The FAMU experiment: muonic atoms to probe the proton structure

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Abstract. The goal of the FAMU experiment is the measurement of the proton Zemach radius using muonic hydrogen, a subject that has raised much interest in recent years due to its implications in the so-called proton radius puzzle. In order to extract the Zemach radius, the FAMU collaboration aims at measuring the hyperfine splitting of the μp ground state, since the effect of the proton finite size affects the HF transition energy. The proposed experimental method requires a detection system which is suited for time resolved X-ray spectroscopy: in this contribution the results of the first measurements performed at the RIKEN-RAL muon facility in order to verify the fitness of the detection system in the pulsed intense muon beam are presented. The characteristic X-rays from atomic transitions in muonic atoms formed in different targets have been detected using a HPGe detector and five scintillating counters based on $LaBr_3$(Ce) crystals, whose output has been recorded for 5 µs using a 500 MHz digitizer to measure both the energy and the time spectrum of the detected events. With a detailed pulse analysis considering pile-up events, both the expected characteristic X-rays and lifetimes of various elements were measured, paving the way for future measurements to be carried out in early 2016.

1. The strange case of the proton radius

The proton is one of the most common particles in the universe and one of the building blocks of ordinary matter; it is also one of the first particles discovered in 1919 by Ernest Rutherford. Since then, the proton has been widely studied but it still manage to astonish physicists.

Until 2010, there were only two ways to dig with high precision into the electromagnetic structure of the proton in order to get information on its size: the first approach is the study of elastic scattering of electrons and positrons on hydrogen nuclei and accurate measurements of the Lamb shift in the hydrogen atom spectrum. Indeed, the Lamb shift groups all the contributions in the energy level that aren't taken into account in the "standard" quantum treatment, such as QED and recoil corrections and the effects due to the nuclear structure, like its finite size. The level of accuracy needed to measure the effect of the nuclear size (namely the root mean square of the charge distribution) was reached in the 1990s, providing a value of the proton charge radius totally consistent with the ones obtained with scattering experiments[1]. In order to increase the accuracy of the this value, a measurement of the Lamb shift in the $2S$–$2P$ transition of *muonic* hydrogen (μp, *i. e.* the bound state formed by a proton and a negative muon) was proposed; indeed the muon, being about 200 times heavier than the electron is also 200 times closer to

[1] The most recent value computed by the Committee on Data for Science and Technology (CODATA) as a weighted average between various experiment is $r_p = 0.8751(61)$ fm [1].

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the proton, and thus much more sensitive to its structure. The results of this measurement were published in 2010 and provided a value of the proton charge radius $r_{\mathrm{p}} = 0.841\,84(67)$ fm that was about an order of magnitude more accurate than previous measurements but totally inconsistent [2].

This result was confirmed by other measurements published in 2013 [3], but nobody has been able to explain the discrepancy between "electronic" and "muonic" measurements and all the hypotheses are still on the table, ranging from experimental accident to effects of unconsidered contributions in the calculations or hints for new physics [4].

2. Concept of the FAMU experiment

To help shedding some light on this puzzle, the FAMU project aims at studying the proton structure using muonic atoms, but instead of the charge radius, the goal of the experiment is the measurement of the Zemach radius[2] of the proton R_{p} which can be extracted performing a precise measurement of the hyperfine splitting of the μp ground state [6, 7]. This quantity has been already measured using ordinary hydrogen, and a comparison with the value extracted from muonic hydrogen may either reinforce or delimit the proton radius puzzle: a substantial agreement with the value of R_{p} obtained with ordinary hydrogen could suggest that the explanation of the puzzle may lie in unconsidered methodology uncertainties, while a big discrepancy would give good reasons to look for new physics beyond the Standard Model.

