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Systematic study of innovative hygroscopic and non-hygroscopic crystals with SiPM array readout

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Different crystals with SiPM array readout were tested in laboratory. Hygroscopic crystals, such as $LaBr_3$:Ce and $CeBr_3$, and innovative non-hygroscopic crystals, such as PrLuAg and CeCAAG were studied. 4×4 SiPM arrays from different manufacturers were used as photodetectors. Best results were obtained with $LaBr_3$:Ce crystals read by Hamamatsu S13361 TSV arrays. For $LaBr_3$:Ce crystals, due to their high photon yield, it was possible to implement a simple readout scheme based on CAEN V1730 FADC, without any amplification. Energy resolutions (FWHM) better than 4% were obtained at the Cs^{137} peak, with a detector linearity better than 2%.

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1. Introduction

Compact X-rays detectors based on crystals with SiPM array readout may find application in many fields such as TOF PET imaging [1], fundamental physics such as the FAMU measurement at Riken-RAL of the Zemach proton radius [2] and homeland security. For our aims it is essential to detect low-energy X-rays in the range 100-700 KeV. PrLuAG [3] and CeCAAG [4] crystals with respect to more conventional $LaBr_3$:Ce, $CeBr_3$[5] and NaI(Tl) crystals, have the advantage to be non hygroscopic and thus do not need encapsulation. Their main properties are shown in table 1.

Table 1: Main characteristics of the crystals under test. Typical energy resolutions (FWHM in %), from published data, are measured at the Cs^{137} peak with a PMT readout.

Scintillators	PrLuAG	Ce:GAGG	Ce:$LaBr_3$	$CeBr_3$	NaI(Tl)
Density (g/cm^3)	6.73	6.63	5.08	5.18	3.67
Light yield (γ/MeV)	22,000	57,000	75,000	47000	38000
Decay time (ns)	20	88 (91 %)	30	25	250
		258 (9 %)			
Peak emission (nm)	310	520	375	370	415
Energy resolution	4.3	5.3	2.6	4.0	7.0
Hygroscopicity	no	no	yes	yes	yes

As one isotope (Lu^{176}) of naturally occurring lutetium is unstable [1] an intrinsic activity for PrLuAg crystals may be expected. The same is true for Ce:$LaBr_3$ crystals, due to the presence of La^{138}, that emits conversion electrons and β particles with energy up to 1.7 MeV. The intrinsic activity for all crystals under test was measured with a HpGe detector. The measured intrinsic activity spectrum is shown in figure 1. While the intrinsic activity of PrLuAg crystals is not negligible ($\sim$ 36 Bq/g), the intrinsic activity of CeCAAG crystals is minimal ($\leq 1.5 \times 10^{-3}$ Bq/g). The activity of Ce:$LaBr_3$ ($\sim$ 0.2 Bq/g) is half-way between the two.

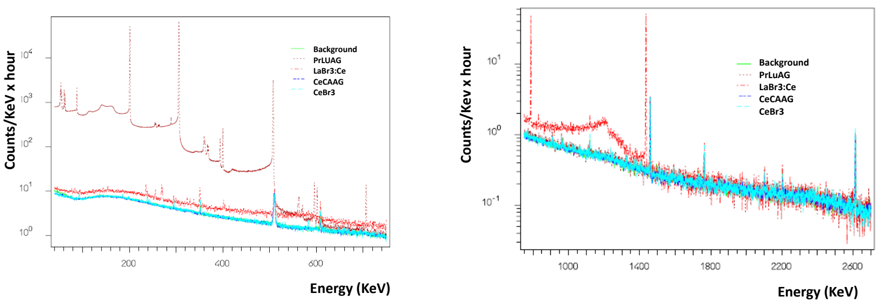

Figure 1: Intrinsic activity of the crystals under test, as measured with a HpGe detector, with a standard spectroscopic chain, based on a Ortec 672 spectroscopy amplifier and a MCA analyzer .

The 1/2 " crystals under test are read by 4×4 SiPM arrays made of 3×3 mm^2 SiPM from SenSL, Advansid or Hamamatsu. Operating voltages (V_{op}) are set according to manufacturer's specs. Their response (PDE) to light of different wavelength depends also on the type of window used, as shown in figure 2 for Hamamatsu S13361 SiPM arrays. Most of our results were obtained

