 MHz	0.01 ppm	182.443 meV	0.1 ppm
δ^{QED}	1.13×10^{-3}	$<0.001\times10^{-6}$	1.13×10^{-3}	10^{-6}
δ^{rigid}	39×10^{-6}	2×10^{-6}	7.5×10^{-3}	0.1×10^{-3}
δ^{recoil}	6×10^{-6}	10^{-8}	1.7×10^{-3}	10^{-6}
δ^{pol}	1.4×10^{-6}	0.6×10^{-6}	0.46×10^{-3}	0.08×10^{-3}
δ^{hvp}	10^{-8}	10^{-9}	0.02×10^{-3}	0.002×10^{-3}

R_Z = *1.0??(13) fm*

improved factor ~3 from PSI results, but δ_{pol} is dominated in error.

We need help of theorists to improve precision.

improvement of proton polarizability correction (δ_{pol}) drastically reduces uncertainty of Rz (as same with hydrogen case)

hydrogen case 1.4(6) ppm
muon case 460(80) ppm

check with R_Z determined by "electronic" and "muonic" measurement

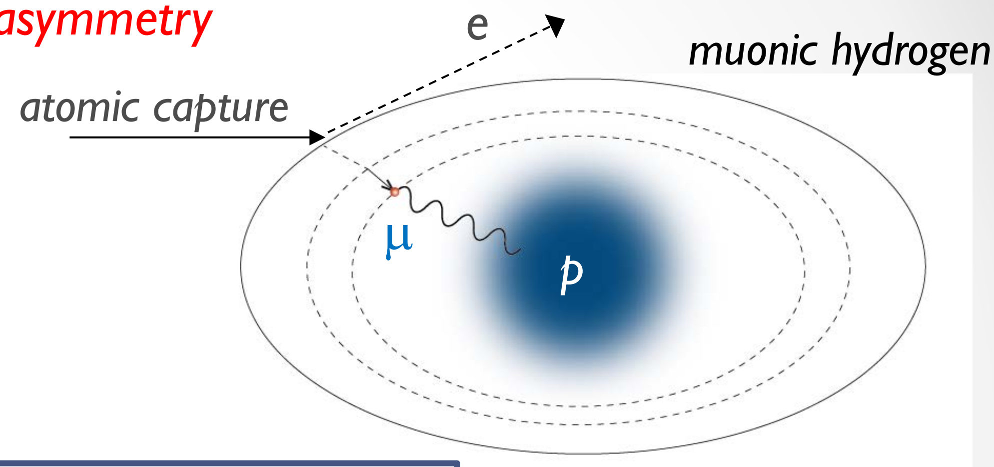
Experimental principle

Experimental principle (I)