The experimental method for this measurement, proposed in [8], combines elementary particles with laser spectroscopy techniques and its schematic representation is shown in Fig. 1. Muons slowed down and stopped in a hydrogen gas target form muonic hydrogen atoms: $\sim 75\%$ in the triplet state ($F = 1$) and the remaining part in the singlet configuration ($F = 0$). Collisions between muonic hydrogen atoms and H_2 molecules quickly de-excite the $\mu\mathrm{p}(1S)^{F=1}$ atoms to the singlet state, leaving thermalized muonic hydrogen atoms in the $(1S)^{F=0}$ state. At this point, a laser tuned on the HFS resonance is sent inside the target, inducing a series of singlet-to-triplet transitions. Muonic hydrogen atoms in the $(1S)^{F=1}$ state are once again de-excited back to the singlet state in collision with H_2 molecules and the transition energy is converted into additional kinetic energy of the μp–H_2 system. In this way the μp atom gains about 2/3 of the hyperfine transition energy ($\approx 120\,\mathrm{meV}$).

To detect these "kicked" μps, Bakalov et al. [9] proposed to exploit the muon transfer from muonic hydrogen to another higher-Z gas. Indeed, although theory predicts the muon-transfer rate at low energies $\lambda_{\mathrm{p}Z}$ to be energy independent, there are few gases in which it is proved that this is not the case. The first gas that was demonstrated to show such a particular behaviour was oxygen [10, 11], that exhibits a sort of peak in the muon transfer rate $\lambda_{\mathrm{p}Z}^{\mathrm{epith}}$ at the epithermal energy ($\sim 100\,\mathrm{eV}$). More recent theoretical and experimental studies suggested that also argon and neon could exhibit similar properties [12, 13]. Thus, adding small quantities of one of these gases to hydrogen, one can obtain the number of accelerated μps from the number of muon-transfer events measuring the characteristic X-rays of the added gas that are emitted few ns after the formation of the muonic atom.

Performing a scan over the laser frequency near the HFS transition one and counting for each frequency the number of the muon transfer events, one can then obtain a resonance plot and thus the value of the hyperfine splitting of the $1S$ state.

3. The 2014 beam test

The proposed experimental strategy requires a multiple efforts on many different items, not last being the development of a detection system suited for high-rate X-ray spectroscopy; indeed,

[2] The *Zemach radius* was defined by A. C. Zemach in 1956 as the convolution of the charge and magnetic moment density [5].

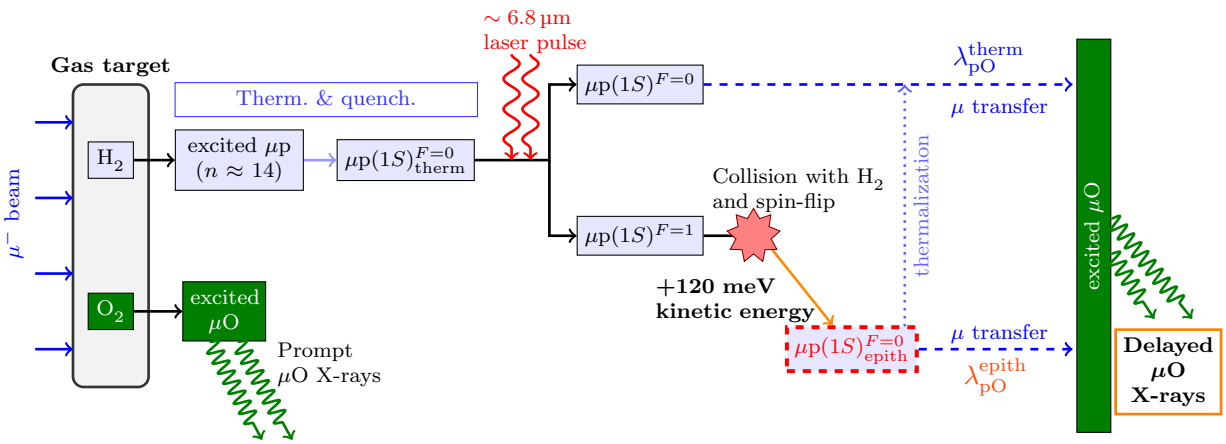


Figure 1: Schematic representation of the FAMU experimental method.

the detection apparatus is not important just in sight of the final experiment, but is also crucial for a series of measurements that are needed in order to validate the method described in the previous section.

