Measurement of the proton Zemach radius from the hyperfine splitting in muonic hydrogen utilizing muon spin repolarization with laser:

Preparation Status

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Three $\mu p$-HFS Projects

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**FAMU**
- $\mu^-$ beam
- $\mu p(n \approx 14)$
- $\mu p(1S)^{F=0}$
- $\mu p(1S)^{F=1}$
- $6.8 \mu$m laser pulse
- Collision with $H_2$ and spin-flip
- $+120 \text{ meV}$ kinetic energy

**PSI**
- Laser
- $\mu p$
- H$_2$ gas 50 K
-_prompt $\mu O$ X-rays
- X-Rays
- X-Rays

**RIKEN**
- Laser
- $p$, $\mu^-$
- $F=1$, $F=0$
- $E_{HFS}$
- Electrons
Our goal is the determination of $\mu$-HFS with the precision of 2 ppm. Hydrogen target, transition laser, and electron detector are key components of the experiment.
Laser Spectroscopy of $\mu p$ HFS

- Laser induced hyperfine transition and muon spin flip
- Parity violating muon decay
- Decay electron angular asymmetry
- Laser frequency scan

1S

\[ F=1 \]

\[ E_{\text{HFS}} \]

\[ F=0 \]

183 meV = 6.8 μm = 44.2 THz

Electron asymmetry

Laser freq. - HFS freq.

Time from muon pulse arrival

Electron counts

Laser Shot

Fwd signal

Bwd signal
Cryogenic hydrogen target

Segmented electron detector

μp atom

μ- beam

High pulse energy mid-IR laser
Cryogenic hydrogen gas target

Non-resonant multipass-cell

Muonic hydrogen atom

Pulsed negative muon beam
Electron counter is necessary to detect laser-induced muon spin flip signal as the asymmetry in electron angular distribution.

Requirements:
- High-rate capability
- High signal-to-noise ratio

Muon beam monitor is needed for an optimization of measurement conditions.

Requirements:
- Pulse-by-pulse monitoring of beam profile and intensity
- Minimum amount of material
- Segmented scintillation counter with SiPM readout.
  - Unit cell has the dimension of 1 cm x 1 cm x 3 mm.
  - 240 mm x 240 mm area, 1152 ch. in total.
- Amplifier, shaper, and discriminator in ASIC.
- FPGA-based multi-hit TDC.
- Developed for a muonium HFS experiment at J-PARC.
Efficiency and Rate Capability

- Detection efficiency was obtained by photon counting measurement.
  - Efficiency > 98% for muon decay electron
- Rate capability was evaluated by event loss analysis
  - Pileup loss < 3% at 3 MHz instantaneous rate
- Detector performance is good enough for the experiment.
Sharp peaks come from muonic silver (Muon beam has double pulse timing structure)

Background events having long-lifetime

- In a spectroscopy measurement, laser light is injected after 1 \( \mu \)s passed since a muon beam pulse arrival.
- Inner walls of the target chamber is covered by silver plates to suppress background events.
- S/N was evaluated by time spectrum fitting.
- Expected S/N is \( 4 \times 10^4 \), good enough for the experiment.
Muon Beam Profile Monitor

Fiber array layer structure
- Cross-configured fiber hodoscope with SiPM readout.
- Online measurement of the beam profile and relative intensity.

40 fibers are bundled for a ch. and connected to MPPC
Transition Laser

- HFS transition is optically suppressed by the selection rule, so high pulse energy is necessary.
- High-performance transition laser is required.
- Requirements:
  - Wavelength 6.8 μm (frequency 44.2 THz)
  - Stable, pulsed operation at 12.5 Hz
  - Wavelength tunability for a resonance scan
  - High pulse energy > 20 mJ
  - Narrow spectral linewidth < 150 MHz
  - Precise wavelength calibration (2 ppm)
  - Circular polarization
Optical parametric amplifiers

Optical parametric oscillator

Quantum cascade laser

Tm,Ho:YAG ceramic laser

2.09 \( \mu \text{m}, 20 \text{ mJ} \)

pump beam

6.8 \( \mu \text{m}, 25 \text{ mW} \)

seed beam

6.8 \( \mu \text{m}, 10 \text{ mJ} \)


2.09 \( \mu \text{m}, 20 \text{ mJ} \)

pump beam
- 2.09 μm light is necessary for 6.8 μm light generation via OPO.
- LD pumped, Q-switching, Tm$^{3+}$,Ho$^{3+}$ co-doped YAG ceramic laser was developed.
- Sufficient performance as a pumping beam for the ZGP-OPO was achieved (E>20 mJ, Width<150 ns).

