PROCEEDINGS OF SCIENCE

FAMU latest results in the measurement of the transfer rate from μp to oxygen

Cecilia Pizzolotto[*][†]
INFN Sezione di Trieste, via A. Valerio 2, 34127 Trieste, Italia
E-mail: cecilia.pizzolotto@ts.infn.it

The main goal of the FAMU experiment is to measure for the first time the hyperfine splitting of the muonic hydrogen ground state and, through this measurement, to determine the proton Zemach radius. To achieve this result, it is necessary to characterize first the muon transfer mechanism from muonic hydrogen to higher-Z elements. This study has been carried on by the FAMU collaboration at the RIKEN-RAL muon facility in the UK. The transfer rate of muonic hydrogen to oxygen as a function of temperature is presented here.

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[*]Speaker.
[†]on behalf of the FAMU Collaboration

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1. Introduction

FAMU aims to determine the proton Zemach radius of the proton by measuring the hyperfine splitting of the 1S state of muonic hydrogen by means of laser spectroscopy [1, 2]. Other experimental proposals, that use different techniques to measure the hyperfine-splitting, have been approved at PSI and JPARC [3, 4]. A precise measurement in muonic hydrogen will be an important contribution in the determination of the proton radius, a topic of renewed interest [5, 6, 7, 8, 9].

The method proposed by FAMU is illustrated in figure 1. The method consists in producing muonic hydrogen atom in a hydrogen gas target. After thermalization, a laser tuned to the hyperfine-splitting resonance energy is shoot in the target to induce a singlet-to-triplet transition (F=0)→(F=1) of the muonic hydrogen. Afterwards, the F=1 atom de-excites back to the F=0 state in collision with the surrounding molecules. This de-excitation can not be observed directly. However, due to momentum conservation, the transition energy is partially converted to kinetic energy; the μp atom in this status is called epithermal. When the muonic hydrogen hits a heavier element, the muon is transferred. For some gases the transfer rate depends on the energy of the muonic hydrogen [10]. Oxygen is one of the gases that shows this dependence. Thus, by using a hydrogen target with a small percentage of oxygen and by tuning the laser energy, when the singlet-to-triplet energy is reached, one can observe a variation of the X-rays signal from oxygen. To exploit this effect, the energy dependence of oxygen must be well known. Therefore in its preparatory phase, FAMU performed the measurement of the transfer rate between 104 K and 300 K.

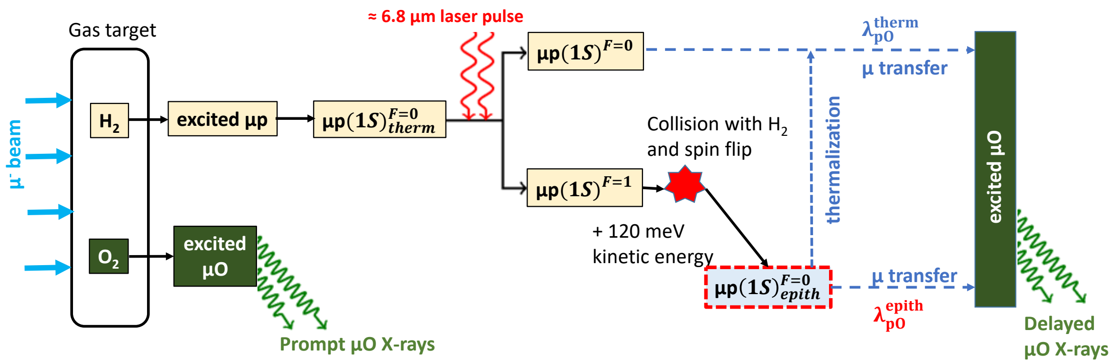

Figure 1: Schematic representation of the FAMU experimental method described in the text.

