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# Detection properties and internal activity of newly developed La-containing scintillator crystals

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## Abstract

In this work we will present the characterization, in terms of gamma response and internal activity of newly developed crystals that contains Lanthanum in their chemical formula. In particular we tested two  $\text{LaBr}_3:\text{Ce},\text{Sr}$ , one CLLBC and two CLLB crystals with different volumes. These crystals just overcome the prototype stage and, even if the production is still not standardized at least for large optics, they have been very recently commercialized in sizes interesting for high-energy gamma-ray spectroscopy, as for application in nuclear physics experiments. In particular, we will report on the study of the decay time, light yield and energy resolution with gamma rays, on the response as a function of the gamma interaction point and on the internal activity due to the presence of Lanthanum.

**Keywords:** Scintillator crystals, Elpasolite, Internal activity,  $\text{LaBr}_3:\text{Ce}$

## 1. Introduction

Since its introduction in the field of inorganic scintillator crystals in 2001,  $\text{LaBr}_3:\text{Ce}$  has undeniably become a reference for gamma spectroscopy applications due to its outstanding detection properties: high light yield, excellent energy resolution, fast decay time constant and a wavelength of emission well matched with standard photomultiplier tubes (PMTs), [1] - [14].

It was only in the latest years that a renewed effort in the material science community led to the development of some new scintillators that imposed their presence in the field as they can be considered real competitors to  $\text{LaBr}_3:\text{Ce}$ . In particular, we can mention  $\text{CeBr}_3$  that provides detection properties approaching that of  $\text{LaBr}_3:\text{Ce}$  with the advantage of having no internal activity, [15] - [20],  $\text{SrI}_2:\text{Eu}$  that is brighter than  $\text{LaBr}_3:\text{Ce}$  but has a very slow decay time constant and suffer of self-absorption, [20] - [24] and CLYC ( $\text{Cs}_2\text{LiYCl}_6:\text{Ce}$ ), a Lithium-containing elpasolite crystal, that not only provides an energy resolution better than 4.5% at 662 keV for gamma rays but is also sensitive to neutrons via the n-capture reaction on Lithium, [25] - [29].

In this new crystals development effort, some interest has been devoted to Lanthanum Bromide-containing scintillators, such as co-doped  $\text{LaBr}_3:\text{Ce}$ , CLLB ( $\text{Cs}_2\text{LiLaBr}_6:\text{Ce}$ ) and CLLBC ( $\text{Cs}_2\text{LiLa}(\text{Br}_6)90\%(\text{Cl}_6)10\%:\text{Ce}$ ) since, in principle, these materials have the potential to approach or even supersede the detection properties of  $\text{LaBr}_3:\text{Ce}$ .

Aliovalent co-doping of  $\text{LaBr}_3:\text{Ce}$  has been considered since few years, [30] - [32]. Anyway, despite the fact that the co-

doping with  $\text{Ca}^+$  or  $\text{Sr}^+$  has showed a considerable improvement in the  $\text{LaBr}_3:\text{Ce}$  light production and an enhancement in the alpha/gamma discrimination, the availability of such crystals was still limited in quantity and size and so a large exploitation of co-doped  $\text{LaBr}_3:\text{Ce}$  was not started yet. As a consequence, the papers available in literature concerning the detection properties of this material, are mostly signed by the crystal producers.

The same argument is valid for CLLB and CLLBC. While the CLYC has been extensively studied, with a consequent proliferation of papers focused on CLYC detection properties and possible fields of application, the other scintillators in the elpasolite crystals family still remain less explored alternatives. In particular, CLLB showed a less effective  $n/\gamma$  Pulse Shape Discrimination (PSD) with respect to CLYC but it is expected to provide an improved gamma-ray energy resolution and CLLBC, due to the presence of  $^6\text{Li}$  and  $^{35}\text{Cl}$ , is sensitive to both thermal and fast neutrons, as well as to gamma rays.

In this communication we will discuss the detection properties and the internal activity of two  $\text{LaBr}_3:\text{Ce},\text{Sr}$  and two CLLB crystals, recently commercialized by Saint Gobain [33], and one CLLBC scintillator, recently commercialized by Radiation Monitor Devices, Inc [34]. In this work we estimated the crystals decay time, light yield, energy resolution and internal background. In particular we are interested in the possibility to use these crystals for high-energy gamma ray spectroscopy experiments, for which large volume and homogeneity in the light yield are very crucial features.

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## 2. Equipments and methods

In this work we compared the detection properties and the internal activity of six cylindrical-shaped Lanthanum-containing crystals. In particular we characterized two CLLB crystals with dimension of  $\varnothing 1'' \times 1''$  and  $\varnothing 2'' \times 2''$  (identified hereby as CLLB1 and CLLB2, respectively), one CLLBC crystal with dimensions of  $\varnothing 1'' \times 1''$ , two Strontium co-doped  $\text{LaBr}_3:\text{Ce}$  with dimension of  $\varnothing 1.5'' \times 1.5''$  and one standard  $\text{LaBr}_3:\text{Ce}$  crystal with dimension of  $\varnothing 1'' \times 1''$ , for comparison. With the exception of the CLLBC, which was procured from RMD, all the other tested crystals have been supplied from Saint Gobain and, at the time of the purchase, the CLLB2 and the co-doped  $\text{LaBr}_3:\text{Ce}$  were the biggest commercially available optics for these scintillator materials. The characteristics of the tested crystals are summarized in table 1.

