Performance of X-rays crystal detectors with SiPM array readout exposed to the RIKEN RAL low energy muon beam

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Abstract

Scintillating crystals coupled to SiPM array readout have been proposed to realize compact X-rays detectors for the FAMU experiment, which aims to accurately measure the hyperfine splitting of the ground state of the muonic hydrogen atom. A measurement of the transfer rate of muons from hydrogen to heavier gases is necessary for this purpose. Since 2015, in a series of test runs, a pressurized gas-target was exposed to the pulsed low-energy muon beam at the RIKEN RAL muon facility (Rutherford Appleton Laboratory, U.K.). The main goal of these tests was the characterization of both the noise induced by the pulsed beam and the X-ray detectors.

Preliminary results are shown on the use of new Pr:LuAG and Ce:GAGG crystals, developed for PET scanners and of more conventional $LaBr_3$:Ce crystals, with a SiPM array readout. The first two crystals are not hygroscopic and have high photon yields, good energy resolution and fast decay time. Spectra of the X-rays produced after the de-excitation of muonic atoms formed from the interaction of the beam muons with different gas targets in the FAMU apparatus are shown, demonstrating the feasibility of these detectors for muonic X-rays spectroscopy.

Introduction

The FAMU experiment goal is the detection of the characteristic X-rays emitted during the de-excitation processes of the muonic hydrogen after the excitation with an IR laser with wavelength set at the resonance of the hyperfine splitting, to measure the muonic atom proton radius with unprecedented precision. FAMU could explain the 7σ disagreement between the experimental values of the proton RMS charge radius extracted from e-p scattering and muonic hydrogen spectroscopy. This discrepancy has not been explained yet (*"proton radius puzzle"*).

The RIKEN-RAL 2016 and 2017 FAMU setups

The pulsed muon source of the RIKEN RAL muon facility at the Rutherford Appleton Laboratory (RAL) is well suited to the scope of the project. It may deliver about 3 to 8 $\times 10^4$ negative muons per second with a pulse repetition rate 50 Hz at momentum in the range p = (30÷ 80) MeV/c, with $\sigma_p/p = 4\%$ and a beam transversal section of $\sigma_x, \sigma_y = 1.5\,cm$. The beam has a double peak structure with 70 ns pulse width (FWHM) and peak to peak distance of 320 ns. The beam may be delivered alternatively to four delivery ports (Port1-Port4).
The experimental apparatus adopted in the FAMU test runs of 2016 and 2017, shown in Fig. 1, is based on:

- a 1 mm pitch X/Y beam hodoscope to tune the beam steering onto the target and thus maximize the efficiency of the data taking.
- a cryogenic target, where the liquid hydrogen and the heavy gas admixture is contained.
- a system for characteristic X-rays detection, based mainly on 1" LaBr3:Ce detectors and HPGe detectors.