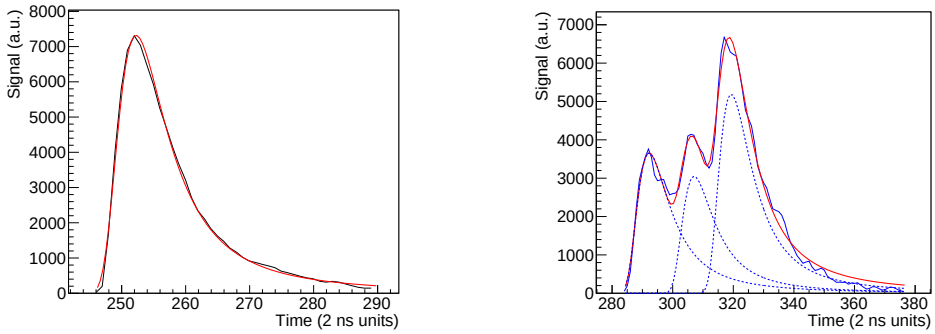
3.1. The experimental set-up

A first test of the apparatus was performed in the summer of 2014 at the Rutherford–Appleton Laboratories (UK) where the RIKEN–RAL muon complex [14] is located, the only facility in the world able to provide the pulsed muon beam which is needed for the experiment. An intense muon beam (up to 10^5 muons/(s· cm^2)) is generated by pion decays produced by 800 MeV protons colliding on a carbon target once they have been accelerated by the ISIS synchrotron. The muon beam is then delivered to four experimental ports, and its shape reflects the behaviour of the ISIS proton beam showing a 50 Hz double-pulse structure. Each pulse is about 70 ns long and the time between the two pulses is 320 ns.

Four different targets were exposed to the muon beam: a pure graphite block and three gas mixture (pure H_2, H_2+2%Ar, H_2+4%CO_2, where the percentages are to be intended by weight) contained into an aluminium vessel.

Muonic atoms characteristic X-rays were detected using two different kind of detectors: the heart of the detection system consisted in five scintillating counters based on $LaBr_3$(Ce) crystals, while two HPGe detectors were used in order to have a benchmark spectrum, since they are too slow for the high rate environment. Lanthanum bromide crystals have been chosen for their outstanding performance in terms of energy resolution (2.6% at 662 keV) and decay time ($\tau = 16$ ns), which make them the best inorganic scintillators currently available. Four of the five cylindrical crystals, having diameter of 0.5″ and height 0.5″, were placed in a $80 \times 80 \times 200$ mm^3 iron box coated on its side with a 2 mm thick lead sheet, forming a 2×2 matrix crystals readout by four Hamamatsu R11265-200 PMTs. The other counter was a commercially available Brillance 380 by Saint-Gobain Crystals with embedded PMT reading out a diameter 1″ × 1″ crystal.

To avoid losing useful information, the whole detector output was recorded for 5 µs after the trigger provided by the beam line, using a 500 MHz 14-bit digitizer (CAEN DT5730). The waveforms were then processed off-line with a dedicated software; this choice was also motivated by the specific requirements of the measurement: on one side, not only the energy spectrum of the detected X-rays is interesting but also their time distribution, that can be easily obtained from the digitizer output once a proper analysis method is implemented [15]. On the other hand, from the analysis of the full waveform of the signal one can discriminate single-pulse (Fig. 2a) from pile-up events (Fig. 2b), and may recover information from pile-up events that otherwise



(a) Single pulse **(b)** Multiple pulses

Figure 2: Examples of single- **(a)** and multi- **(b)** pulse events as obtained by one of the $LaBr_3$(Ce) counters and processed off-line.