The scintillators are encapsulated in an 0.5 mm-thick Aluminum housing to protect them from moisture, the space between the crystal and the housing is filled with diffusive material and the scintillation light is collected from a 5 mm thick window.

The measurements presented in this work have been carried out at the “Institut de Physique Nucléaire d’Orsay” (IPNO) and at the Gamma Spectroscopy Laboratory of the “INFN - Sezione di Milano”. In both laboratories, the scintillation light was read-out coupling the crystals with a high quantum efficiency, low gain-PMT from Hamamastu, the R6231-100-SEL-MOD, and a common scintillators preparation procedure was applied for the tests. In Orsay the PMT anodic signals have been collected with a 14-bit CAEN digitizer (DT5730), while in Milan a standard spectroscopic chain composed by a preamplifier, a spectroscopic amplifier (TENNELEC TC244) and a multichannel analyzer (ORTEC ASPEC MCA 926) was used for the signal collection.

## 3. Results and discussion

### 3.1. Decay time and integration time

At IPNO, in order to evaluate the CLLB and  $\text{LaBr}_3:\text{Ce},\text{Sr}$  characteristic decay time constants, and thus the best suited integration time for the gamma-ray spectroscopic measurements, we irradiated the detectors with a  $^{137}\text{Cs}$  source and we evaluated the variation of the 662 keV peak position, in terms of QDC channels, as a function of the digitizer gate length, fig. 1.

Table 1: The tested scintillators.

Crystal	Dimensions inches <sup>3</sup>	Producer	Home base
CLLB (CLLB1)	$\varnothing 1'' \times 1''$	Saint Gobain	IPNO
CLLB (CLLB2)	$\varnothing 2'' \times 2''$	Saint Gobain	IPNO
CLLBC	$\varnothing 1'' \times 1''$	RMD	INFN-MI
$\text{LaBr}_3:\text{Ce},\text{Sr}$	$\varnothing 1.5'' \times 1.5''$	Saint Gobain	IPNO
$\text{LaBr}_3:\text{Ce},\text{Sr}$	$\varnothing 1.5'' \times 1.5''$	Saint Gobain	INFN-MI*
$\text{LaBr}_3:\text{Ce}$	$\varnothing 1'' \times 1''$	Saint Gobain	IPNO

\*The  $\text{LaBr}_3:\text{Ce},\text{Sr}$  is owned by Saint Gobain and temporary lent to the “INFN - Sezione di Milano” for testing.

For the CLLB, the data distribution has been fitted with a double exponential decay curve, as:

$$y = A_0 + A_1(1 - e^{(-x/\tau_1)}) + A_2(1 - e^{(-x/\tau_2)}) \quad (1)$$

In addition to the fast component of  $154.39 \pm 0.04$  ns, with a relative intensity of 63%, we observed a slow component of  $1096.8 \pm 0.3$  ns, with a relative intensity of 37%. For the  $\text{LaBr}_3:\text{Ce},\text{Sr}$ , instead, no slow component was observed; the data distribution is fitted with a single exponential decay distribution, for which we estimated a decay time constant equal to  $30.80 \pm 0.01$  ns.

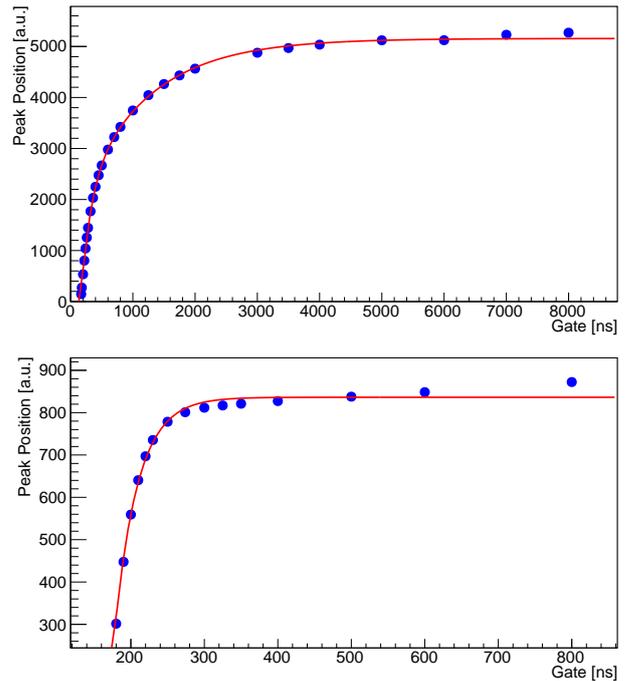


Figure 1: 662-keV  $^{137}\text{Cs}$  peak position as a function of the digitizer gate length for the CLLB1 (top) and the co-doped  $\text{LaBr}_3:\text{Ce}$  (bottom). The error bars are within the size of the markers. The red lines are the fitting functions.