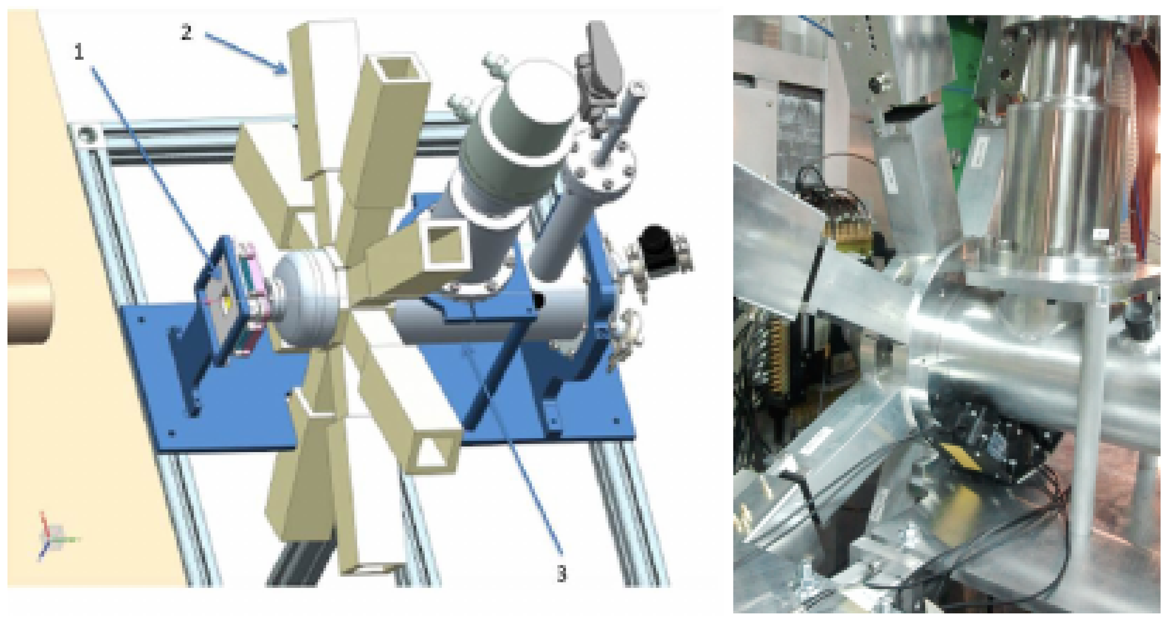

Figure 1: Left: layout of the FAMU setup at RIKEN-RAL. The beam is coming from the left. Visible are the 1 mm pitch beam hodoscope (1), the $LaBr_3$:Ce crystals with PMT readout (2), arranged in a crown of 8 elements and the cryogenic target (3). Right: image showing the cryogenic pump and some $LaBr_3$:Ce crystals.

Compact X-rays detectors with SiPM readout

To equip regions otherwise difficult to be instrumented, due to lack of space, as the ones under the target vessel, it was chosen to use 1/2" crystals with a compact SiPM array readout. In 2016 run, non-hygroscopic Ce:GAGG or Pr:LuAG crystals, for which no encapsulation is needed, were tested. Then, detectors based on $LaBr_3$:Ce were used in the 2017 run, to have a better energy resolution. In the 2016 run two 1/2" Ce:GAGG and four 1/2" Pr:LuAG detectors were put under the taget in a cross-shape. In the 2017 run, as the 1" $LaBr_3$:Ce detectors with PMT readout were assembled in two half-crowns shifted along the target, eight 1/2" $LaBr_3$:Ce with SiPM array readout were positioned in a way to complete the two half-crowns.
The 1/2" crystals under test were read by 4×4 SiPM arrays made of 3×3 mm^2 SiPM. The detector holder was realized with a 3D printer. Operating voltages(V_{op}) were set according to manufacturer's specs. Most of our results were obtained with Hamamatsu S13361 arrays, based on a TSV ("through silicon via") technology. A picture of this setup is shown in Fig. 2.

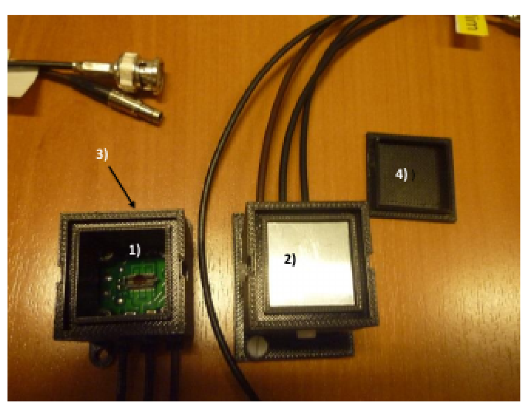

Figure 2: crystal mounting. 1) is the PCB; 2) the crystal under test; 3) the crystal holder and 4) the cover to ensure light-tightness.

Results from March 2016 run

We first show some results on Pr:LuAG and Ce:GAGG crystals read by SiPM arrays from the 2016 run. A study of the time spectrum of the MiB08 Ce:GAGG shows how these detectors are able resolve well the two beam pulses structure, see figure 3. Among the six detectors, only the three closest to the target window (MIB04, MIB08, MIB09) were able to produce spectra with clear peaks, demonstrating that the muon captures are exhausted just after the $LaBr_3$:Ce detector crown. Figure 3 shows the overall spectra (a.u.) of the six detectors with a H_2-O_2(1%) gas mixture as an example: two Ce:GAGG and one Pr:LuAG detectors show evidence of a multi-peak structure, with the best performance from the MiB08 Ce:GAGG detector.
This is the first time that these detectors are shown to be be effectively adopted for the muonic atoms spectroscopy. More detailed analysis with enlarged statistics is foreseen to possibly extract information on the muonic atoms delayed capture rate in 2016 FAMU data.

