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Characterization of Large Volume 3.5" x 8" $LaBr_3$:Ce Detectors for the HECTOR$^+$ array

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Abstract. A selection of the properties of large volume, cylindrical 3.5" x 8" $LaBr_3$:Ce scintillation detectors coupled to a 3.5" PMT (model R10233-1000SEL from HAMAMATSU) and a special designed Voltage Divider (LABRVD) will be discussed. A number of 10 of such detectors constitute the HECTOR$^+$ array which, in fall 2012, measured at GSI coupled to the AGATA DEMOSTRATOR at the PRESPEC experimental setup. These crystals are among the largest ever produced and needed to be characterized. We have performed several tests and here we discuss, in particular, the energy resolution measured using monochromatic γ–ray sources and in-beam reactions producing γ–rays up to 22.6 MeV. As already measured in two previous works a saturation in the energy resolution was observed in case of high energy gamma rays. Crystal non-homogeneities and PMT gain drifts can affect the resolution of measurements especially in case of high energy γ–rays.

1 Introduction

The scintillation properties of $LaBr_3$:Ce crystal were discovered in 2001 [1] and the crystal is commercialized by St. Gobain with the name of Brillance® 380. The number 380 indicate the values of the wavelength of the emitted scintillation light [2,3]. The first cylindrical large volume 3" x 3" crystals was produced approximately in 2006. In 2007 it was possible to reach the size of 3" x 6" while one year later the first 3.5" x 8" detector was delivered [4-6] to Milano.
The $LaBr_3$:Ce is a crystal with an hexagonal (UCL3 type) structure with a P63/m space group [7]. It is extremely hygroscopic (more than NaI:Tl) and its crystal structure produces an anisotropic thermal expansion. In addition, the crystal has a relatively weak (100) cleavage plane which makes the growth of crystals complex [3].
The physical properties of $LaBr_3$:Ce crystals, relevant for a scintillator detector, are summarized and compared with those of traditional scintillators in table 1 [1,8]. It is evident that, if compared with all

the other scintillators, $LaBr_3$:Ce presents the highest light yield. As the light yield is directly connected to the detector energy resolution (the relation is however not linear) these crystals provide the best energy resolution among all scintillators. In addition to the best energy resolution, $LaBr_3$:Ce has an extremely high density and a sub-nanosecond time resolution. The pulse line shape in case of events induced by alpha particles differs from those induced by gamma of approximately 5% in case of small $LaBr_3$:Ce crystals [9]. The scintillation light emitted by $LaBr_3$:Ce has a wavelength concentrated between 300 and 500 nanometers so that one can use normal borosilicate glass instead of expensive quartz for the PMT window as, for example, in the case of BaF_2 crystals.

A large amount of works with small sized $LaBr_3$:Ce detectors can be found in the literature (see ref. [10] and references therein), but only very few works related to medium volume detectors are available (see ref. [11] and references therein) and even less information is available for large volume $LaBr_3$:Ce detectors (see ref. [12,13] and references therein). It is also important to point out that the properties of large volume $LaBr_3$:Ce crystals cannot be easily derived from those of small and medium sized detectors. In fact, several factors may affect the detector performances: i) self absorption, ii) possible crystal internal non-homogeneities that may result in variation of the crystal light yield depending on the detector area affected by the interacting γ ray (both of which are more likely to appear with scaled up dimensions), iii) the much longer mean free path of the scintillation light towards the photo-cathode and iv) non-ideal photo-multiplier tube (PMT) properties [13].

Table 1. Properties of inorganic scintillators (from ref. [1,8])

Scintillator	Light Yield (ph/keV)	Wavelength of maximum emission	Density (g/cm3)	Attenuation length at 511 keV (cm)	Principal decay time (ns)	Melting point °C
BaF2 fast/Slow	1800/ 10000	220/310	4.88	1.1	0.7/630	1354
NaI:Tl	38000	415	3.67	3.3	230	660
LSO	24000	420	7.4	1.2	40	1050
BGO	8200	505	7.13	1.1	300	1050
CsI(Na)	39000	420	4.51	2.3	630	621
LaBr3:Ce	63000	360	5.08	2.1	16	783

2 Energy Resolution

The energy resolution of large volume $LaBr_3$:Ce detectors have been measured using two different methods: i) a standard analogue approach, based on shaping amplifiers and peak sensing ADCs and ii) a digital approach, based on free running ADC signal acquisition and subsequent digital processing.
The measurements with analogue electronics were performed during the in-beam experiment at the ATOMKI Institute; we used an amplifier derived from the BaFPRO NIM module [14] with shaping time of about 700 ns, followed by a peak sensing VME ADC (CAEN model V879) controlled by a specifically developed KMAX-based acquisition software. The measurements based on the digital approach were performed in the Milano Detectors Laboratory, a much more controlled environment inside the Physics Department of “Università degli Studi di Milano”. We used a 400 MHz, 5 GHz sampling frequency oscilloscope (LeCroy Waverunner 44X1). The estimation of the released energy was performed using a straightforward box-car integration algorithm (over 250 ns) with the additional subtraction of the pulse baseline level (calculated over 250 ns).