Fig. 2 shows the 662-keV FWHM-energy resolution measured as a function of the signal integration time, for the two tested crystals. For the co-doped  $\text{LaBr}_3:\text{Ce}$  we can observe that the energy resolution is better than 2.5% for a gate width longer than 350 ns and up to 800 ns, so we decided to use a gate of at least 500 ns when integrating the digitized signals produced with this crystal, for the gamma spectroscopy measurements. For the CLLB, the energy resolution is slightly bigger than 4%, for a gate width between 600 ns and  $2 \mu\text{s}$ , i.e., when mostly the fast component is collected. Increasing the gate width up to  $8 \mu\text{s}$ , the energy resolution decreases up to values bigger than 5%; in this case, the slow decay time component starts to contribute, but background noise and, possibly, pile-up events, contribute as well with a consequent degradation of the energy resolution.

### 3.2. Light yield

The gamma ray response, for the CLLB, the  $\text{LaBr}_3:\text{Ce},\text{Sr}$  and the  $\text{LaBr}_3:\text{Ce}$  crystals under study, has been measured, at

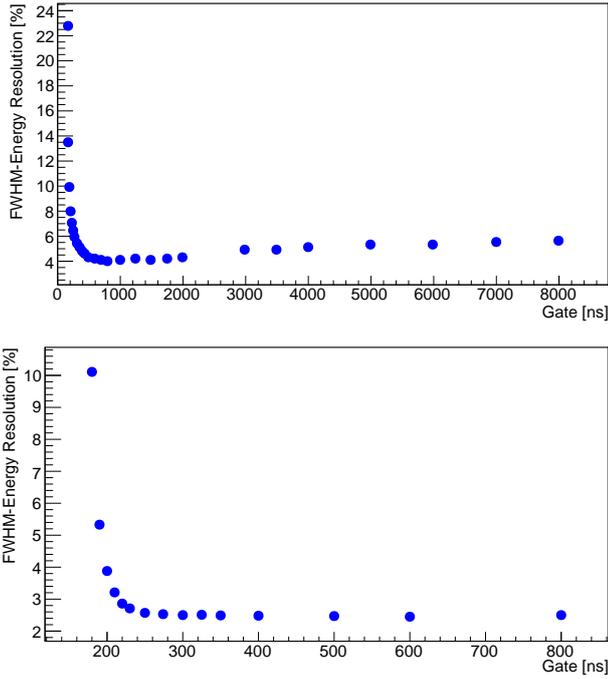


Figure 2: 662-keV FWHM-energy resolution as a function of the digitizer gate length for the CLLB1 (top) and the co-doped LaBr<sub>3</sub>:Ce (bottom). The error bars are within the size of the markers.

the IPNO, in the energy range between 60 keV to 1.7 MeV using standard gamma-ray emitting sources (<sup>22</sup>Na, <sup>60</sup>Co, <sup>152</sup>Eu, <sup>133</sup>Ba, <sup>207</sup>Bi and <sup>137</sup>Cs). The PMT was operated at 800 V (corresponding to a gain of  $7.2 \cdot 10^4$ ) while collecting the light of the two CLLB crystals and at 750 V (corresponding to a gain of  $4.7 \cdot 10^4$ ) for the LaBr<sub>3</sub>:Ce and the LaBr<sub>3</sub>:Ce,Sr. For this set of measurements we used the CAEN digitizer with a gate length of 4  $\mu$ s, to acquire the charge spectra for the CLLB1 and CLLB2 crystals and a gate of 500 ns for the LaBr<sub>3</sub>:Ce and LaBr<sub>3</sub>:Ce,Sr. For each acquired spectrum, we performed a gaussian fit on the main emission peaks to evaluate the position and the full width at half maximum (FWHM). While the statistical uncertainties associated to the light yield measurements are estimated to be smaller than 0.5%, the systematic variances associated to the measures reproducibility have been estimated to be of the order of  $\pm 2\%$ .

The light produced, expressed in terms of number of photoelectrons (phe), is presented in fig.3 as a function of the irradiation energy.

It is interesting to observe that the co-doped LaBr<sub>3</sub> is considerably brighter than the standard one.

This effect is well visible in the comparison of <sup>152</sup>Eu spectra acquired with the two crystals, shown in fig. 4. The higher light yield of the LaBr<sub>3</sub>:Ce,Sr not only results in a higher number of collected photoelectrons at the PMT photocathode, for a given energy, but as well in a better energy resolution leading to a better separation of close peaks (at 1085.9 keV and 1112.1 keV for example).

