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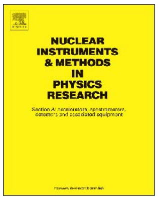

Performance evaluation of novel $LaBr_3$(Ce) scintillator geometries for fast-timing applications

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ABSTRACT

We evaluate the performance of two $LaBr_3$(Ce) crystals that were produced with special geometries, aimed at enhancing the scintillation light collection and thus the time resolution. Their design was motivated by the construction of high-performance fast-timing arrays like the FAst TIMing array for DESPEC (FATIMA), which demands a high packing factor in addition to good time and energy resolutions.

Energy resolution and efficiency were measured using standard calibration sources. Timing measurements were performed at ^{60}Co and ^{22}Na γ-energies against a fast BaF_2 reference detector. The time resolution was optimized by the choice of the photomultiplier bias voltage and the fine tuning of the constant fraction discriminator parameters. Monte Carlo simulations using the Geant4 toolkit were performed in order to achieve a better understanding of how the new geometries affect the light transport and thus the performance of the crystals. It is found that the conical-shaped $LaBr_3$(Ce) crystals are optimal for fast-timing applications and for the construction of arrays such as FATIMA.

1. Introduction

$LaBr_3$(Ce)-based detectors that combine good energy resolution and fast response own a great potential for applications such as medical imaging [1] and lifetime measurements in γ-ray spectroscopy [2]. Additionally, they provide high intrinsic γ-ray detection efficiency, and a photon yield of 63 photons/keV. With these outstanding properties, they have been selected for the application of the Advanced Time-Delayed (ATD) $\beta\gamma\gamma(t)$ technique since 2005 [2], becoming nowadays the standard choice for fast-timing spectroscopy [3–7].

The ATD method, which was introduced as a Germanium-gated β-γ electronic timing technique with ultra fast scintillators [8,9], allows the measurement of nuclear level lifetimes down to a few picoseconds by using the fast coincidences between the radiation populating and de-exciting a nuclear level. The sensibility of the ATD technique is directly influenced by the time resolution of the detectors in use, being the size and the shape important factors to be considered. Therefore, we have designed special geometries of $LaBr_3$(Ce) crystals aimed at enhancing the light collection, with the expectation of an improved time response. Additionally, the new geometries make it possible to construct rings of detectors surrounding implantation detectors (or catcher foils) with higher packing factor than cylindrical geometries, increasing the γ-ray detection efficiency.

The enhanced light collection and the size of the crystals also influence on the energy resolution which is an important factor to be considered, since it enables a proper selection of decay branches and moreover it contributes to minimize the time corrections arising from Compton background under full-energy γ-peaks. Additionally, the overall efficiency of the detectors as a function of γ energy (and distance to the source) needs to be taken into account as well.

In this paper we report on two new $LaBr_3$(Ce) crystal geometries along with an in-depth performance evaluation, where we studied their time response, energy resolution and γ-ray detection efficiency. To achieve the best timing performance, we have optimized the most influential set-up parameters, namely the external Constant Fraction Discriminator (CFD) delay, the CFD zero-crossing value (Z) and the photomultiplier tube (PMT) bias voltage, following the procedures described in [10–12]. Excellent results have been obtained for the conical geometry, as discussed below.

We have also performed Monte Carlo simulations of optical photons using the Geant4 toolkit, getting access to a better understanding of how the geometries influence the photon reflection and light-transport processes, assessing how they affect the detector performance.