2. Experimental setup

The setup of the FAMU apparatus is shown in figure 2. Details on the setup are given in [11] and references therein. In front of the target, a fiber beam hodoscope characterizes the beam. The pressurized and thermalized gas target is surrounded by an X-rays detection system. Eight scintillating counters based on Lantanium Bromide crystals read by photomultipliers are used to register the energy and time spectra. Germanium detectors complete the setup; they have a slower response and are used as a cross reference thanks to their better energy resolution. The measurement was performed at the RIKEN-RAL muon facility (UK) where muons are produced in bunches with

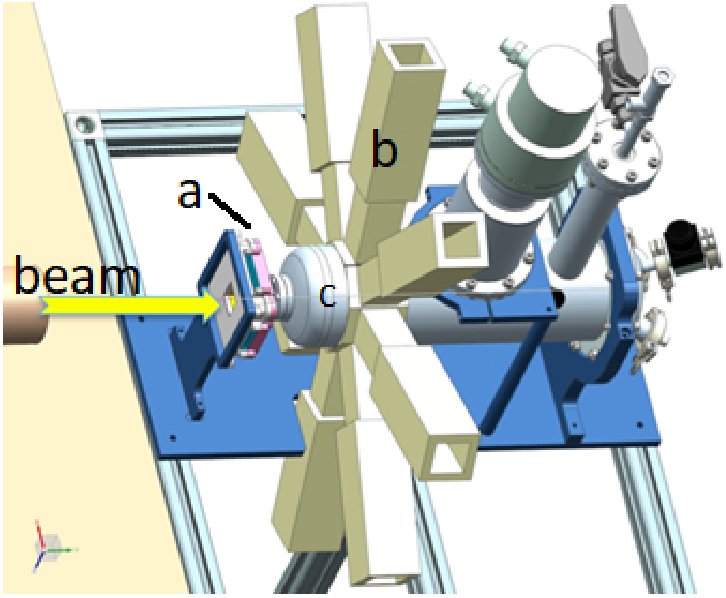

Figure 2: CAD design of the FAMU apparatus. Beam direction is left to right, indicated by the yellow arrow. The beam hodoscope is represented in pink and identified by letter 'a'. The LaBr detectors (yellow, 'b') are arranged in a star-like structure around the cylindric target (grey, 'c').

a repetition rate of 50 Hz. Each bunch consists of two spills, of an almost gaussian shape with FWHM of 70 ns. The time between the spills is about 320 ns. The optimal beam momentum for the experiment was chosen to be 57 MeV/c. A more detailed description of the setup is given in reference [12].

3. Analysis

Data used in this analysis were acquired with a mixture of hydrogen and hydrogen with the oxygen concentration of 190 ppm. The target was filled at room temperature at 41 bar, and then sealed and brought to lower temperatures in steps. The six target temperature were: 300, 272, 240, 201, 153, and 104 K; each temperature was kept stable for three hours.

The measurement of the transfer rate must be performed in thermalized conditions. The target number density, at which the measurement was performed, enabled fast thermalization, less than 150 ns, while the chosen oxygen concentration allowed a mean transfer rate much greater than 150 ns. In these conditions, the system is fully thermalized after few hundred nanoseconds from the arrival of the last muon. To measure the transfer rate a study of the time evolution of the oxygen line emission cam be performed. The variation of the number $N_{\mu p}$ of μp atoms in the target in the time interval dt is:

$$dN_{\mu\mathrm{p}}(t) = -N_{\mu\mathrm{p}}(t)\lambda_{\mathrm{dis}}(T)\,dt \tag{3.1}$$

$$\lambda_{dis}(T) = \lambda_0 + \phi\left(c_p\Lambda_{pp\mu} + c_d\Lambda_{pd}(T) + c_O\Lambda_{pO}(T)\right) \tag{3.2}$$

where $\lambda_{dis}(T)$ is the disappearance rate of the muonic atoms at a temperature T; $\lambda_0 = (4665.01 \pm 0.14) \times 10^2\ \mathrm{s}^{-1}$ [13, 14] is the rate of disappearance of the muons bounded to proton (that includes