If we normalize the light yield to that of LaBr<sub>3</sub>:Ce, used as reference, then the ratio of the light yields for the different

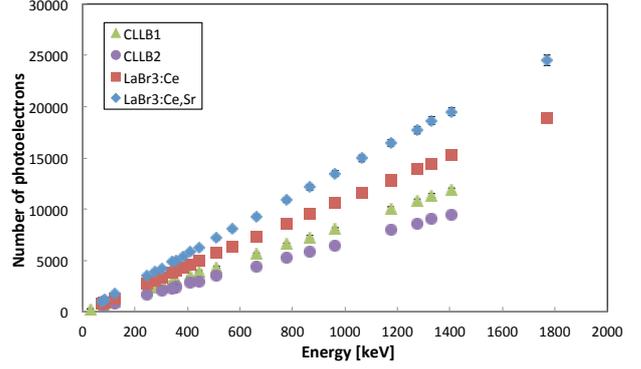


Figure 3: Number of phe measured as a function of the irradiation energy. The error bars are within the marker size.

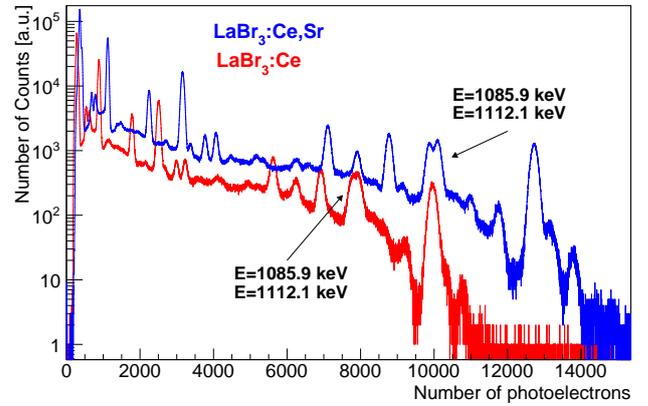


Figure 4: <sup>152</sup>Eu spectra acquired with the LaBr<sub>3</sub>:Ce (in red) and with the LaBr<sub>3</sub>:Ce,Sr (in blue).

crystals can be summarized as follow:

LaBr <sub>3</sub> :Ce	LaBr <sub>3</sub> :Ce,Sr	CLLB1	CLLB2
1	1.29	0.78	0.63

It also interesting to compare the two CLLB samples: for the smaller optic we collect 25 % more light than for the bigger one. This can be partially explained by a loss of light at the level of the PMT/crystal interface for the CLLB2 crystal. As a matter of fact, this crystal has a surface of 2 inches in diameter thus matching the entrance window of the PMT, on which a smaller surface photocathode ( $\varnothing$  46 mm) is deposited; as a consequence, a small fraction of the scintillation light has less chance of being collected. To this effect, lower optical properties of the CLLB2 with respect to the CLLB1 may also contribute.

Performing a linear fit on the data distributions of fig.3 we could estimate that the deviation from linearity is less than 1% for all the tested crystals, in the investigated energy range.

### 3.3. The energy resolution and response uniformity

The FWHM-energy resolution was measured in the Gamma Spectroscopy Laboratory in Milan, for all the tested crystals. For this study we irradiated the scintillators in the energy range between 276 keV and 1.33 MeV and we acquired the spectra

with a standard spectroscopic chain, selecting a shaping time<sup>187</sup> of  $2 \mu\text{s}$  for the CLLBs and for the CLLBC and  $0.5 \mu\text{s}$  for the LaBr<sub>3</sub>:Ce and the LaBr<sub>3</sub>:Ce,Sr in order to optimize the energy resolution measurements.

The <sup>137</sup>Cs spectra, acquired with the tested crystals, are reported in fig. 5. For the two co-doped LaBr<sub>3</sub>:Ce we measured a FWHM of  $15.9 \pm 0.1 \text{ keV}$  and of  $17.1 \pm 0.1 \text{ keV}$ , for the peak at 662 keV, corresponding to an energy resolution of 2.5%, and 2.6% for the IPNO and the “INFN-MI”, respectively.

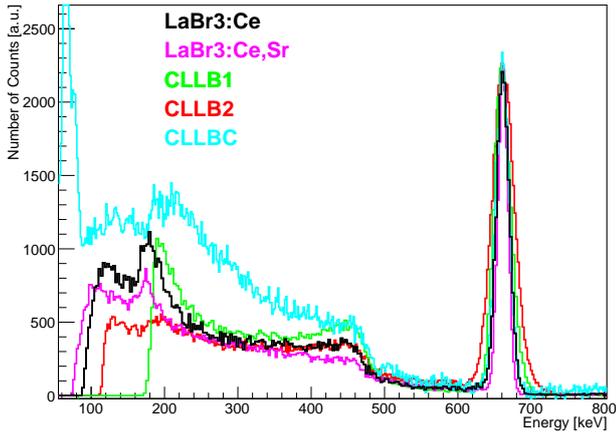


Figure 5: <sup>137</sup>Cs spectra acquired with the crystals under study: in black the LaBr<sub>3</sub>:Ce, in pink the LaBr<sub>3</sub>:Ce,Sr, in green the CLLB1, in red the CLLB2 and in sky-blue the CLLBC. Being the spectra acquired with the two LaBr<sub>3</sub>:Ce really similar, we just reported one, to help the readiness of the figure.