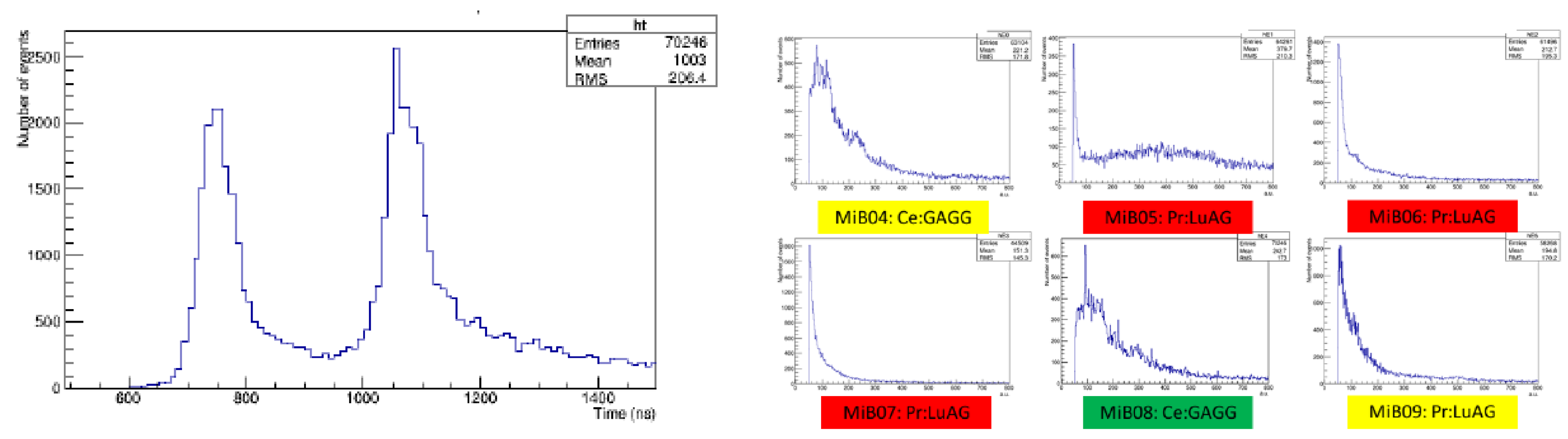

Figure 3: Left: Time spectrum of muonic capture events from Ce:GAGG detector analysis of data from H_2-O_2(1%) gas mixture: the two beam spills are well resolved. Right: overall spectra of the six Pr:LuAG and Ce:GAGG detectors for a H_2-O_2(1%) gas mixture, P = 57 GeV/c and at T = 285 K.

Results from March 2017 run

Better performance has been achieved by the $LaBr_3$:Ce detectors with SiPM array readout, tested in the FAMU March 2017 run. All eight detectors were first calibrated with a ^{57}Co source and a source that was an admixture of ^{241}Am and ^{137}Cs.

$LaBr_3$:ce	59 keV	122 keV	662 keV
MiB10	15.2%	9.5%	4.7%
MiB11	14.4%	11.5%	5.0%
MiB12	15.8%	9.1%	5.4%
MiB13	20.0%	11.8%	5.5%
MiB14	19.3%	11.2%	4.8%
MiB15	20.9%	15.6%	5.4%
MiB16	15.2%	10.3%	3.8%
MiB17	11.8%	7.8%	6.2%

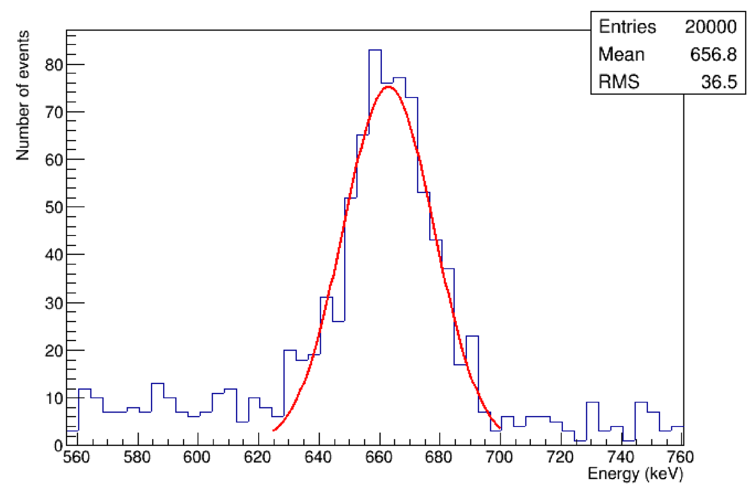

Figure 4: Left: energy resolutions of the eight $LaBr_3$:Ce read by SiPM arrays relative to few calibrations sources. Right: example of calibration with ^{137}Cs line at 662 keV with MiB15 $LaBr_3$:Ce detector.