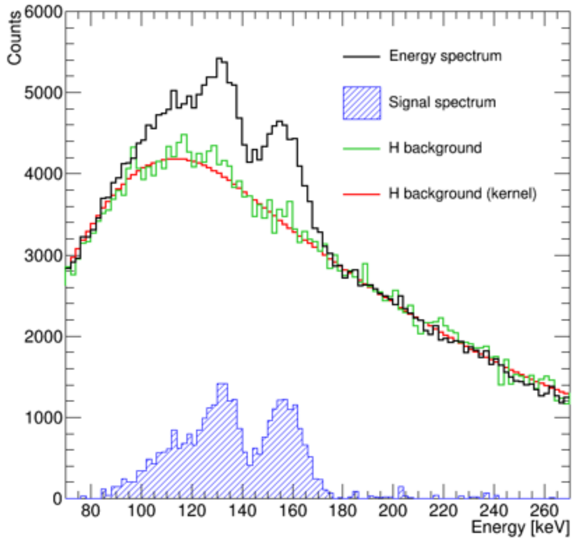

Figure 3: Energy spectrum at 300 K in the time interval 1450 to 1650 ns. Black solid line represents data, green line is the background estimation with a pure H_2 sample, the red line is the background smoothed with a gaussian kernel algorithm. The blue histogram is the signal obtained after background subtraction.

both muon decay and nuclear capture); $\Lambda_{pp\mu} = 2.01 \times 10^6$ s^{-1} [13] denotes the formation rate of the $pp\mu$ molecular ion in collision of μp with a hydrogen nucleus normalized to liquid hydrogen density; $\Lambda_{pd}(T) \approx (1.6 \pm 0.3) \times 10^{10}$ s^{-1} is the muon temperature-dependent transfer rate from μp to deuterium [15], which, for the temperatures of interest, varies within the indicated uncertainty range, and $\Lambda_{pO}(T)$ is the muon transfer rate from μp to oxygen atom. The number density of the atoms in the target gas is $\phi = (4.869 \pm 0.003) \times 10^{-2}$ in LHD units, and c_p, c_O, and c_d are the number concentrations of hydrogen, oxygen, and deuterium respectively. We used hydrogen with measured natural deuterium abundance $c_d = (1.358 \pm 0.001) \times 10^{-4}$. The oxygen concentration was $c_O = (1.90 \pm 0.04) \times 10^{-4}$ and $c_p = 1 - c_O - c_d$.

LaBr detector signals were identified and reconstructed fitting the detectors waveform. Small time drift of the detector signals were corrected, and signals calibrated. Good events were selected with loose criteria on the reduced χ^2 from the wavefit and the time distance between two consecutive signals. Selection efficiency and live time were estimated and taken into account in the analysis. More details about the analysis can be found in reference [11].

At each trigger corresponds a data acquisition window of 10 μs. The data analysis consists in the study of the time evolution of the oxygen X-ray signal, in particular in the delayed phase, that we identified between 1200 and 10000 ns from trigger. This delayed time window was split into 20 bins of increasing width, the smallest being 140 ns wide. For each time bin, the energy spectrum from 50 keV to 500 keV was considered. A background was evaluated and subtracted from the oxygen lines of K_α =133 keV, K_β =158 keV, K_γ =167 keV. The estimation of the background was a crucial aspect of the data analysis. This was estimated using data from a pure H_2 target gas at the same temperature and pressure conditions. Events were selected from the pure H_2 with the same criteria. Spectra are shown in figure 3. Since the H_2 data had a low statistic, before performing the