For the elpasolite crystals we measured an energy resolution of 21.7 keV, 27.5 keV and 35.7 keV at 662 keV, for the CLLBC, the CLLB1 and the CLLB2 respectively.

The energy resolution, measured as a function of the irradiation gamma energy, is presented in fig. 6.

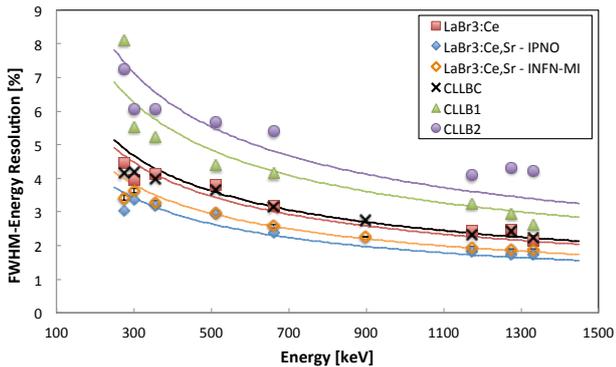


Figure 6: FWHM-energy resolution, as a function of the irradiation energy. The continuous lines represent the trend  $R \propto 1/\sqrt{E}$ . The error bars are within the markers size.

While the energy resolution measured with the CLLBC really approaches that of LaBr<sub>3</sub>:Ce, for the CLLB1 and CLLB2 the measured values are larger than expected. In order to investigate the observed degradation for the CLLB scintillators, we studied the detectors response as a function of the interaction point along the axes for the crystals.

For this test, we scanned the detectors with a highly collimated <sup>137</sup>Cs beam along the X, Y and Z axes and we studied the variation of the centroid, the FWHM and the area of the 662 keV peak as a function of the incident radiation position. The <sup>137</sup>Cs source, providing an activity of 400MBq, is collimated with a 8-cm thick heavy metal collimator, equipped with an exit hole of 1 mm in diameter; this set-up is placed on a support that allows rigid translations on two directions via a micrometer screw. The scintillators are then, in turn, placed on a second platform, at a fixed position, in front of the source at a distance of about 2 cm from the exit hole. A non-collimated <sup>60</sup>Co source is placed nearby and its two gamma peaks are used as calibration reference.

In fig. 7 we present the variation of the 662 peak position for the scan that we performed on the X and Y axes along the CLLB1, CLLB2, CLLBC and LaBr<sub>3</sub>:Ce,Sr round surfaces, respectively. We identified the origin of the axes as the center of the crystals front face and we performed a 2-mm step scan for the elpasolite scintillators and a 4-mm step scan for the co-doped LaBr<sub>3</sub>:Ce. Imposing the energy value of 662 keV for the centroid of the <sup>137</sup>Cs peak acquired in the center of the crystal face, we then scaled accordingly the peaks acquired in different positions. While we observed a variation of the peak position that does not exceed 3 keV along the X and Y axis for the CLLB1 and the LaBr<sub>3</sub>:Ce,Sr, for the other two tested crystals the variation results more pronounced, mostly at the edges, at the level of 7 keV and 9 keV for the CLLBC and the CLLB2, respectively.

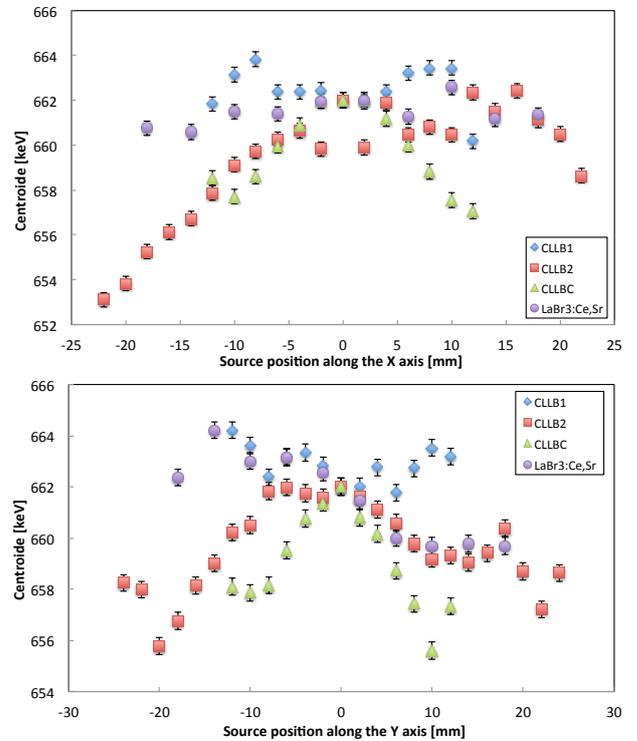


Figure 7: <sup>137</sup>Cs peak position as a function of the interaction point along the X (top) and Y axis (bottom), for the CLLB1 (red square), CLLB2 (blue diamond), CLLBC (green triangle) and LaBr<sub>3</sub>:Ce,Sr (purple round). The origin of the axes corresponds to the center of the crystal surface.

