High precision physics with exotic atoms

The FAMU experiment and the most challenging transition in muonic hydrogen

One intriguing question of modern atomic physics is the discrepancy in the determination of the proton charge radius extracted from measurement of transition frequency in hydrogen atom and a recent measurement of the Lamb shift in muonic hydrogen.

The FAMU (**F**isica degli **A**tomi **MU**onici – physics of muonic atoms) experiment aims to precisely determine the Zemach radius of the proton by measuring the hyperfine splitting in muonic hydrogen ground state. Competing proposals to measure the hyperfine splitting with pure hydrogen target have been recently approved at other facilities. This situation confirms the fundamental interest in a new and independent high precision measurement on muonic hydrogen.

Topic of studies:

- **Laser system:** the development of a tunable and powerful laser system is one of the technological challenges of this experiment. The system is based on mixing single frequency single longitudinal mode Nd:YAG laser (1.064 μm) and a tunable, narrow bandwidth, Cr:forsterite laser (~ 1.262 μm) pumped by a second Nd:YAG synchronized to the first one. It is an attractive scheme due to its compactness, energy scalability and ability to fulfil the other required laser parameters like tunability and narrow line-width. Further studies aim to improve the system for future runs, expecially to increase the power of the laser.

- **Simulation studies using GEANT4**. A dedicated simulation has been developed for studies supporting the analysis or layout optimization of future runs.

- **Data analysis:** analysis is carried on in small teams that follow the whole procedure from signal reconstruction and calibration to final results.

Working in FAMU is an opportunity for an inclusive experience: it is an international collaboration (Italy, Bulgary, Poland, Japan, India, and China) yet small enough to allow and encourage its members to work on a wide range of activities: from setting up the detectors before an acquisition run, to deeply understand the various aspect of the experiment, ranging from the hardware to the physics and to most theoretical point of view.
The FAMU group in Trieste is very active: the Principal Investigator is located here, as well as the full analysis and simulation team. Moreover, the Trieste group is responsible for the laser development and construction. The laser is being assembled in dedicated laboratories at INFN Area di Ricerca and at Elettra Synchrotron.

Currently, FAMU is reaching its most exciting phase. Six preparatory beam times have been acquired at the RIKEN RAL muon accelerator facility in Oxford (UK) to test the feasibility of the method, investigate different gas composition and confirm the

profitability of the transfer method for oxygen. The final setup is being tested and assembled in the first half of 2022.
FAMU started the acquisition of the first physics runs in 2023.

In-depth: the physics of FAMU

Muonic hydrogen allows high precision spectroscopy studies of the fundamental interaction of the structure of the proton. FAMU proposes an innovative method to measure the hyperfine splitting.
Muonic hydrogen is formed by collision of a muon beam in a gas target containing a mixture of hydrogen and oxygen. A thermal muonic hydrogen atom in the para state (total spin F=0), after absorbing a photon having the resonance energy ΔEhfs ≈ 0.182 eV is excited to the ortho (F=1) spin state. Very quickly then, in subsequent collisions with the surrounding H2 molecules, muonic hydrogen de-excite to (F=0). Because of energy and momentum conservation, at the exit of the collision, the muonic hydrogen is accelerated by ~2/3 of the ΔE^{hfs} excitation energy which takes away as kinetic energy. The muon is transferred from $\mu^{-}p$ to μO at a rate λo(E) that considerably increases with the energy of the $\mu^{-}p$. By varying the emission wavelength of a tunable laser, it is possible to experimentally observe the number of muonic atoms that have undergone the above sequence of processes and in this way to identify the resonance wavelength as the value for which the number of spin-excited atoms and hence of X-rays from transfer to oxygen is maximal. The observable is the time distribution of the characteristic X-ray of the muonic atoms formed by muon transfer from hydrogen to oxygen and its response to variations of the laser wavelength.

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