Laser spectroscopy : *signals of the resonance frequency*

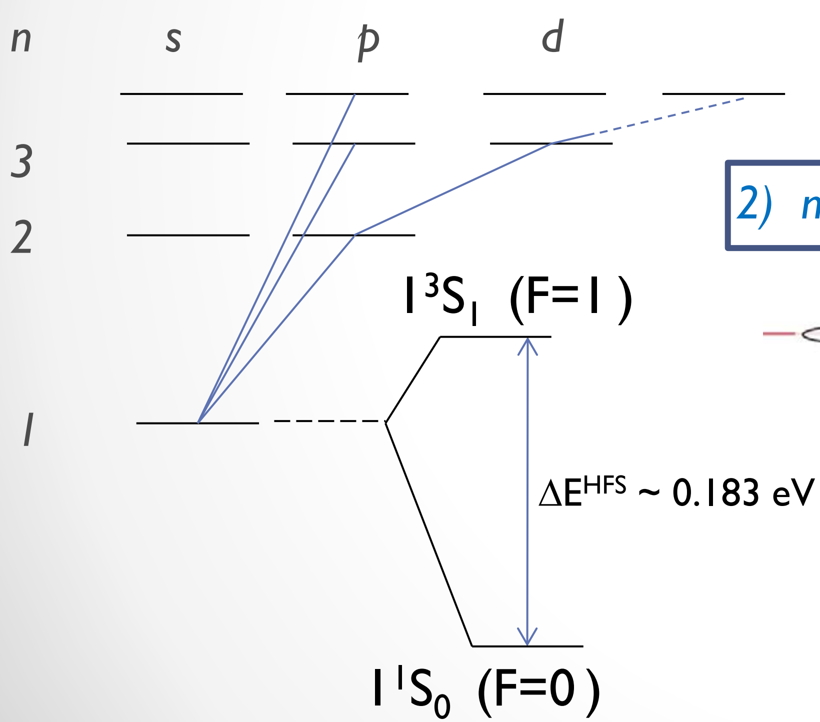
→ *muon decay asymmetry*

1) Produce μ-p atom by pulsed muon source

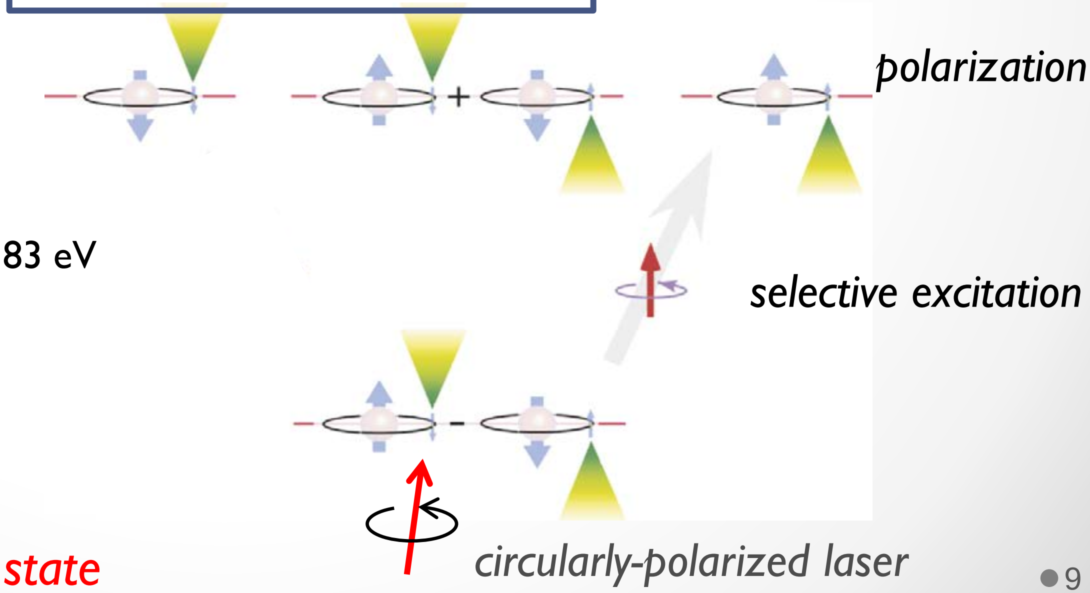


stop μ^- in hydrogen

→ g.s. μ^--p atom



2) make polarization by laser



polarization in F=1 state

Experimental principle (2)

