Measuring the proton Zemach radius with the FAMU experiment at RIKEN-RAL

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On behalf of the FAMU Collaboration
Spatial charge and magnetic moment distributions $\rho_E(r)$, $\rho_M(R)$ in non-relativistic picture.

The complete set of moments $R^{(k)}_{E,M} = \int \rho_{E,M}(r) r^k d^3r$ is related to the observable quantities:

$$r_{ch} = (R^{(2)}_E)^{1/2}$$
$$R_Z = \int (\int \rho_E(r') \rho_M(r-r') d^3r') d^3r$$

Large errors on $R_Z \rightarrow$ we need new measurements.
1. Create muonic hydrogen in a hydrogen gas target and wait for its thermalization;
2. Laser shot at resonance wavelength ($\lambda_0 \sim 6.8\mu$): spin state of $\mu^-p$ from $1^1S_0$ to $1^3S_1$, spin is flipped: $\mu^-p(\uparrow\downarrow) \rightarrow \mu^-p(\uparrow\uparrow)$;
3. De-excitation and acceleration: $\mu^-p(\uparrow\uparrow)$ hits a H atom. It is depolarized back to $\mu^-p(\uparrow\downarrow)$ and is accelerated by $\sim 120$ meV $\sim 2/3 \Delta E_{HFS}^{1S}$;
4. $\mu^-$ are transferred to heavier gas contaminant ($O_2$) with energy-dependent rate;
5. $\lambda_0$ is determined by maximizing the time distribution of $\mu^-$ transferred events.
6. At this point $\Delta E_{HFS}$ is determined from: $\lambda_0 = \frac{hc}{\Delta E_{HFS}^{1S}} \sim 6.8\mu \sim 0.183$ eV and then $R_Z$ with a precision $\sim 1\%$. 
The FAMU experimental method (II)

$R_Z$ is then determined via QED with a precision up to 1%, more than enough to discriminate between different Hypothesis

$$\Delta E_{hfs} = \frac{16}{3} \alpha^2 c R_e \left( \frac{\mu_2}{\mu_1} \right)^2 \left( 1 + \frac{m_e}{m_p} \right)^{-3} \times \left[ 1 + \frac{3}{2} \alpha^2 - 2 \frac{< r > Zernack}{a_0} + \beta + \delta \right]$$

Other $\mu p$ HFS projects

| Method      | FAMU (UK) | PSI (CH) | RIKEN (JP)  |
|-------------|-----------|----------|-------------|
| Laser       | DFG-MIR 1-5 mJ | QCL-seeded ZGP-OPO > 20 mJ in development |
| Detection   | X-rays    | X-rays   | electrons   |
| Beam        | pulsed    | continuos| Pulsed      |
The RIKEN-RAL muon facility at RAL

**RIKEN-RAL facility**

- 4 experimental ports.
- FAMU presently use port 1 and has used port 4 for previous runs.

**ISIS at RAL**

- 800 MeV p accelerator, 200 mA, 50 Hz

**Typical beam size** ~10 cm²

\[ \Delta p/p \text{ FWHM 10\% (decay), 5\% (surface)} \]

Double pulse structure (see below)

**Beam time structure**

- 320 ns
- 70 ns
- 20 ns (50 Hz)
- 20 ns (50 Hz)

The RIKEN-RAL facility: 4 experimental ports. FAMU presently use port 1 and has used port 4 for previous runs.
1. Validation of X-rays detector system based on LaBr3:Ce in a noisy environment. Detection of X-rays both in the prompt and delayed component.

2. Development of a high energy MIR laser system
   - Wavelength $\sim 6780$ nm
   - Line width $< 0.07$ nm
   - Tunability $\sim 0.007$ nm
   - Repetition rate 50 Hz
   - Energy $\sim 1$ mJ

3. Optimization of run conditions: best gas mixture at temperature $T$ and pressure $p$ (to be determined) to observe and measure the transfer rate energy dependence.

At this point the validity of the method to measure HFS is demonstrated.
Expected results from the final run & conclusions

- All preliminary steps done and working
- Final data taking foreseen for March 2020. Delayed in steps to June 2021 due to COVID-19 pandemic
- We hope to have results soon on $r_Z$ with 1% accuracy

Expected results with a 1 mJ/ 4 mJ laser energy
The determination of the Zemach radius from the experimental value of the hfs is based on the theoretical relation between the hyperfine splitting, the lowest order Fermi hyperfine energy $E_F$ and the corrections to it $\delta^{QED}$ due to QED effects, $\delta^{rec}$ recoil, $\delta^Z$ the static electromagnetic structure of the proton, $\delta^{pol}$ to dynamical proton polarizability and $\delta^{hwp}$ to hadron vacuum polarization respectively:

$$\Delta E^{hfs} = E_F \left( 1 + \delta^{QED} + \delta^{rec} + \delta^Z + \delta^{pol} + \delta^{hwp} \right)$$

Of these quantities $E_F$, $\delta^{QED}$ and $\delta^{rec}$ are known or calculable with accuracy $10^{-6}$ or better, and $\delta^{hwp}$ is small and may be neglected. This relation $\delta^Z$ is related to the Zemach radius $r_Z$ by means of

$$\delta^Z = 2\alpha(1 + k) \cdot \frac{M_\mu M_p}{M_\mu + M_p} \cdot r_Z$$

where $M_\mu$ and $M_p$ are the particle masses and $k = 0.0152$ is a QED correction, approximately $\delta^Z = -7.3 \times 10^{-3}$. Using phenomenological data the proton polarizability term $\delta^{pol}$ was evaluated to $\delta^{pol} = (4.6 \pm 0.8) \times 10^{-4}$.

The uncertainty in the value of the Zemach radius is limited by the uncertainty of $\delta^{pol}$ to about 1%.
The MIR laser system
The Nd:YAG will be at "fixed" wavelength 1064.14nm with linewidth max - 0.34pm (90MHz) and min - 0.11pm (30MHz).

The Cr:forsterite will have linewidth max - 1pm (188MHz) and min - 0.5pm (90MHz).

The Cr:forsterite will be tunable from 1252nm to 1272 nm which corresponds to tunability from 6500nm to 7090nm, which is 3765GHz. The required tunability 6760nm ±3nm corresponds to tunability range = 39GHz.
Physics measurements: transfer rate $\mu p \rightarrow \mu O$

- Transfer rate measured as a function of temperature
  - Target filled $H_2+(120 \text{ ppm})O_2$ at 41 bar at 300 K
  - Six temperatures (300, 272, 240, 201, 153, 104 K)
  - Each temperature kept stable for three hours each

- At each trigger we acquire a window of 10 microsecond
  - Produce $\mu p$’s and wait for their thermalization (about 150 ns)
  - Study the time evolution of Oxygen X rays
Some references for further infos

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