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Measuring the muonic H ground state hyperfine splitting with FAMU

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Summary. — The FAMU experiment will measure the hyperfine splitting in the ground state of muonic hydrogen $\Delta E^{hfs}(\mu^- p)1s$ with a precision $\delta\lambda/\lambda < 10^{-5}$ providing $\mathbf{r}_Z$, the Zemach radius of the proton with higher precision, than what was previously possible, disentangling discordant theoretical values. The aim is to set a cornerstone result about not yet explained anomalies on the charge radius $\mathbf{r}_{ch}$ of the proton. The Zemach radius $\mathbf{r}_Z$ and the charge radius $\mathbf{r}_{ch}$ are the only proton shape-related values that can be directly extracted from experimental data, and $\mathbf{r}_Z$ is the only one that gives information about the proton's magnetic dipole moment distribution. The status of the experiment is presented.

1. – Introduction

Muonic hydrogen allows high-precision spectroscopy studies of the fundamental interactions and of the structure of the proton. The typical binding energies and distances in the muonic hydrogen atom are rescaled with the muon-to-electron mass ratio $\rho = m_\mu/m_e \approx 200$. Physical phenomena at a range of distances of the order of 250fm can be observed, relativistic and higher order QED effects on the energy spectrum are enhanced by the factor $\rho \approx 200$; the overlap of muon and proton densities is enhanced ρ^3 times, this makes accessible the spatial distribution of the proton charge and magnetic moment. The rescaled transition energies between levels in muonic hydrogen are shifted to spectral ranges that allow high precision laser spectroscopy. This, together with the evolution in precision of the theoretical calculations, allows to experimentally explore the fundamental interactions from the low-momentum transfer front [1] [2] [3]. The availability of pulsed, intense, low-energy negative muon beams and IR laser sources unlocks the possibility to realise the measurement of the hyperfine splitting (hfs) in the ground state of muonic hydrogen $\Delta E^{hfs}(\mu^- p)1s$ [4] [5] [6].

The FAMU (Fisica Atomi MUonici, Muonic Atom Physics) measurement of $\Delta E^{hfs}(\mu^{-}p)1s$, with a relative accuracy 10^{-5}, will contribute to the determination of r_Z, the first moment of the convolution of proton's electric charge and magnetic moment distributions with an accuracy of 1% or better. This will boost the resolution of the ambiguities about the electromagnetic structure of proton and explore the limits of the theoretical predictions becoming sensitive to new phenomena and potentially probe physics beyond the Standard Model connecting the fields of precision atomic and high energy physics. The exceptional precision of the experimental value of ΔE^{hfs} in hydrogen makes this measurement sensitive, in addition to QED corrections, to the contribution from proton finite size and polarizability. Both cannot be extracted from a single experimental value. A measurement of $\Delta E^{hfs}(\mu^{-}p)1\mathbf{s}$ with an accuracy better than 10^{-4} provides another independent combination of the non QED part and would therefore be a significant step forward in the study of the proton structure. It also allows to investigate the stubborn discrepancy among measurements of the proton charge radius $\mathbf{r}_{ch}$ with a new independent high precision measurement on muonic hydrogen [7] [8].

A recent evaluation of the 1S-hfs in μp leads to:

$$\Delta E^{hfs}{}_{th}(\mu^{-}p)_{1s} = 182.819(1)[meV] - 1.301[meV/fm]r_Z + 0.064(21)[meV] \quad (1)$$

where the first term includes the Fermi energy, QED corrections, hadronic vacuum polarization, recoil corrections and weak interactions, the second term, proportional to r_Z, is the finite size contribution containing also higher order mixed radiative finite size corrections, and the third term is given by the proton polarizability contribution [1] [10] [11] [12] [13] [14]. Each of these terms is subject to constantly improved calculations, and the specific numerical values and their uncertainty may vary in the future. FAMU [15] realises a new method to obtain the first measurement of $(\mu\text{-p})_{1S}$ hfs. It will become possible to deduce r_Z with a relative accuracy better than 5×10^{-3} limited by the relative accuracy on the polarizability contribution. By now the value of r_Z has been extracted from the hyperfine splitting in ordinary hydrogen by 4 independent groups and the results of 3 of them converge to the value r_Z=1.03 fm [12].

2. – The progression

The steps leading to the original idea are summarized in the following articles [16] [17] [4] [5] [6] [18]. An experimental proposal was presented in 2013 at the *Program Advisory Committee of the RIKEN laboratory* where it received the first approval. Subsequently two proposals with the same physics target have been approved [19] [14]. Since 2013 the FAMU team at the RIKEN-RAL muon facility has demonstrated that the proposed method, the beam, and the detection systems are all optimal for the task [20] [21].

