Optimizing the conditions to measure the hyperfine splitting in the μp ground state

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Experimental studies were performed during 2017 at Port 1 of the RIKEN RAL facility, in preparation for the measurement of the hyperfine splitting in the 1S state of muonic hydrogen $\Delta E_{hfs}(\mu - p)_{1S}$, to allow the choice of the final layout and confirm the details of the foreseen methodology.[1–6] By measuring the transition $\Delta E_{hfs}(\mu - p)_{1S}$ in μp with a precision of $< 10^{-5}$, the experiment will provide the Zemach radius of the proton $\mathbf{r_Z}$ with high precision, allowing diesntanglement of the discordant theoretical values. The level of discrepancy between the values of $\mathbf{r_Z}$ as extracted from the normal and muonic hydrogen atoms will be quantified, a result that is also important for the not yet explained anomalies on the charge $\mathbf{r_{ch}}$ radius of the proton. The physical process behind this experiment is as follows: μp are formed in a mixture of hydrogen and a higher-Z gas. When a photon is absorbed at resonance-energy $\Delta E_{hfs} \approx 0.182$ eV, in subsequent collisions with the surrounding H_2 molecules, the μp is quickly de-excited and and accelerated by $\sim 2/3$ of the excitation energy. The observable is the time distribution of the K X-rays emitted from the μZ formed by muon transfer $(\mu p) + Z \rightarrow (\mu Z)^* + p$, a reaction whose rate depends on the μp kinetic energy. The maximal response, to the tuned laser wavelength, of the time distribution of K X-ray from the $(\mu Z)^*$ cascade indicates the resonance.

During 2017, using the set of beam-hodoscopes[7] developed for this purpose, it has been possible to show the adaptability of the beam to our layout and to verify its shape and position. Figure 1 shows the total charge deposited in the hodoscope, an increase of about 10% indicates that by tuning the beam optics a muon beam intensity increase was obtained.

Subsequently, as an addition to the previously performed measurements (in 2016) of the muon transfer rate to oxygen at different temperatures, the same FAMU cryogenic gas target[8] was used to perform a detailed study of the shape of the background underneath the peaks of the x-rays characterizing the delayed transition of the muon from μp to oxygen. The target loaded with high purity hydrogen was exposed to the 57 MeV/c muon beam, the x-ray spectra was detected with LaBr fast detectors.[9]

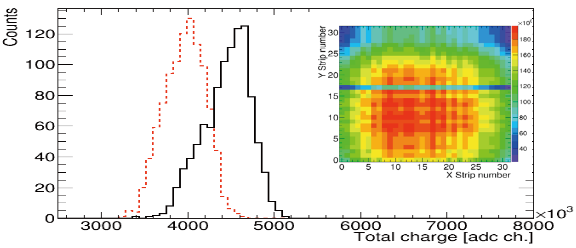

Fig. 1. Total charge detected by the hodoscope before (red dashed line) and after (black solid line) the tuning of the magnets and, in the insert, the two dimensional beam profile of 1 mm per strip.

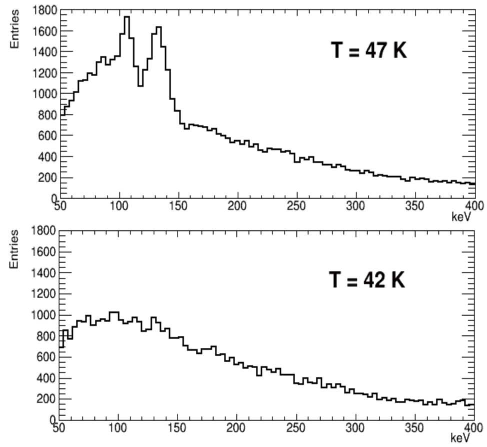

Fig. 2. Upper panel, shows the delayed nitrogen X-rays lines at a temperature of 47 K. In the lower panel the same spectrum is shown at a temperature of 42 K.

During the following phase, dedicated to extending the temperature range of the 2016 transfer rate measurements, it was discovered with great disappointment that the custom delivered gas mixture was badly polluted with nitrogen. Since it was impossible to obtain a new delivery on time, by virtue of necessity and to obtain useful data, we investigated the condensation temperature limits of the heavy elements in the available mixture. Under the assumption of perfect gases and the Dalton law, we can calculate that the gas condensation on the internal vessel surface occur at 54 K for oxygen and 46 K for nitrogen, however in our experimental conditions of pressurized gas mixture, this needs to be verified experimentally.

The delayed nitrogen X-rays lines, at the temperature of 47 K, is shown in the upper panel of Fig. 2. At 42 K the nitrogen lines disappear and pure hydrogen background distribution remains visible in the lower panel. The equipment used in the 2017 experiments performed as expected except for the gas contamination. This has restricted our program especially the possibility to extend the study of transfer rate to oxygen at higher temperatures.

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