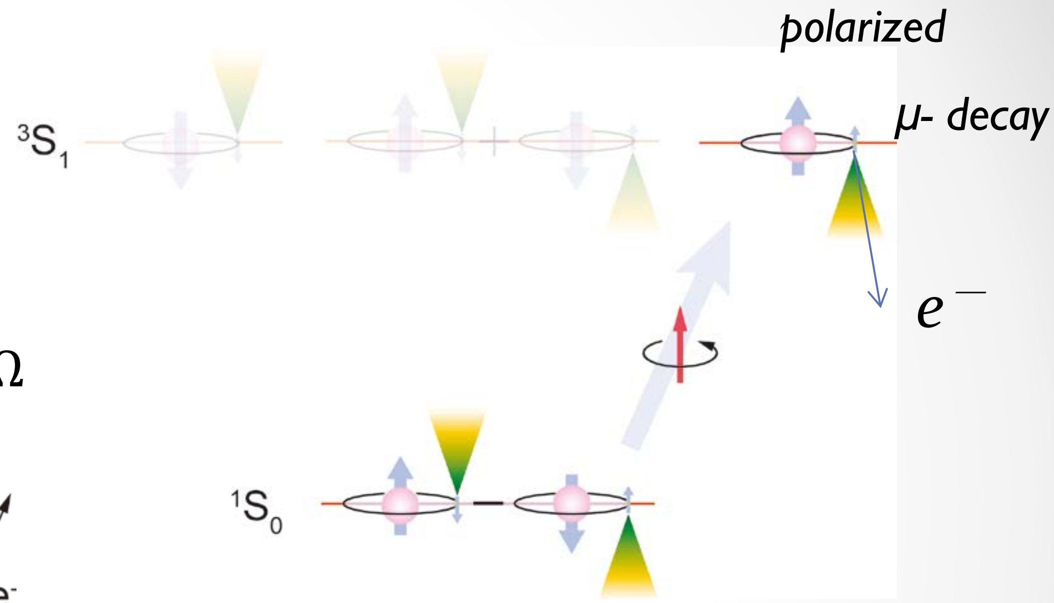
3) detect decay electron

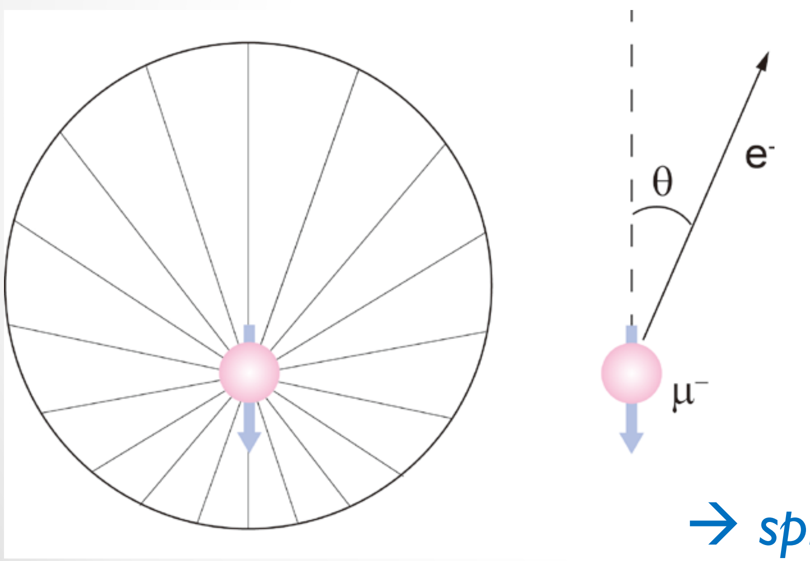
$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

muon decay asymmetry

with polarization (P) : V - A theory

$$d\sigma_{e^-}(\theta)d\Omega \propto \left(1 - \frac{1}{3} P \cos\theta\right) d\Omega$$



