The FAMU experiment: measurement of the ground state hyperfine splitting of muonic hydrogen

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FAMU Collaboration
FAMU
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≈60 researcher
20 institutions
Where: Rutherford Appleton Laboratory - UK

The brightest pulsed muon beam facility in the world!
FAMU aim:
Measure HFS of muonic hydrogen ground level

The properties of the proton can be studied with
\textbf{Scattering} or \textbf{Spectroscopy} experiments

Muonic hydrogen (µp) is more sensitive to nuclear structure effects
Information on the magnetic structure of the proton is brought by the hyperfine splitting (HFS) of $\mu^p$, this arises from the interaction between the magnetic moment of the muon and the magnetic moment of the proton.

Ground state level is split by the hyperfine interaction into triplet ($F=1$) and singlet ($F=0$) states.
FAMU goals:

• measure the hyperfine splitting (hfs) in the ground state of muonic hydrogen with a relative accuracy better than $10^{-5}$

• deduce the Zemach radius with a relative accuracy better than 1%.

This measurement will provide a benchmark for the models of the proton.
The proton charge radius

- Need of **precision experiments** carried with different techniques
- **Importance of correct estimation** of systematic uncertainties

Modified from Xiong et al. DOI:10.1038/s41586-019-1721-2
• Create muonic hydrogen and wait for thermalization;
• Shoot laser at variable wavelength ($\lambda_0 \sim 6.8 \mu$), when it matches the resonance: spin is flipped: $\mu^- p(\uparrow \downarrow) \rightarrow \mu^- p(\uparrow \uparrow)$;
• 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 ;
• $\mu^-$ are transferred to heavier gas with energy-dependent rate;
• $\lambda_0$ resonance is determined by the maximizing the time distribution of $\mu^-$ transferred events.
FAMU Laser

Characteristics:
- Wavelength range: 6800 ± 50 nm
- Energy output: > 1 mJ
- Linewidth: < 0.07 nm
- Tunability steps: 0.03 nm
- Pulses duration: 10 ns
- Repetition rate: 25 Hz

Absolute calibration of the 6.8\(\mu\)m energy with CH\(_4\) line absorption

![Diagram of FAMU Laser setup]

M1 - Mirror HR 1064 nm, M2 - Mirror HR 1262 nm, M3 - Mirror HR 1064 & 1262 & 6785 nm, M4 - Mirror HR 6785 nm, T1 and T2 - telescopes, BS1 - beamsplitter/beamsampler 1064 nm, BS2 - beamsplitter/beamsampler 1262 nm, BS3 - beamsplitter/beamsampler 6785 nm, DC1 - dichroic mirror (reflecting 1064 nm, transmitting 1262 nm), DC2 - dichroic mirror (reflecting 1064 nm and 1262 nm, transmitting 6785 nm), NL - nonlinear crystal, MU - measuring units (wavelength meter, energy meter, dimensions)
FAMU Timeline

1993

First idea of the experimental method

2014 - 2018

FAMU preliminary phase: study and preparation

- Laser development
- Test target and detectors (LaBr and Ge)
- Study the muon beam
- Measure transfer rate of different gases
- Study of the gas mixture
- Measure the transfer rate temperature dependence for oxygen

First measurement of the oxygen transfer rate

- measured for the first time the temperature dependence of the transfer rate for oxygen in the range 70-336 K
- the energy dependence of the transfer rate increases by a factor 8 for energies in 0.01-0.08 eV

This dependence is very important for the FAMU experiment where the energy dependence of the transfer rate is used a signature
FAMU Timeline

1993
First idea of the experimental method

2014 - 2018
Study and preparation

2019-20
Installation of the full set up and measurement of the HFS

Set up at Port1 at RAL
FAMU Set up
FAMU set up

- Laser injection
- LN2 and cryogenic tank
- Germanium detector
- LaBr detectors
- Muon beam injection
Target and cavity

- LN2 tank
- H2 gas
- Copper braids
- Target cavity
- Target
- Cavity
Port 1
February 2020
FAMU Timeline

1993
First idea of the experimental method

2014 - 2018
Study and preparation

2019/20
Full set up and measurement of the HFS
March 2020 – first assembly
September 2020
December 2020
June 2021

2021-22
June 2021- June 2022: accelerator shutdown for maintenance & upgrades

2022
Data taking with full setup at the end of 2022

Meanwhile in our local labs ...
• Further studies on laser
• Cavity characterisation
• Detector integration
Laser: new setup and further studies at Trieste

New non linear crystals

Energy curves BaGa$_7$Se$_4$ 10x9x28mm
Optical cavity

The cavity number of reflections remain stable against small variations of the incident angle (tip/tilt movement)
Detectors: mechanical integration

Trieste, October 2021
Conclusions

• FAMU aims to **measure the hyperfine splitting** in the ground state of muonic hydrogen with a relative accuracy better than $10^{-5}$

• Assembly of the complete setup is foreseen in summer 2022

• **First data taking at the end of 2022**
  About 1 month beam time, a scan of ~30 frequency points
Thank you for your attention