3. – The method

FAMU measures the weak magnetic M1 transition between the hyperfine para-state with spin F=0 and ortho-state F=1 of the $(\mu\text{-p})_{1S}$. The muonic hydrogen atoms are formed and propagate in a gas container with a mixture of hydrogen and a high Z gas at low concentration. The observable is the time distribution of the characteristic X-ray events of the muonic atoms formed by muon transfer from hydrogen to the atom of the admixture gas and its response to variations of the laser wavelength. The efficiency of the method is bound to the collisional energy dependence of the muon transfer rate.

There are experimental evidences, confirmed by FAMU recent experimental results, that oxygen has a sharp energy dependence [21] [22] [23].

The chain of physical processes is the following: a muonic hydrogen atom in the ground F=0 state, after absorbing a photon at the hyperfine splitting resonance energy $\Delta E^{hfs} \approx 0.183$ eV, and being excited to F=1, is very quickly de-excited to F=0 in subsequent collisions with the surrounding H_2 molecules (the de-excitation (F=1)⇒(F=0) cross section exceeds the elastic (F=1)⇒(F=1) cross section by a factor ∼20) [24]. Because of energy and momentum conservation, at the exit of the collision the muonic atom is accelerated by ∼2/3 of the excitation energy ΔE^{hfs}, which takes away as kinetic energy. Since the muon is transferred from μ^-p to μ^-O at a rate λo(E) that increases with energy, by varying the emission wavelength of the tunable excitation-laser, it is possible to experimentally observe the number of muonic atoms that have undergone the above sequence of processes and identify the resonance wavelength as the value for which the number of spin-excited atoms is maximal. The thermalization of μ^-p has to be slower than the epithermic μ^- transfer, this dictates the physical conditions of the gas mixture and target. Within the FAMU preliminary experiment we have reached a confirmation of the method for oxygen [21] [6].

The experiment needs an intense pulsed low momentum negative muons beam and a pulsed tunable narrow-band mid-infrared laser in the 6.78 micron wavelength range with energy output of more than 1 mJ coupled to a multi-pass highly reflective cavity. Requires also fast high energy resolution X-ray detectors with best efficiency for the muonic oxygen characteristic X-rays (100–200 KeV).

The beam structure, of the RIKEN-RAL pulsed muon facility at the ISIS accelerator of the Rutherford-Appleton Laboratory (UK), has two subsequent pulses 320 ns apart each with 70 ns FWHM delivering about 10^4 (depending on the momentum) negative muons per second, with 30-80 MeV/c, with a pulse repetition rate 50 Hz, σ_p/p= 4% and a beam transversal section of σ_x,σ_y = 1.5 cm [25].

The pulsed laser, tunable around 6785± 3 nm, with energy output of ∼4 mJ with linewidth less than 0.07 nm, tunability steps 0.007nm, 20 ns pulses at repetition rate 25 Hz, is based on direct difference frequency generation (DFG) in lithium thioindate ($LiInS_2$) non-oxide crystals, cut for type II difference frequency generation, with pump and signal coming from one narrow band fixed wavelength and one tunable laser emitting at wavelengths below 2 μm. This scheme 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 synchronised to the first one. It is an attractive scheme due to its compactness, energy scalability and ability to fulfil the required laser parameters. The results obtained by a test system showed that the $LiInS_2$ is among the most appropriate crystals [26]. To maximize the spin-flip probability, the target volume has to be efficiently irradiated by the laser light pulse by means of a multi-pass optical cavity.

FAMU is a time resolved X-ray spectroscopy experiment, the detector of choice is the scintillator $LaBr_3$(Ce). It offers the appropriate energy resolution, fast emission and excellent linearity. High purity germanium HpGe detectors are used as cross reference complementing the LaBr based detectors [15]. The detector's output is recorded for 5μs after the trigger using a 500MHz 14-bit digitizer. The waveform is then processed to extract the energy spectrum of the detected X-rays, their time distribution and and disentangle pile-up events [6] [27]. The optimization of all the aspects of the FAMU experimental lay-out is obtained through an experimentally validated simulation [28] [18] [23].

4. – Conclusions

A set of tests on the RIKEN RAL muon beam using a high pressure, cryogenic, hydrogen gas target confirms the FAMU experimental method - *pulsed muon beam and the muon transfer technique* -. The results of the study on muon transfer rate to oxygen *at different temperatures* indicates the working conditions needed to optimise the two complementary effects of μp thermalization and μ transfer to oxygen. This data are of crucial importance for the detailed planning of the subsequent spectroscopy experiment.

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