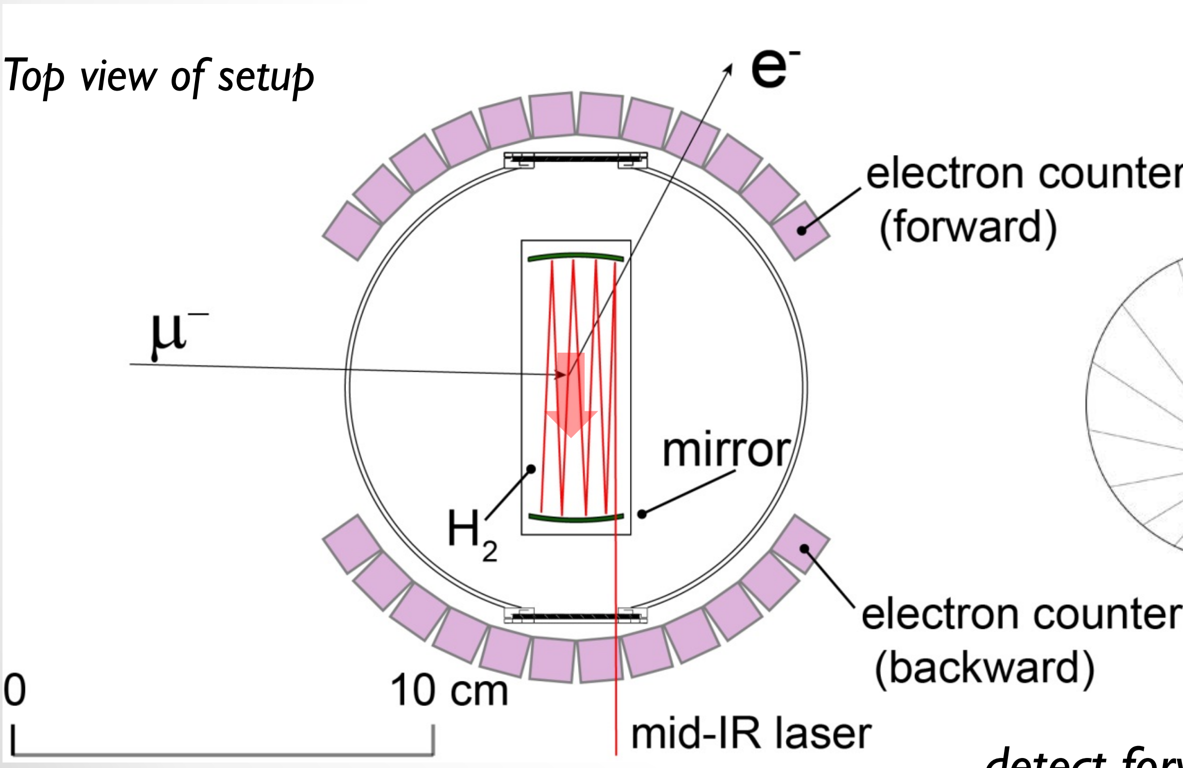


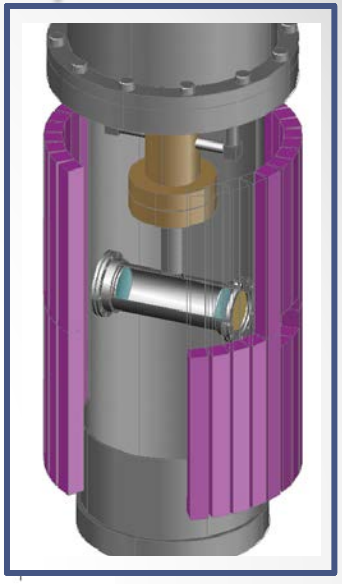
more decay electrons in opposite direction of muon spin

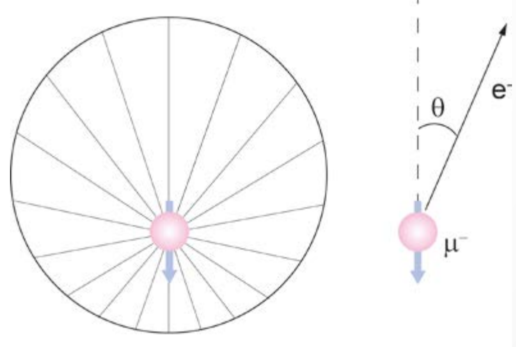
→ spin polarization (= resonance frequency) can be detected decay asymmetry of muons

Conceptual design of experimental setup

1) *H_2 target*
2) *tunable mid-infrared laser*
3) *decay electron counter(forward and backward)*







detect forward/backward electrons

decay asymmetry = N_F - N_B

Feasibility?