216 The scan along the Z axe is shown in fig. 8, in this case  
 217 the origin of the axe is identified at the crystal/PMT interface  
 218 and we imposed the energy value of 662 keV for the centroid  
 219 of the  $^{137}\text{Cs}$  peak acquired in the center of the crystal length.  
 220 The response of the  $\text{LaBr}_3:\text{Ce,Sr}$  and the CLLBC is quite stable  
 221 along the scintillator axe, with a deviation below 8 keV for the  
 222 CLLBC response when the gamma rays are detected in the rear  
 223 face of the crystal. For the CLLB crystals instead, we observed  
 224 a strong response anisotropy, with the  $^{137}\text{Cs}$  peak placed at  
 225 higher ADC channels when the interaction between the gamma  
 226 ray and the scintillator occurs closer to the crystal/PMT interface.  
 227 We can estimate the contribution of this anisotropy to be  
 228 at the level of 17 keV (2.6%) and 32 keV (4.8%) for the CLLB1  
 and CLLB2, respectively.

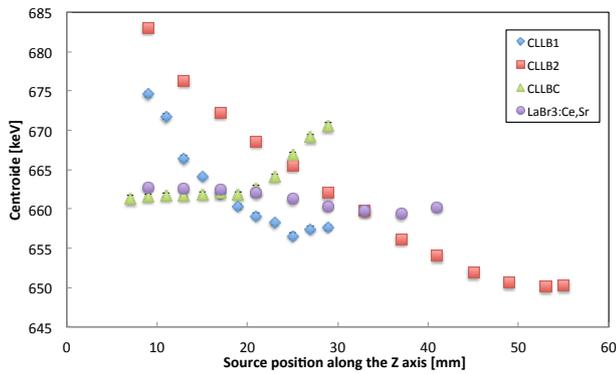


Figure 8:  $^{137}\text{Cs}$  peak position as a function of the interaction point along the Z axis for the CLLB1 (red square), CLLB2 (blue diamond), CLLBC (green triangle) and  $\text{LaBr}_3:\text{Ce,Sr}$  (purple round). The position  $Z=0$  corresponds to the PMT entrance window.

229 Fig. 9 presents the variation of the energy resolution, at 662  
 230 keV, as a function of the interaction point along Z, for the elpa-  
 231 solite crystals and for the co-doped  $\text{LaBr}_3:\text{Ce}$ . For the CLLB1,  
 232 we observe no evident correlation between the interaction point  
 233 and the measured energy resolution. For the collimated source  
 234 we achieve an energy resolution between 3.1 and 3.5% at 662  
 235 keV, thus strongly competitive with other similar high-energy  
 236 resolution scintillator, such as  $\text{LaBr}_3:\text{Ce}$  or  $\text{CeBr}_3$ . For the  
 237 CLLB2 crystal, instead, moving the irradiation point far from  
 238 the PMT entrance window, the energy resolution changes from  
 239 7% to 4.3%. The fact that we cannot achieve, for the CLLB2,  
 240 an energy resolution approaching that of  $\text{LaBr}_3:\text{Ce}$ , even with  
 241 a collimated source, might be explained by the 9 keV drift that  
 242 was observed along the X and the Y axes.

### 3.4. Internal activity

244 To study the internal activity of the crystals, we placed them,  
 245 in turn, in a lead box and we acquired the self-produced signals  
 246 for more than 48h. With the exception of the  $\text{LaBr}_3:\text{Ce,Sr}$  lent  
 247 by Saint-Gobain to the “INFN - Sezione di Milano”, that was  
 248 placed in a 10-cm-thick lead box, the internal activity of all the  
 249 other crystals has been studied using a 5-cm-thick lead box. The  
 250 estimated counting rates, for the different crystals, for energies  
 251 higher than 100 keV, are reported in table 2, together with the  
 252  $\alpha$  contribution to the total counting rate.

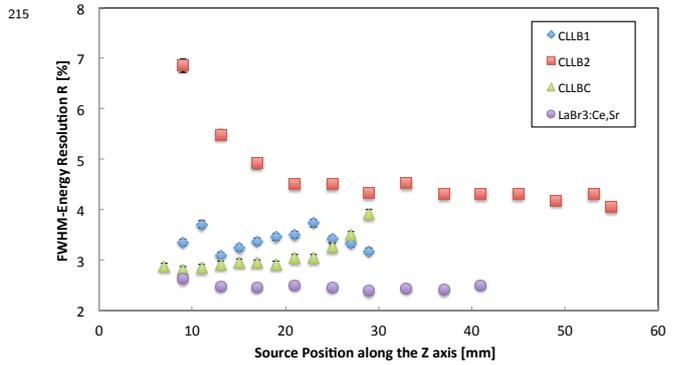


Figure 9: Energy resolution of the  $^{137}\text{Cs}$  peak as a function of the interaction point along the Z axis for the CLLB1 (red square), CLLB2 (blue diamond), CLLBC (green triangle) and  $\text{LaBr}_3:\text{Ce,Sr}$  (purple round). The position  $Z=0$  corresponds to the PMT entrance window.