[1] $\tau_{1/2} = 3.78 \cdot 10^{10}$ years, 2.59 % abundance

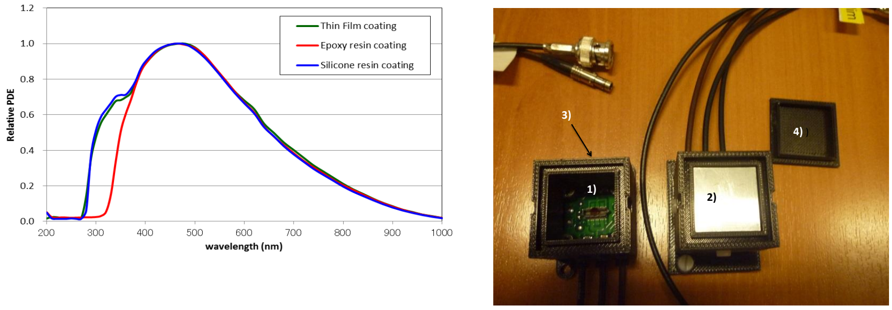

Figure 2: Left panel: response of Hamamatsu S13361 SiPM arrays to incident photons of different wavelengths and with different windows [courtesy of Hamamatsu Italia]. Right panel: crystal mounting. 1) is the PCB; 2) the crystal under test; 3) the crystal holder and 4) the cover to ensure light-tightness.

with Hamamatsu S13361 arrays, based on a TSV ("through silicon via") technology. For PrLuAg (with emission in the near UV) and $LaBr_3$ crystals SiPM arrays with a Silicone window were used to increase response at NUV wavelengths.

The output from each pixel of the 4×4 SiPM array is summed up on a custom PCB ("basette"). The crystal and the "basette" are mounted inside a light-tight housing printed with a 3D printer (see the right panel of figure 2 for details). The optical coupling between the crystal and the SiPM array was obtained with a Bicron BC630 optical grease [2]. Five out of six faces of the crystal were covered with an optical reflector. As the PrLuAg emission is around 310 nm it was difficult to find a proper optical diffuser or reflector. The best solution was to use the water based Avian-B optical coating (mainly based on $BaSO_4$) that has a $\geq 97\%(93\%)$ reflectance in the range 400-850 (250-400) nm. An Al diffuser was used instead for CeCAAG crystals.

2. Experimental results

Detectors' response has been studied at room temperature, using a standard spectroscopic chain based on various types of amplifiers [3] and a CAEN N957 MCA . The acquired data, written in ASCII format, were then analyzed with the ROOT package. Temperature excursions in the test setup were monitored with a precision thermometer [4]. The best results were obtained with the Ortec 672 Spectroscopy amplifier, with a 3 μs shaping time. In the other cases energy resolutions were a 10-30 % worse. Figure 3 shows a typical MCA spectrum obtained from a PrLuAg ($LaBr_3$:Ce) crystal read by a S13361 Hamamatsu SiPM array, using a Cs^{137} source.

With a PrLuAg (CeCAAG) crystal the best resolution obtained is around 7% (6%). The result obtained for PrLuAg is worse as compared with what obtained with a PMT readout in reference [3], but is better compared with what obtained with a SiPM array readout in reference [6]. Probably this is due to the lower dark noise of the new TSV S13361 Hamamatsu SiPM arrays used. As a reference, with $LaBr_3$:Ce crystals we obtain at the Cs^{137} peak a resolution better than 4%. Typical results obtained for the crystals under test, with SiPM array readout, are resumed in table 2.

[2] with a nearly flat transmission (95%) between 280 and 700 nm
[3] Ortec 672, Ortec 579, Phillips Scientific PLS774 and CAEN A1423 amplifiers were used
[4] Hanna Checktemp 1 with 0.1^0C resolution and $\pm 0.3^0C$ accuracy

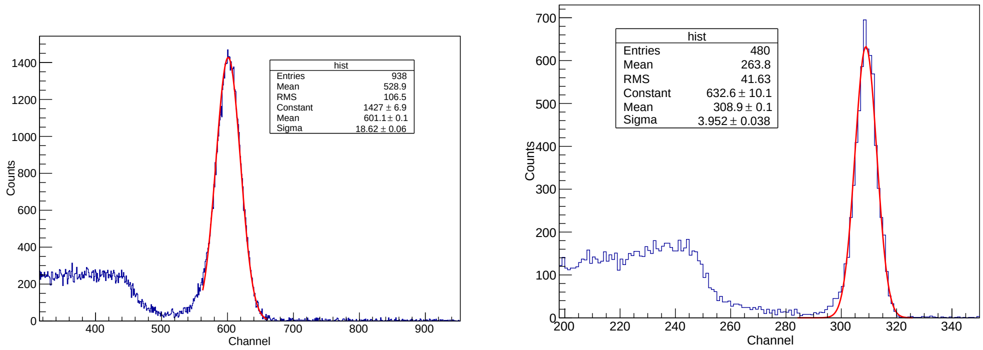

Figure 3: Energy spectrum of the 662 keV gamma rays, as measured with the $14 \times 14 \times 13$ mm^3 PrLuAg (left) and $LaBr_3$ (right) crystals coupled to the MPPC array (Hamamatsu S13361 with a Silicone window). MCA counts are reported on the abscissa. Plots are not corrected for linearity.