- *F=0 → F=1 transition probability*

  expected to be small because of M1 transition

  ∝ laser power

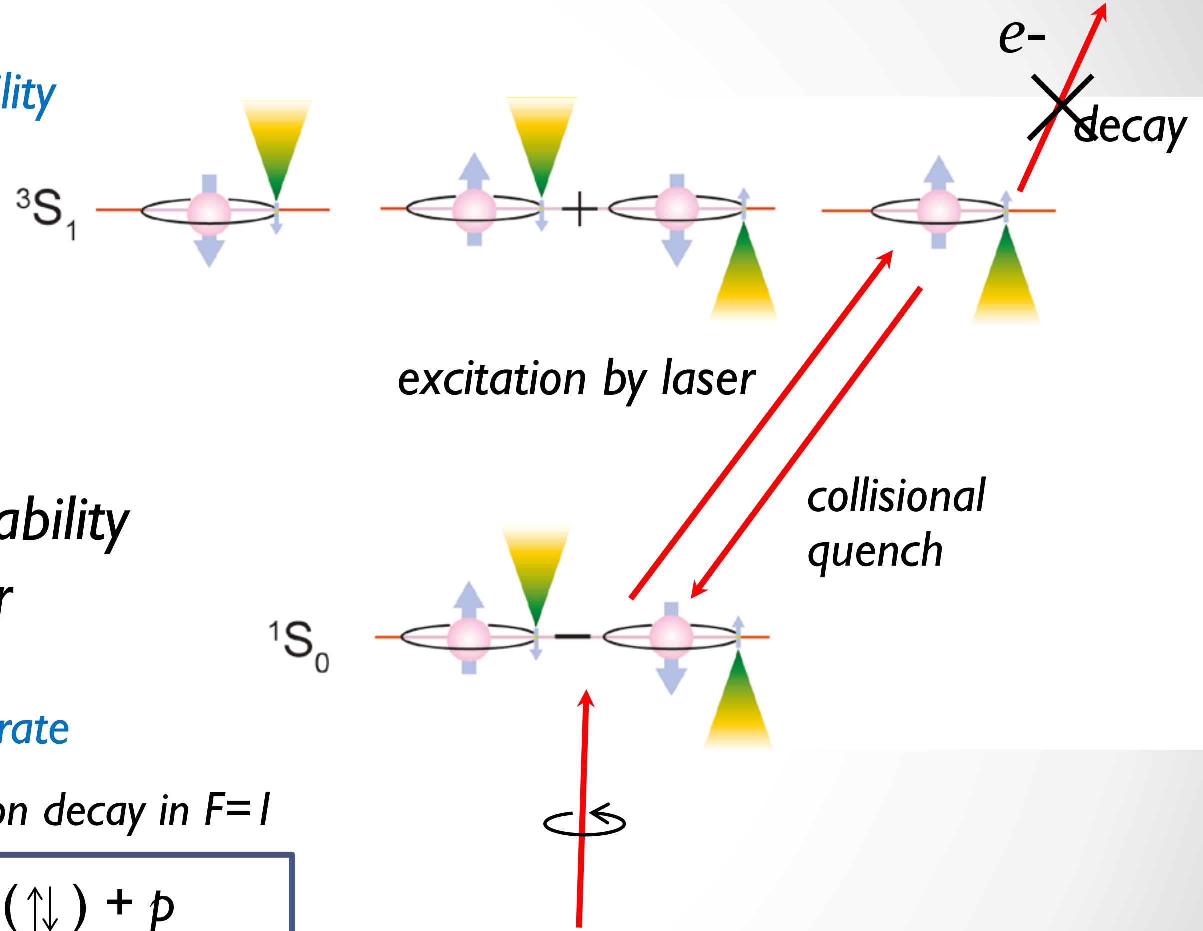
estimate transition probability with realistic laser power

- *F=1 → F=0 collisional quench rate*

  competitive process with muon decay in F=1

  $\mu p(\uparrow\uparrow) + p \rightarrow \mu p(\uparrow\downarrow) + p$

  then, polarization is lost



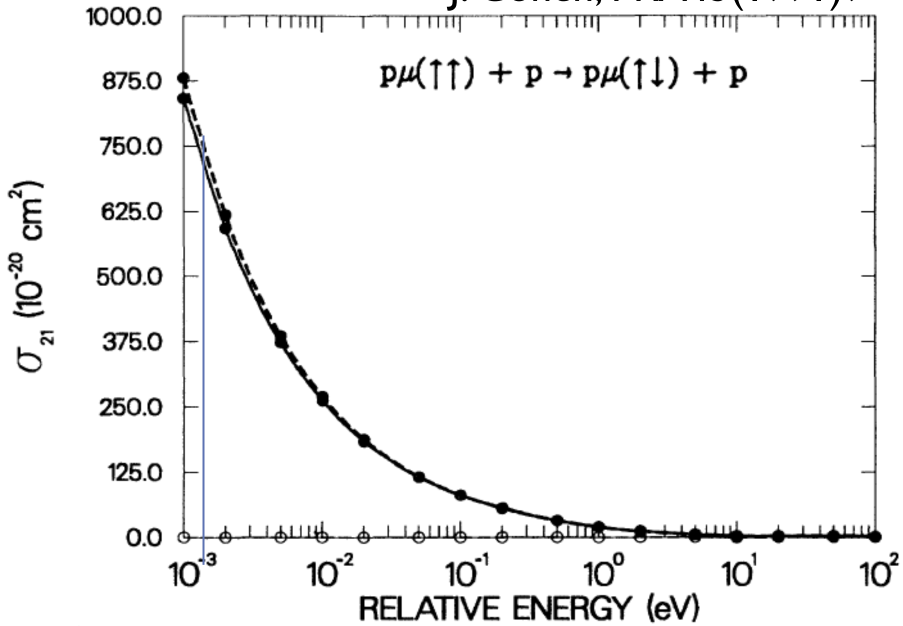
τ_{quench} VS τ_{μ}(= ~2.2 us)