As an example, we show the overall calibrated spectrum from a run with a H_2-O_2(0.3%) gas mixture, P = 57 GeV/c and room temperature, taken with MiB12 detector. We do not observe any Oxygen lines at 133 keV and at 160 keV in the spectrum built with events delayed with respect to the prompt events which are on time with the beam. For this reason, the lines we show can be recognized as produced by materials composing the FAMU gas target, namely the two Nickel lines at 107 keV and 310 keV, and lines from Gold (170 keV) and Aluminium (347 keV).

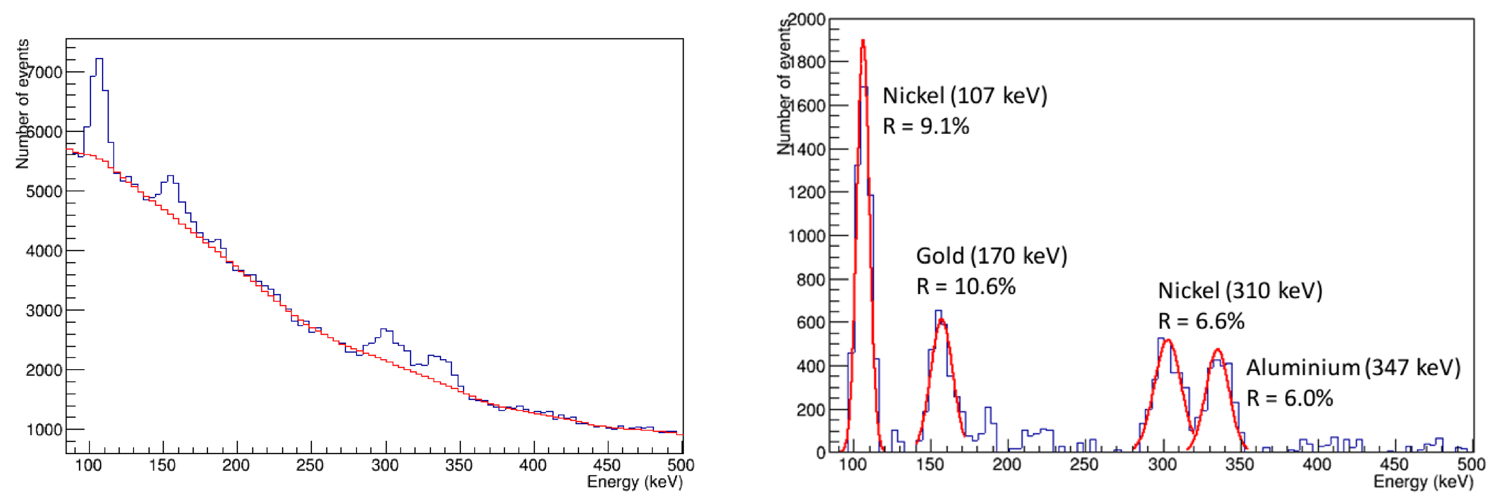

Figure 5: Left: Spectrum from a run with a H_2-O_2(0.3%) gas mixture, P = 57 GeV/c and room temperature, taken with MiB12 detector. Right: Same spectrum with background subtracted: X-ray line peaks due to gas target materials are highlighted with the corresponding energy resolutions.

Outlook

This work shows the feasibility of rare earth crystal-based detectors with compact SiPM arrays readout for muonic atom spectroscopy, once exposed to intense muon beams such as the RIKEN-RAL low energy one. In particular, $LaBr_3$:Ce have good performance in terms of resolution at the energies of few hundred keV, comparable with the FAMU baseline choice, which foresees $LaBr_3$:Ce detectors with standard PMT read-out. Therefore these detectors should be well suited to measure the muon transfer rate from hydrogen to oxygen in the final FAMU experiment setup.