FAMU: latest results in the measurement of the transfer rate from $\mu^-$p to Oxygen

Cecilia Pizzolotto

for the FAMU Collaboration

International Conference on Precision Physics and Fundamental Physical Constants

FFK-2019
Outline

• Motivation
• The FAMU experiment
• Measurement of the transfer rate from μp to oxygen
• Outlook
FAMU
Fisica degli Atomi Muonici
Physics with muonic atoms
Fundamental physics: the proton

Study of the properties of the proton

1) scattering: electron experiments
2) scattering: elastic muon-proton

3) spectroscopy: electronic atoms and ions
4) spectroscopy: exotic atoms

FAMU aim:
HFS of muonic hydrogen ground level
→ the Zemach radius of the proton
FAMU method and workflow (I)

1. Create muonic hydrogen and wait for thermalization;
1. Create muonic hydrogen and wait for its thermalization;
2. Shoot laser at resonance ($\lambda_0 \sim 6.8 \mu$) 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;
4. $\mu^-$ are transferred to heavier gas with energy-dependent rate;
5. $\lambda_0$ resonance is determined by the maximizing the time distribution of $\mu^-$ transferred events.
**FAMU: principle of operation**

**Method:**
1. Create muonic hydrogen and wait for thermalization;
2. Shoot laser at resonance ($\lambda_0 \sim 6.8\mu$): 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 $\sim120$ meV ;
4. $\mu^-$ are transferred to heavier gas with energy-dependent rate;
5. $\lambda_0$ resonance is determined by the maximizing the time distribution of $\mu^-$
   transferred events.

**Ingredients:**
- high intensity muon beam
- proper gas mixture
- high energy and fine-tunable laser
- fast and accurate X-rays detectors
FAMU: Phases of the project

1993
First idea of the experimental method


2014
First FAMU data taking
Study the muon beam, test target and detectors, measure transfer rate @ constant conditions PTV

2016
Find the best gas mixture, temperature and pressure
**measure the transfer rate energy dependence for oxygen**

2018
Data taking: Measurement with the final target PVT conditions
Optimisation of the laser system

2019-2020
Full set up (with laser) and measurement of the HFS
FAMU - Set Up
RIKEN RAL muon facility

Rutherford Appleton Laboratory – Oxfordshire UK

The brightest pulsed muon beam facility in the world!
Cryogenic thermalized target

Gas:
H₂+O₂ (120ppm)
41 bar @300 K
LaBr$_3$(Ce): fast timing X-rays detectors

- 8 cylindrical 1 inch diameter 1 inch long lanthanum bromide LaBr$_3$(5%Ce) crystals
- read by PMTs
- fast electronics and fast digital processing signal available

Lab test before detector assembly
Experimental setup
Experimental setup
Experimental setup

LaBr
Hodoscope
$\mu^-$
HPGe
target
Measurement of the transfer rate
\[ \Lambda_{\mu p} \rightarrow \mu O \]
Transfer rate measurement

- Transfer rate measured as a function of temperature
  - Target filled H$_2^+$(120 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 $\mu$'s and wait for their thermalization (about 150 ns)
  - Study the time evolution of Oxygen X rays

[Graph showing prompt and delayed emission with time and number of counts]
Data Analysis

Signal amplitude:
• Detector signals are fitted

Loose data selection:
• Good Chi2 from the wavefit
• Distance between pulses > 30 ns
• No saturated events
Energy spectrum

K_\alpha @133 keV
K_\beta @158 keV
K_\gamma @167 keV

Oxygen signal

\[ T = 300 \text{ K} \]

Time bin = [1450,1650] ns
Background evaluation: pure hydrogen

T = 300 K
Time bin = [1450,1650] ns

Pure hydrogen data taking within the same beam time and with the same pressure and temperatures.

However: poor statistics...

Smoothed with a Gaussian kernel algorithm
Time evolution at a fixed temperature $T = 300$ K
Data fit

Counts per trigger vs. Time from trigger [ns] for different temperatures:
- 300 K
- 104 K
Transfer rate vs Temperature

\[ \Lambda_{p0} \left[ 10^{10} \text{s}^{-1} \right] \]

- This work
- Werthmüller et al.

Hyperf.Interact. 1996

Submitted to PRA and http://arxiv.org/abs/1905.02049
Transfer rate vs Temperature

Fitting function:
\[ \Lambda_{po}(T) = P_1 + P_2 T + P_3 T^2 \]
\[ \chi^2/ndf = 1.13/3 \]

- \( P_1 = (-1.3 \pm 0.6) \times 10^{10} \text{ s}^{-1} \)
- \( P_2 = (4.9 \pm 0.7) \times 10^8 \text{ s}^{-1} \text{K}^{-1} \)
- \( P_3 = (-5.4 \pm 1.8) \times 10^5 \text{ s}^{-1} \text{K}^{-2} \)

Submitted to PRA and http://arxiv.org/abs/1905.02049
Transfer rate vs Energy

![Graph showing transfer rate vs energy](image_url)

- **This work**
- Werthmüller et al. 1998
- Dupays et al. 2004
- Le and Lin 2005

Gray band: Uncertainty of the fit

Submitted to PRA and http://arxiv.org/abs/1905.02049
Transfer rate model systematics

Submitted to PRA and http://arxiv.org/abs/1905.02049
Transfer rate vs Energy

Fit-model systematics
Uncertainty of the fit

Submitted to PRA and http://arxiv.org/abs/1905.02049
Results

- measured for the first time the **temperature dependence** of the transfer rate for oxygen in the range 100-300 K
- the **energy dependence** of the transfer rate **increases by a factor 8** for energies in 0.01-0.08 eV

---

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

1993
First idea of the experimental method


2014
First FAMU data taking
Study the muon beam, test target and detectors, measure transfer rate @ constant conditions PTV

2016
Find the best gas mixture, temperature and pressure
measure the transfer rate energy dependence for oxygen

2018
Data taking: Measurement with the final target PVT conditions
Optimisation of the laser system

2019-2020
Full set up (with laser) and measurement of the HFS

Transfer rate energy dependence for Oxygen

2018 Analysis being finalized
- confirms 2016 results & extends range
- tested final target conditions

Final steps towards the muonic HFS measurement
Towards the final measurement

Laser optimisation

Target & cavity studies
Towards the final measurement

X rays detectors

Dedicated MC simulation
Full set up will be ready
to perform the measurement of HFS in muonic hydrogen
at the end of this year!
Thanks for your attention