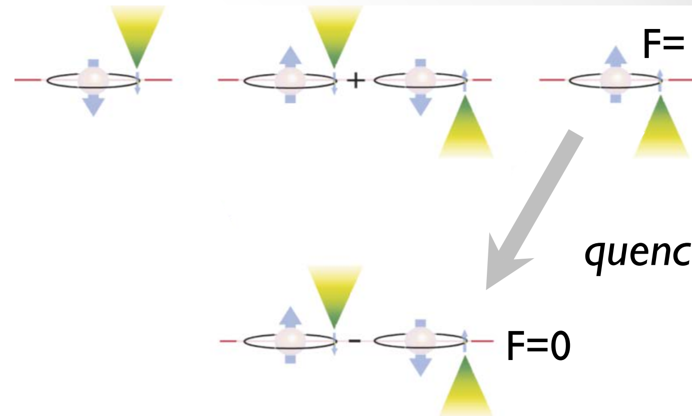
Collisional quench rate

- *F=1* → *F=0* quench by collision with surrounding atoms

$$\mu p(\uparrow\uparrow) + p \rightarrow \mu p(\uparrow\downarrow) + p$$

J. Cohen, PRA43(1991)9





quench rate (λ_Q)

$$\lambda_Q = \sigma_Q \left\langle v_{\mu p}^{eff} \right\rangle \rho_{H_2}$$

$(\rho_{H2} = \Phi \rho_{liquid})$

proportional to H_2 density

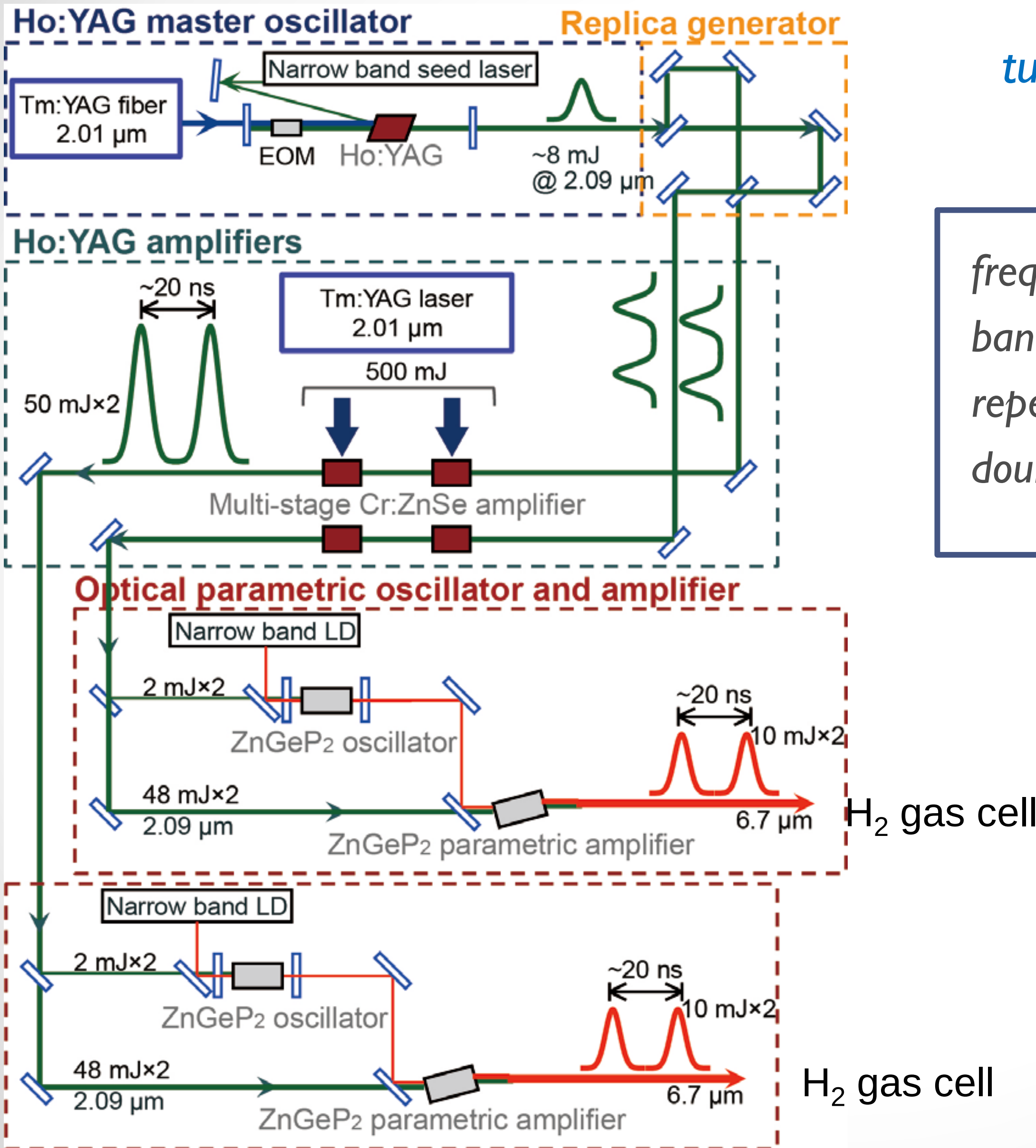
Quench rate (λ_Q) at 20 K

liquid H_2 then τ = 50 ps (Polarization is lost quickly before muon decay)

→ *gas target is indispensable*

If Φ = 0.01% LHD (liquid hydrogen density), then τ_{quench} = 500 ns

mid-infrared laser system