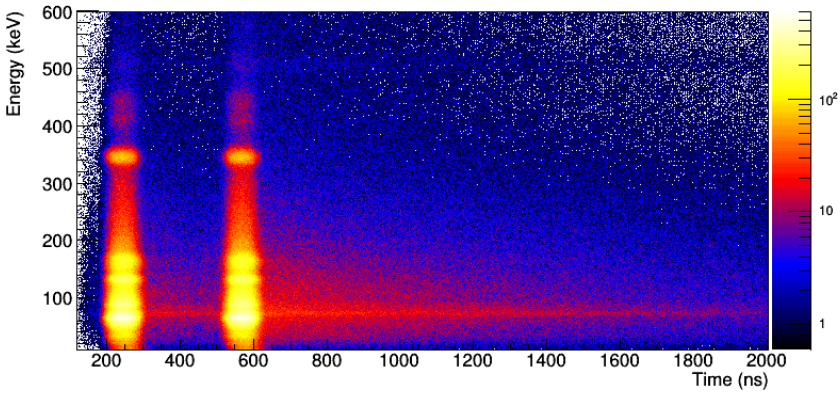


Figure 3: Example of time evolution of the X-ray spectrum for the H_2–CO_2 target. The double pulse structure of the muon beam is evident.

would be lost. Indeed, performing a fit of the signal output, pile-up events were identified and disentangled, recovering more of the 25% of the full data set.

3.2. Data Analysis

Once every pulse induced in the $LaBr_3$(Ce) detectors has been reconstructed, it is easy to extract its starting time and its integral, so to build the time evolution of the X-ray spectrum (Fig. 3).

Once reconstructed the energy spectrum it was possible to look for muonic atoms characteristic X-rays; since muonic atoms are usually formed in highly excited states and quickly de-excite to the ground state emitting photons in the keV range.

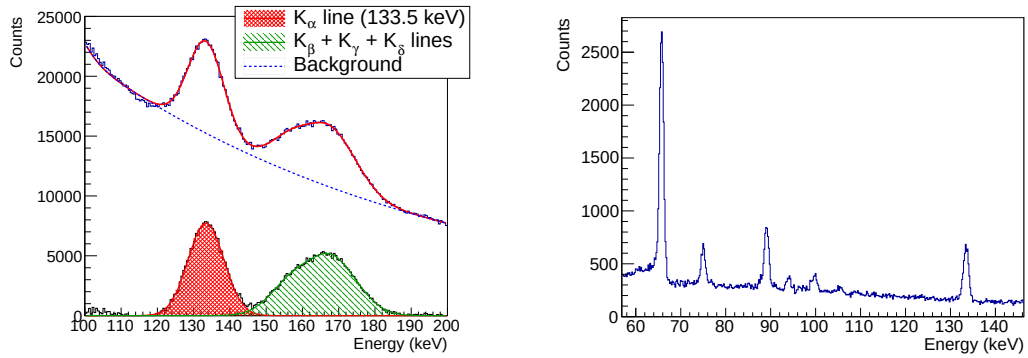
The characteristics of the detection system did not allow to reconstruct the energy spectrum below 60 keV, so μp characteristic X-rays ($\sim$ 2 keV) are well below the detectability threshold of our system. However, the X-rays emitted by the atomic transitions in heavier atoms and listed in Table 1 were detected.

Because of its peculiar behaviour in the muon transfer process, the detection of oxygen X-rays was one of the goal of the beam test. In the figure a close-up of the region of interest of the spectrum recorded with the four smaller $LaBr_3$(Ce) counters is shown: the K_α line (133.5 keV) is well resolved and also the other K transition lines are present, though not resolved because of the limited energy resolution, as shown in Fig. 4a.

The reference spectra provided by the ORTEC GLP HPGe detector (Fig. 4b) does not show

Transition	Transition energy for various elements (keV)			
	μC	μO	μAl	μAr
K_α	75.258*	133.535	346.828	644.004
K_β	89.212*	158.422*	412.877†	770.6†
K_γ	94.095*	167.125*	435.981†	815.0†
L_α			65.756*	126.237
L_β			88.771*	170.420*
L_γ			99.423*	190.870*

Table 1: Atomic transitions detected for different muonic atoms. The asterisk * indicates transitions that were not well resolved because of detectors limited energy resolution, while dagger † refers to those lines with small statistic or low efficiency of the detectors.



