Studies of the muon transfer process in a mixture of hydrogen and higher Z gas

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The final aim of this experiment is a precision spectroscopic measurement of hyperfine splitting (hfs) in the 1S state of muonic hydrogen $\Delta E^{hfs}(\mu^- p)_{1S}$ - providing crucial information on proton structure and muon-nucleon interaction in order to provide the proton Zemach radius r_Z with higher precision than previously possible.[1] This will allow discordant theoretical values to be disentangled and evidence any level of discrepancy that may exist between values of r_Z extracted from normal and muonic hydrogen atoms. It will also set a needed cornerstone result about not yet explained anomalies within the proton charge mean square radius r_{ch}.[2,3] By measuring the $\Delta E^{hfs}(\mu^- p)_{1S}$ transition wavelength with an unprecedented precision of $\delta\lambda/\lambda < 10^{-5}$, the final experiment will establish new limits on the proton structure parameters and shed light on the low momentum limit of the magnetic-to-charge form factor ratio.[4] The physical process behind this experiment is the following: muonic hydrogen atoms are formed in a gas target containing a mixture of hydrogen and a higher-Z gas. A muonic hydrogen atom in the ground state, after absorbing a photon of energy equal to the hyperfine-splitting resonance-energy $\Delta E_{hfs} \approx 0.182$ eV, is very quickly de-excited in subsequent collision with the surrounding H_2 molecules. At the exit of the collision, the muonic atom is accelerated by ~2/3 of the excitation energy ΔE_{hfs}, which is taken away as kinetic energy. The experiment will observe the products of a reaction whose rate depends on the kinetic energy of the muonic atoms. The observable is the time distribution of the characteristic X-ray emitted from the muonic atoms formed by muon transfer from hydrogen to the atom of the admixture gas $(\mu p) + Z \rightarrow (\mu Z)^* + p$ and its response to variations of the laser radiation wavelength. The $(\mu^- p)_{1S}$ hfs resonance is recognized by the maximal response to the tuned laser wavelength of the time distribution of X-ray K-lines cascade from the $(\mu Z)^*$. By means of Monte Carlo simulations based on the existing data it has been shown that the described method will provide the expected results.[5]

During the first tests in 2014 at the beam delivery Port 4 of the RIKEN-RAL facility, the detection system and the beam condition allowed a satisfactory background situation.[6,7] Because the efficiency of the method is bound to the collisional energy dependence of the muon transfer rate, the main focus in 2015-2016 has been a detailed experimental analysis of the muon transfer mechanism by measuring the muon transfer rate at various temperatures.

While for many gases the transfer rate at low energies is nearly constant, there is experimental evidence of a relevant energy dependence for oxygen.[7] Our team has performed, at PORT4, the needed dedicated study of muon transfer from hydrogen to the atom of an admixture gas, and, in particular, to oxygen, at temperatures between 300 and 100 K to confirm the energy dependent muon transfer rate for oxygen and the profitability of this method (see Fig. 1). While the final data are still subject to careful verification, the presently extracted behavior of the transfer rate confirms the expectations and the proposed experimental method.

To achieve this result, great care has been put into the simulation,[8] final design, and construction of the experimental layout with particular regard to the cryogenic high-purity gas-target able to work at temperatures below 50K and pressures up to 40 atmospheres. The tasks were the following: to minimize the material at the beam entrance window of the thermally isolated structure so as to keep a minimal induced spread of the low momentum beam, to minimize the thickness of the lateral walls so as to allow high transparency for the X-rays of the muonic cascade of interest, and finally to coat the internal vessel with thin layers of high Z material in order to promote fast nuclear muon capture for non-hydrogen muonic atoms and minimize the non-prompt noise induced by decay electrons.

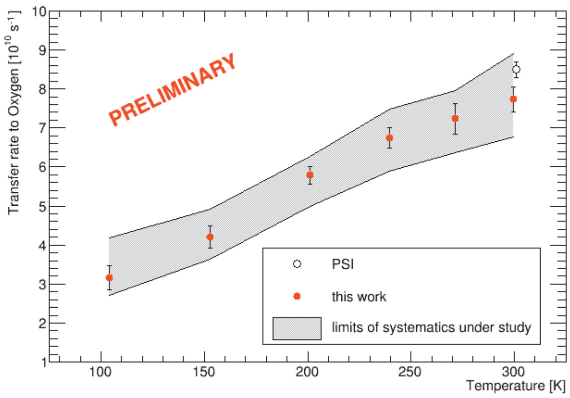

Fig. 1. Transfer rate to oxygen as function of temperature.

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