tunable mid-infrared laser

(developed in RIKEN Wada group)

frequency ~6.8 um = ~44 THz

band width ~50 MHz

repetition ~ 50 Hz

double pulse 10 mJ x 2 set = 40 mJ

- *Wavelength will be controlled by seeded OPO with $ZnGeP_2$ non-linear crystal.*
- *6.8 µm seed light will be provided from Quantum cascade laser.*

40 mJ laser power is possible

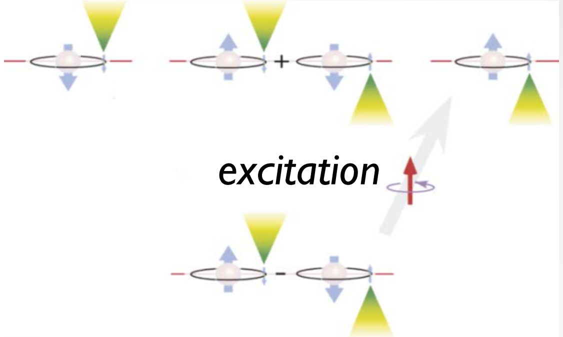
laser-induced transition probability

F=0 → F=1 transition probability

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

E/S : laser power density [J/m²], T : temperature [K]

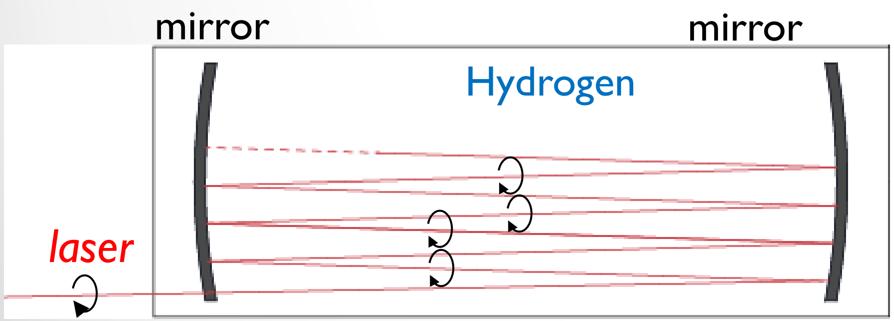
NIM B281(2012)72 & D. Bakalov, private communication