Table 2: Obtained FWHM energy resolutions (in %) at the Cs^{137} peak for some specimen of the crystals under test. H/A refers to the used Hamamatsu S13361/Advansid ASD-P-4-TD NUV SiPM arrays.

resolution	$LaBr_3$ (H)	$LaBr_3$ (A)	$CeBr_3$ (H)	CeCAAG (H)	PrLuAg (H)	NaI(Tl) (H)
Ortec 672	3.1 %	3.8 %	4.7 %	6.4 %	7.2 %	8.4 %
Ortec 579	3.4 %	4.3 %	5.0 %	-	-	8.9 %

As LaBr3:Ce crystals with a SiPM array readout give a sizeable signal in the 100-200 mV range, a simple FADC readout scheme may be implemented. The signal is either shaped by an Ortec 672 spectroscopic amplifier and then fed to a CAEN V1730 FADC(12 bit, 500 Ms/s) or directly fanned into the FADC. Bias to the SiPM is common for all the 16 cells of an array and is given by an ISEG NHS 6001 NIM module.

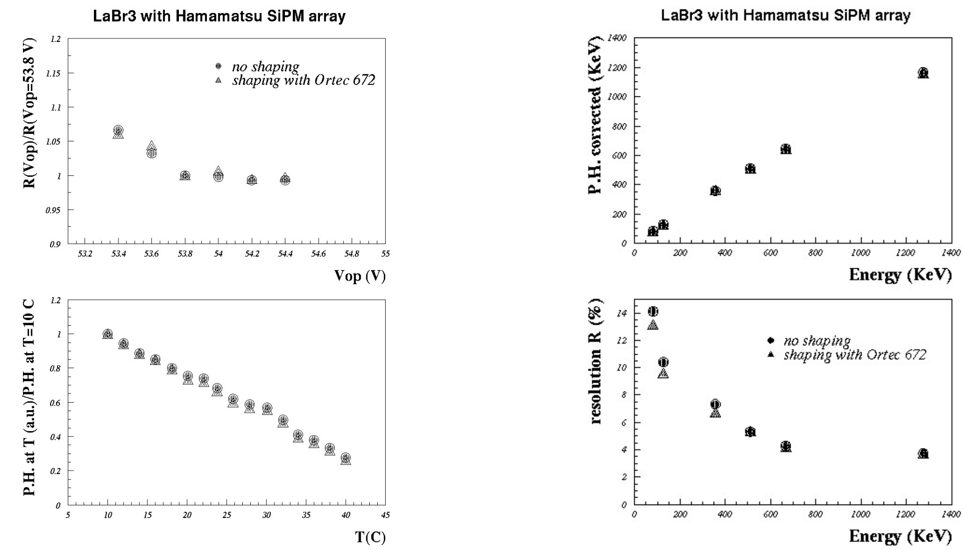

Figure 4: Left top panel: energy resolution (FWHM) dependence for $LaBr_3$:Ce crystals from the operating voltage (V_{op}). Left bottom panel: dependence of the detector response from temperature, at fixed V_{op} = 53.8 V. Right panel: linearity and energy resolution of a typical $LaBr_3$ crystal , at room temperature .

The variation of energy resolution at the Cs^{137} peak for $LaBr_3$ crystals with Hamamatsu readout, as a function of the operating voltage V_{op}, is shown in the left panel of figure 4 together with the dependence of the response from temperature, measured inside a Memmert IPV30 climatic chamber. The right panel of figure 4 shows instead the linearity and the resolution (FWHM) for a typical $LaBr_3$ crystal under test at $V_{op} = 53.8V$ using Na^{22}, Cs^{137}, Ba^{133} and Co^{57} exempt sources.

For effective use in experimental conditions, one has to take into account the SiPM gain drift with temperature. In the present setup, a thermistor is mounted on the "basette", to make an offline correction afterwards. In the near future, we plan to correct online the SiPM gain drift by using a NIPM-12 SiPM power module from Nuclear Instruments srl Lambrugo (IT) that integrates a temperature HV loop, to regulate the SiPM bias voltage as a programmable function of the SiPM temperature coefficient.

3. Conclusions

Preliminary results for the used crystals with a SiPM array readout show that they are promising for what regards energy resolution, even if performances for PrLuAg are not yet optimal. Their possible use with low-energy X rays needs further optimization. Good results are obtained with more conventional $LaBr_3$:Ce crystals using the new low-noise NUV SiPM arrays from Hamamatsu and Advansid, making this our best choice for the time being. A simple electronics front-end based on CAEN V1730 FADC, without an amplification stage, gives resolution (FWHM) at the Cs^{137} peak better than 4%, comparing well with the best available results.

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