Table 2: Self activity counting rate.

Crystal	Counting Rate [cts/s/cm <sup>2</sup> ]	$\alpha$ contribution [%]	$\alpha$ range [GEE MeV]
$\text{LaBr}_3:\text{Ce}$	0.47	2.79	1.7 - 2.7
$\text{LaBr}_3:\text{Ce,Sr}$ IPNO	0.81	15.0	2.2 - 3.4
$\text{LaBr}_3:\text{Ce,Sr}$ INFN-MI*	0.76	13.7	2.2 - 3.4
CLLB1	0.28	7.1	3.0 - 4.6
CLLB2	0.30	1.9	3.0 - 4.6
CLLBC	0.54	7.4	3.0 - 4.6

\*The activity was measured placing all the crystals in a 5-cm-thick lead box with the exception of the of the  $\text{LaBr}_3:\text{Ce,Sr}$  INFN-MI that was placed in a 10-cm-thick lead box.

254 The acquired spectra are presented in fig. 10. For each spec-  
 255 trum, we can identify the peak at  $\sim 1470$  keV, due to the emis-  
 256 sion of the  $\gamma$ -ray at 1436 keV from the  $^{138}\text{La}$  in coincidence  
 257 with the  $K_\alpha$  x-ray of  $^{138}\text{Ba}$ , and the series of  $\alpha$ -peaks due to the  
 258  $^{227}\text{Ac}$  contamination. These alpha peaks are placed in differ-  
 259 ent regions of the gamma equivalent energy (GEE) range, for  
 260 the different investigated scintillator materials, thus indicating  
 261 a different quenching factor for charged particles for the tested  
 262 crystals. In particular, the alpha peaks are placed between 1.7  
 263 and 2.7 MeV-GEE for the  $\text{LaBr}_3:\text{Ce}$ , between 2.2 and 3.4 MeV-  
 264 GEE for the co-doped  $\text{LaBr}_3:\text{Ce}$  and between 3.0 and 4.6 MeV-  
 265 GEE for the CLLBC and the CLLB crystals, in agreement with  
 266 previous works ([35] - [38]).

267 Fig. 11 shows the direct comparison of the background  
 268 spectra of the co-doped  $\text{LaBr}_3:\text{Ce}$  crystal (in red the crystal  
 269 owned by IPNO and in purple the crystal lent by Saint Gob-  
 270 ain to the “INFN - Sezione di Milano”) and the standard one (in  
 271 blue), normalized to account for volume and acquisition time  
 272 differences. In the  $\text{LaBr}_3:\text{Ce,Sr}$  spectrum, the superior energy  
 273 resolution of this scintillator led to a clear separation between  
 274 the peak at  $\sim 1440$  keV, due to the 1436 keV  $^{138}\text{La}$   $\gamma$ -ray in  
 275 coincidence with the L and M x-rays of  $^{138}\text{Ba}$ , and the neighbor  
 276 one at 1470 keV. Furthermore we can observe that not only the  
 277 charged particle quenching factor, but also the level of the in-  
 278 ternal activity is considerably different between the two scintil-  
 279 lator materials with, in particular, the alpha contribution being  
 considerably higher for the  $\text{LaBr}_3:\text{Ce,Sr}$ . The same comparison

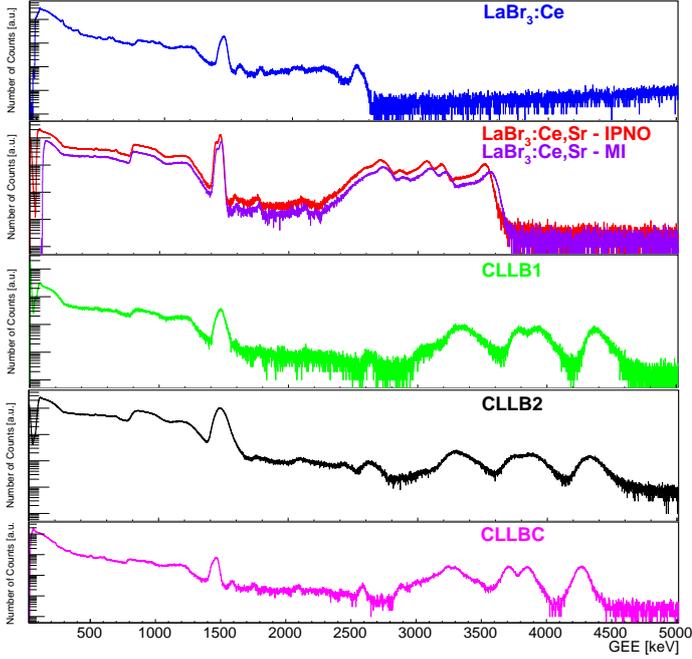


Figure 10: The internal background for the six tested crystals, from the top: LaBr<sub>3</sub>:Ce (in blue), LaBr<sub>3</sub>:Ce,Sr (in red and purple), CLLB1 (in green) and CLLB2 (in black), CLLBC (in pink). The spectra have been acquired placing the detectors in a lead box and acquiring self-triggered signals for more than 48 hours.