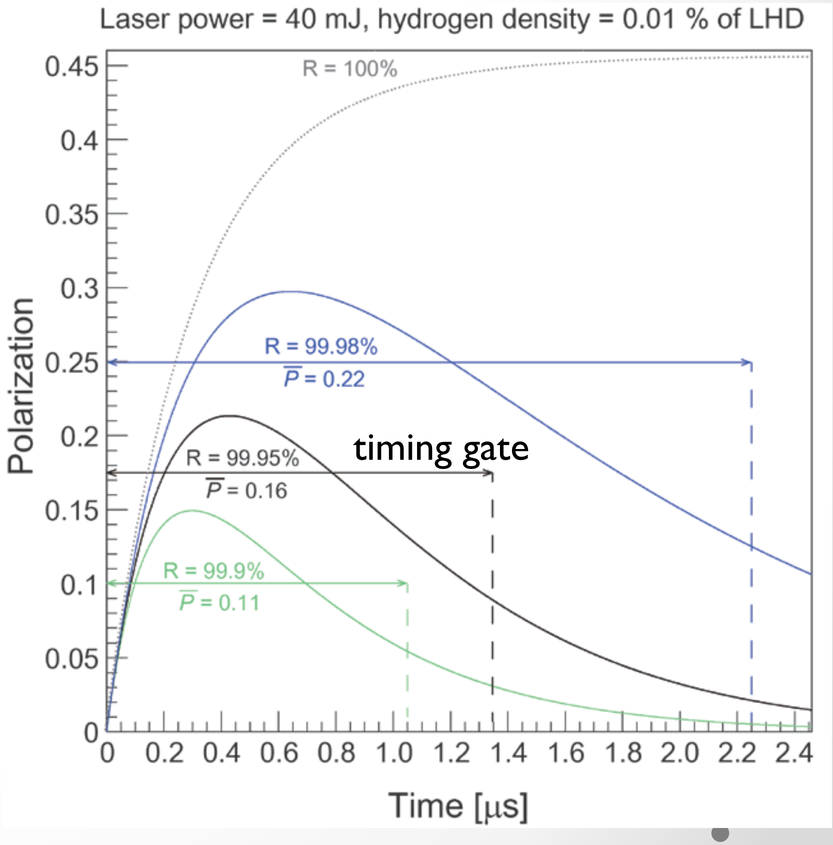
ex. E = 40 mJ, S= 4 cm², T= 20 K, then P = 4.5 x 10^{-4}

too small !

multi-pass cavity



reflective index R = 99.95 % → $\overline{P}$ = ~ 16%



Beam time estimation

- *RIKEN-RAL pulse muon source*

  Parameters for estimation

  - negative muon
    - 2.4×10^4 [s^{-1}] (50 Hz repetition)
    - P_μ = 40 MeV/c
    - dp/p = ±4 %
  - laser (~6.8 um)
    - Power 40 mJ
    - repetition 50 Hz
    - band width 50 MHz
    - mirror R 99.95 %
  - H_2 target
    - density 0.0001 LHD

- *scanning region and steps*

  scan interval : 100 MHz

  scan region: ±5.7 GHz $(\sim \delta^{Zemach} + \delta^{pol})$

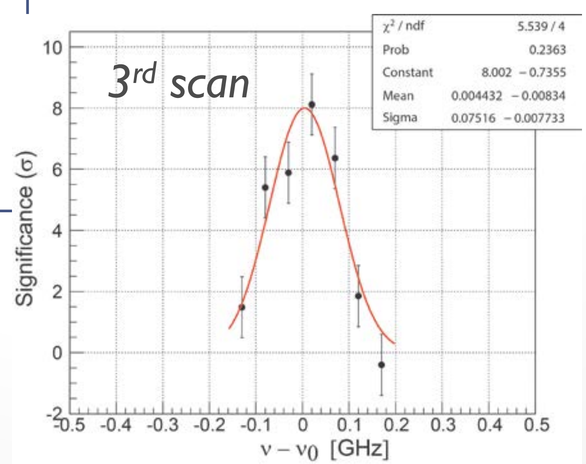
$$Significance(\sigma) = \frac{signal}{fluctuation} = \frac{(N_F - N_B)}{\sqrt{(N_F + N_B)}}$$

beam time estimation (3-stage scan):

(1) 4.8 hours x120 points for σ *>3 scan = 25 days*

(2) 13.4 hours x20 points for σ *>5 scan = 11 days*

(3) 26 hours x 7 points for σ *>7 scan = 8 days*



44 days in total

Summary

- We propose a new measurement of ground state hyperfine splitting energy in muonic hydrogen with mid-infrared laser

- Accuracy of ΔE_{HFS} : ~ 2 ppm, derive Zemach radius of proton

  (We need help from theory for further precision)

- Experiment is feasible in RIKEN RAL muon facility with pulsed muon source and the present laser technique

Collaboration

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