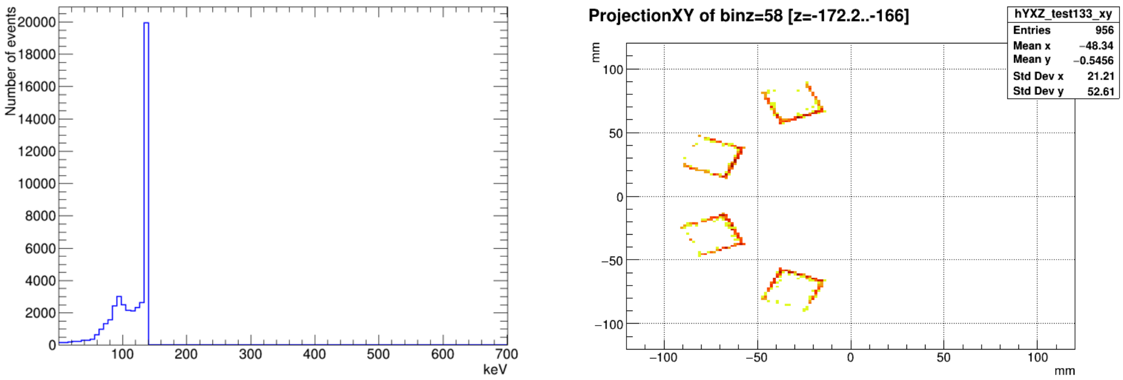

Figure 4: Left: Monte Carlo spectra showing the energy deposited in the detector by X-rays of 133 keV that enter the crystal. The initial energy of 133 keV is not always fully deposited and collected in the detector. Right: Spatial distribution of Monte Carlo events that deposited less than 120 keV in the detector (although the particle entering the detector was a 133 keV X-ray). The plot shows the X-Y plane at a fixed Z. The plane is perpendicular to the muon incoming direction. The shape of the edges of four crystals that surround the target are recognizable.

subtraction, the hydrogen data was smoothed using a gaussian kernel algorithm [11, 16]. Signal tails towards lower energy are mostly due to signals whose energy is not fully contained in the detectors, as demonstrated by Monte Carlo simulations. In fact, since the target size is large and X-rays arrive to the detectors from very different directions, a small but detectable part of events appear to be on the border of the LaBr crystals and their energy deposit is not fully contained, see figure 4.

Fluctuations in the number of signal events due to the normalization of the background and to the background subtraction were considered as systematic errors and summed up in quadrature to the statistical errors. The effect of the systematic is between 5% and 20% depending on the bin statistics.

For each temperature, a set of points representing the integrated signal after background is obtained. These are fitted with the function in equation 3.1 to obtain the transfer rate. A study of the systematic errors, not shown here, includes the uncertainty on the parameters of equation 3.1 and of the oxygen concentration in the gas mixture. These accounted for few percent ($< 5\%$) on the final measurement.

4. Results and conclusion

Results of the transfer rate as a function of the temperature are shown in figure 5. FAMU is the first experiment to measure the transfer rate of oxygen as a function of temperature. This measurements agrees well with the previous data point by Wertmüeller et al. [10]. Error bars represent the error on the fit result and include only statistical and background-related systematical, as explained in reference [11]. Other systematics are not included here.

This measurement is very important to confirm the feasibility of the FAMU method for the measurement of the muonic hydrogen hyperfine splitting. The full experimental setup to perform

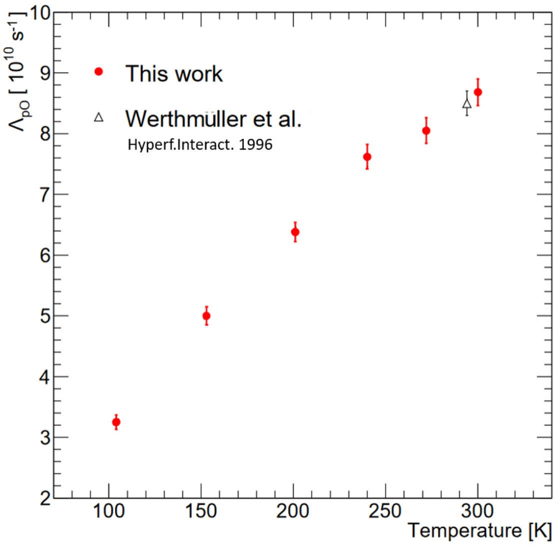

Figure 5: Transfer rate as a function of temperature compared to a previous measurement [10]. Systematic errors are not shown.

the hyperfine splitting measurement is being realized, including the optical cavity [17], the target and the innovative mid infrared laser [18].

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