The Figure 1 shows the energy spectra measured in the reaction ^{23}Na+p = ^{24}Mg with a proton energy of 1416.9 keV (left panel) and ^{11}B + p = ^{12}C with a proton energy of 7250 keV (right panel) [13].
In both spectra of figure 1 it is evident that the full energy peak and the first escape one are well separated. In addition, because of the crystal large volume, the second escape peak is barely visible

and, up to 10 MeV, the full energy peak is higher than the first escape one. The capability to efficiently measure and separate the full energy peak from the first escape one for γ-rays up to at least 25 MeV is unique . Only HPGe detectors can provide such separation (HPGe can provide an energy resolution 10 times better than that of $LaBr_3$:Ce) however with less efficiency and more complexity. This is extremely important especially in the fore coming facilities [15-16] where it will be possible, for example, to study highly collective nuclear states like the Giant or the Pygmy Dipole Resonance [17-19] by means of Nuclear Resonance Fluorescence (NRF) using high-energy γ rays as incident beam. In general, being able to efficiently identify high-energy γ rays, lanthanum bromide detectors would thus additionally enforce the physics program of a HPGe detector array.

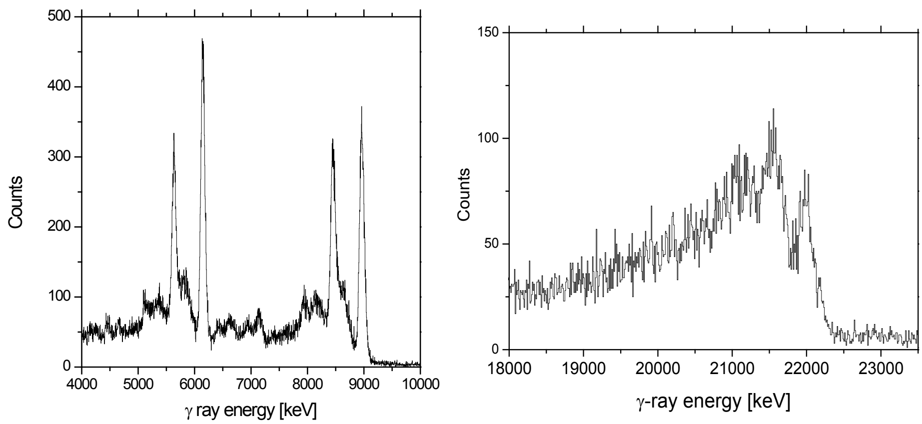

Figure 1: The high-energy gamma-ray spectra measured with a large volume $LaBr_3$:Ce 3.5”x8” and analogue electronics for monochromatic gamma rays of 6.13, 8.9 and 22.6 MeV [13].

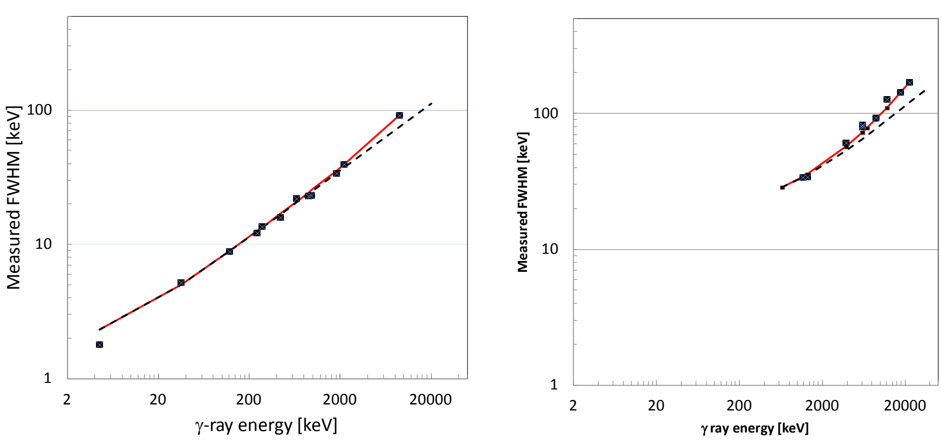

Figure 2: The energy resolution measured in large volume $LaBr_3$:Ce detectors for γ-rays ranging from 1 to 22600 keV. In the left panel, the measurements with digital electronics are shown while in the right panel those taken with the analogue one are displayed. The dashed line shows the expected $(E)^{1/2}$ trend while in the continuous line a term linear with energy was added [13].

In both the plots of figure 2, the energy resolution of the $LaBr_3$:Ce detectors deviates from a strictly statistical behavior in the case of high-energy γ rays. The energy resolution of $LaBr_3$:Ce detectors tends, in fact, to saturate at a constant value around 0.5-1%. This was already reported in the literature [10,11] and confirmed by this work. The saturation behavior can be understood adding a linear dependence in the energy resolution equation, namely $FWHM^2 = a+bE+cE^2$ [13]. In this equation the first term ‘*a*’ represents the electronic noise, the second term ‘*b*’ modulates the contribution of the scintillation light production while the third term '*c*' can account for gain drift or non--homogeneities effects [13].

3 Conclusion

Large volume $LaBr_3$:Ce scintillators are very promising detectors to be used in combination or, in some cases, even as an alternative to HPGe detectors. They may provide very good results in case of high-energy γ–ray measurements, for example γ rays coming from the decay of highly collective nuclear states. These measurements can be performed using present and future radioactive and Nuclear Resonance Fluorescence (NRF) facilities like, for example, ELI-NP or HiγS. The demonstrated capability to efficiently measure and separate the full energy peak from the first escape one for γ–rays up to at least 25 MeV is a unique feature of large volume $LaBr_3$:Ce detectors. The energy resolution limitation between 0.5% and 1% in case of high-energy γ rays, already observed in previous works, was confirmed. We were able to correct the energy resolution deviation from the statistical behavior at energies above pair production by introducing a linear term which considers gain drift or non-homogeneity effects.

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