has been performed to the background spectra of the two CLLB crystals, again normalized in terms of volume and acquisition time, fig. 12. In this case the gamma and beta activity, due to the presence of the radioactive isotope of the Lanthanum, is higher for the bigger crystal while it is present a much lower <sup>227</sup>Ac contamination **might be due to a better purification of the raw materials during the crystal production process.**

#### 4. Conclusions

In this work we studied the detection properties and the internal activity of three new developed La-containing scintillator crystals and, in particular, for two of the studied materials we tested the largest volume optics that were available on the market at the time of the purchase.

The two tested Co-doped LaBr<sub>3</sub>:Ce showed similar excellent detection properties, superseding standard LaBr<sub>3</sub>:Ce. We measured, for both samples a FWHM-energy resolution better than 2.6% at 662 keV but we observed for these scintillators the highest counting rate within the tested crystals. In particular, the alpha contribution to the total counting rate results particularly high, at the level of 14-15%, indicating a still high Actinium-227 contamination in the material.

For the CLLB scintillators we observed a very strong light yield anisotropy along the crystals longitudinal axes, especially for the bigger optic, with a consequent degradation of the measured energy resolution. Anyway, while for this scintillator material the observed detection properties are still not approaching those of the LaBr<sub>3</sub>:Ce, the measured internal activity re-

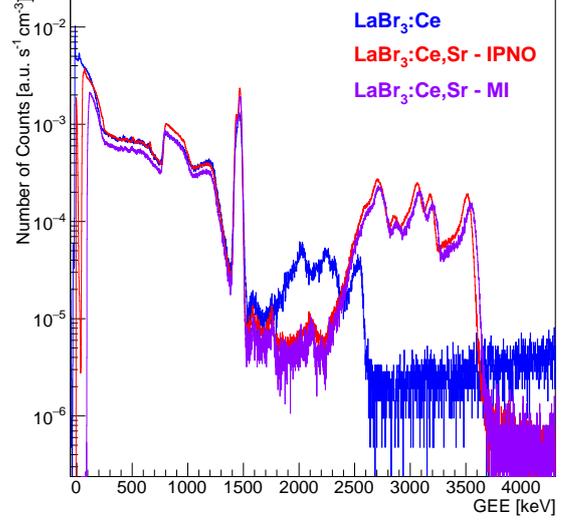


Figure 11: The internal background spectra for LaBr<sub>3</sub>:Ce,Sr (in red) LaBr<sub>3</sub>:Ce (in blue), normalized to account for volume and time acquisition differences.

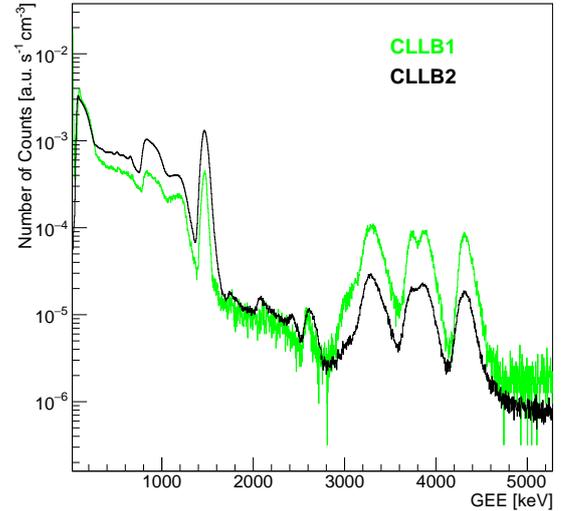


Figure 12: The internal background of CLLB1 (in green) and CLLB2 (in black), normalized to account for volume and time acquisition differences.

sults considerably smaller. It is interesting to remark that for the two scintillators the total counting rates are really similar but the  $\alpha$  contribution is much stronger for the CLLB1 than for the CLLB2. As the  $\varnothing 2'' \times 2''$  scintillator was delivered few months later than the smaller sample, **we can speculate that in the period between the production of the two crystals a more efficient purification process of the raw materials was developed. Anyway as the sources of raw materials might vary over time and the purification process is not trivial, to confirm our hypothesis more CLLB crystals should be tested.**

The CLLBC scintillator tested in this work completely satisfied the high expectation we had concerning the use of this material for gamma detection. The total internal activity is close to that of LaBr<sub>3</sub>:Ce and the higher  $\alpha$  contribution provides scope for improvement in this sense if a more sophisticated purification procedure can be achieved.

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