S. Kanda et al., RIKEN APR51 (2018).
Optical parametric oscillator provides two lower frequency lights from a pumping light via non-linear optical effect.

ZGP is an optimum from viewpoints of the damage threshold and non-linear optical coefficient.

All-solid mid-infrared light source covers both $\mu p$ 1S-HFS and $\mu He$ 2S-HFS at the same time by just changing of the crystal angle.
The ZGP-OPO was demonstrated with Cr:ZnSe laser (2.4 μm).
Similar performance is expected with 2.09 μm pump.
The conversion efficiency of 13% or above is achievable.
Quantum cascade laser (QCL) for a seeder was developed.

Oscillation at $1473.03 \text{ cm}^{-1} = 6.778 \mu\text{m}$ was confirmed.

Radiant output power was 25 mW at 6.778 \mu\text{m} (high enough).

Spectral linewidth measurement is in preparation.
Highly reflective mirrors for the multi-pass cell were developed.
High reflection at 6.8 μm was confirmed.
Cavity ring-down measurement is in preparation.
Hydrogen Target

- Muon stopping in target is needed for muonic hydrogen formation.
  - High density is efficient.
- Lifetime of the muon spin polarization is short due to inelastic scattering $\mu p(F=1)+p\rightarrow\mu p(F=0)+p$.
  - Low density gives longer lifetime.
- Linewidth of the resonance is dominated by Doppler broadening effect.
  - Low temperature makes the linewidth narrower.

Requirements:
- Stable operation at 20 K and 0.1 atm.
- High purity
Collisional quenching of the HFS triplet state
- Inelastic scattering $\mu p(F=1) + p \rightarrow \mu p(F=0) + p$
- Only theoretical predictions are known and no measurement had been performed.

Quenching rate depends on collision energy and gas pressure.
- Expected lifetime at 20 K, 0.06 atm is approximately 50 ns.
- A new experiment for direct measurement of the quenching rate was proposed.

Collisional Quenching Measurement

Experimental setup

- Initial muon spin is polarized along the beam axis.
- Muon forms a muonic atom after stopping in the target.
- Muon spin rotates under a static magnetic field.
- Angular asymmetry in electron emission from muon decay is measured.

Muon decay time spectrum was measured using the gaseous deuterium target at the pressure of 1 atm.

Muon spin rotation was observed and the asymmetry was obtained.

Residual polarization is calculated after corrections.

Electron time spectrum (zero field)

Electron asymmetry (120 Gauss)
On the residual polarization

- Theoretical calculation (Bukhvostov1982)
  - 10.5% at 40 atm ($\lambda=625$ ns)
  - 9.7% at 10 atm ($\lambda=2500$ ns)
  - 8.4% at 1 atm ($\lambda=25000$ ns)

- Exp. results
  - D2 1 atm (This work)
    - 7.1%±1.7%
  - D2 10 atm (Bin’ko1989)
    - 7.2%±2.1%
  - D2 40 atm (Bystritskii1981)
    - Relaxation was too fast

The residual polarization is 7.1±1.7% and consistent with the theoretical prediction (8.4%).
- New target chamber for better B-field uniformity was developed.
- Beam tuning and background study were done in this July.
- Spin precession measurement is scheduled in Nov.
- Target temperature is controlled by using a GM cryostat.
- Temperature ranges from RT to 4 K.
- Gas density is monitored by a baratron pressure gauge.
- Target cell is made of tungsten for background suppression.
- Modifications for solid target is in preparation.
Slow muonic hydrogen is emitted from solid hydrogen thin film.

- Emission energy has two components: 2 meV and 0.2 eV.
- Slow $\mu p$ yield is approximately 0.5% of incident muons.

- In-flight spectroscopy is free from the collisional quenching.
- Systematics is dominated by the Doppler effect
  - 500 MHz at 0.2 eV (7 mm/μs velocity).
- Electron tracking with fiber hodoscopes.
Simulated $\mu p$ positions in vac.

- Funding for a solid target development is secured.
- Preparation for a target chamber is in progress.
- Fiber hodoscope for electron tracking is to be developed.
- Next step is a measurement of the space-time distribution of $\mu p$. 
We proposed a new measurement of the HFS in muonic hydrogen atom.

Hydrogen target, transition laser, and detectors are three key components of the experiment.

Hydrogen target
- Gaseous target is completed.
- Solid target is in preparation as an alternative.

Laser
- Pump, and seed lasers are completed.
- Improvement in OPO is in preparation.
- Multi-pass cell is fabricated and to be tested.

Detectors
- Electron and muon detectors are completed.