(a) $LaBr_3$ counters spectrum **(b)** HPGe spectrum

Figure 4: X-ray spectrum recorded using **(a)** the four smaller $LaBr_3$(Ce) counters and **(b)** the HPGe detector.

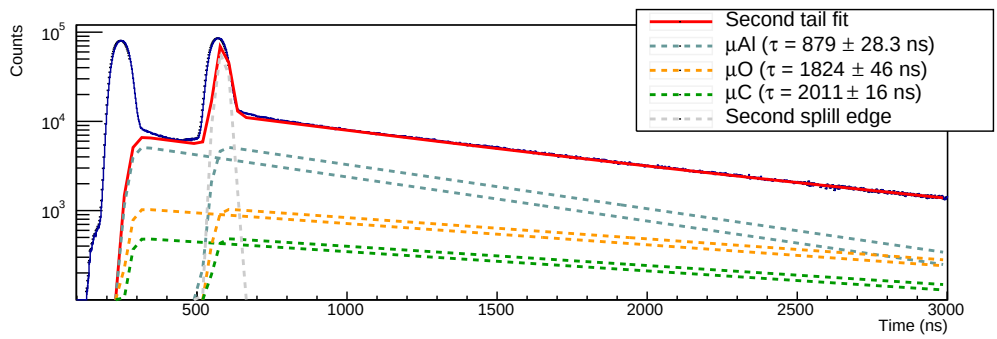


Figure 5: Time distribution of the events recorded with the H_2–CO_2 target using the four smaller $LaBr_3$ detectors.

characteristic X-rays due to unwanted contaminations, confirming the purity of the gas mixture under study.

As mentioned in the previous section, also the time distribution of the events needs to be reconstructed. From Fig. 5 it can be inferred that the time spectrum can be divided in two main contributions: the "prompt" peak, roughly in time with the muon spills, and the "tails" of the delayed events. The main part of the characteristic X-rays is concentrated inside the prompt peak, while the tails are populated by the products of muon decay (low energy electrons and bremsstrahlung photons); thus, while characteristic X-rays indicate the composition of the target, the tails of the distribution carry information about the muonic atoms lifetimes.

	This work (ns)	Suzuki et al. (ns)
μC	2011 ± 16	2026 ± 1.5
μp	2141 ± 98	2194.53 ± 0.11
μAl	879 ± 28	864 ± 2
μO	1824 ± 46	1795 ± 2
μAr	564 ± 14	537 ± 32

Table 2: Lifetimes of various muonic atoms as measured by the FAMU experiment and their values reported in [16] (and references therein).

Starting from the simplest target, the graphite block, the tails of the time spectrum have been fitted with gaussians convolved with exponentially decaying functions. The fit was performed considering only the far delayed part of the time spectrum ($t > 2500$ ns) and the falling edge of the second muon beam spill, because in gaseous targets the time spectrum might present distortions in the time region near the muon spill caused by the muon transfer process.

The lifetimes obtained for the various muonic atoms are shown in Table 2 together with the values reported in literature [16]; the fit for the H_2–CO_2 and H_2–Ar targets was performed fixing the lifetimes of μp, μAl and μC using the values obtained from the graphite and the pure H_2 targets.

From these two gas mixtures, one can notice that the μp component of the time spectrum is strongly suppressed; this happens because all the μp atoms transfer their muons to O, C and Ar before they have time do decay.

4. Conclusions

The experimental method adopted by the FAMU experiment for the measurement of the proton Zemach radius requires a detection system suited for time resolved X-ray spectroscopy with high resolution both on energy and time. Scintillating detectors based on $LaBr_3$(Ce) crystals with their output recorded by a 500 MHz digitizer for an off-line pulse analysis were tested at the RIKEN-RAL muon facility and met the requirements both on energy and time resolution, correctly reconstructing the relevant characteristic X-rays and the lifetimes of the muonic atoms.

The good performance achieved with this detection techniques make $LaBr_3$(Ce) crystals optimal candidates for further studies on the muon transfer process and for the final experiment.

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