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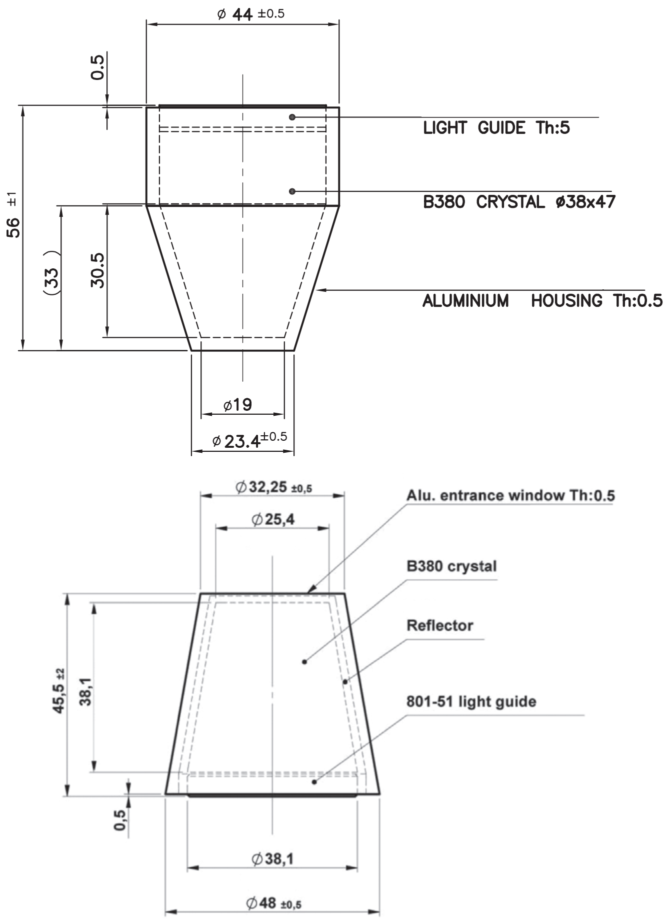

Fig. 1. $LaBr_3(Ce)$ geometries evaluated in this work. The top picture shows the tapered Studsvik's design and the bottom one shows the truncated cone crystal. Dimensions of the crystals in mm are depicted as provided by Saint Gobain.

This work is part of a broader study of ultrafast scintillator detectors equipped with crystals of different materials, sizes and shapes, that were coupled to state-of-the-art photosensors. The aim is to construct high performance fast-timing arrays for $\gamma - \gamma$ and $\beta - \gamma$ spectroscopy, and specifically the optimal FAst TIMing Array (*FATIMA*) [7], which will be placed at the focal plane of the SuperFRS at FAIR [13].

2. The $LaBr_3(Ce)$ detectors

Crystals were specially designed in two novel geometries to enhance the time resolution and the packing factor. The first design, which is shown at the bottom panel of Fig. 1, is a truncated cone shape crystal, with nominal height of 38.1 mm (1.5 in.) and bases of $\varnothing = 38.1$ mm (1.5 in.) and $\varnothing = 25.4$ mm (1 in.). The second one (top panel of Fig. 1) is based on the advantageous "Studsvik" design for BaF_2 crystals [14], a tapered hybrid crystal with a total height of 47 mm, with a cylindrical section of nominal $\varnothing = 38.1$ mm in the base and 16.5 mm in height, and a 30.5 mm long conical section with $\varnothing = 19$ mm in the small base. Both crystals were commercially produced and encapsulated by Saint Gobain with a Ce doping concentration of 5%. Several inner layers of light reflector and shock absorbing material protect the crystal, ensuring its stability and minimizing photon losses [15].

For crystals tests, we selected the 8-stage Hamamatsu R9779 PMT [16] as the optimal photosensor. It is an ultra fast device equipped with a bialkali photocathode and a 2-in. diameter window. It exhibits much superior timing performance than any other PMT model [17,10,12] and is the current standard in the application of the ATD technique [6]. Due to its special design aimed at enhancing the time response, the energy resolution is compromised to some extent. Therefore, we have evaluated the energy resolution of both geometries by means of two different PMT models, the ultra fast Hamamatsu R9779 and the Hamamatsu R6231 [18], which is designed for spectroscopy. Crystals are coupled to the PMT using Viscasil silicon grease, which favours light transmission. In order to avoid photon losses and maintain the detector properly isolated from light, crystals and PMTs are wrapped into opaque tape.

3. Description of the measurements

The detector performance critically depends upon the timing resolution. Other important parameters are the energy resolution and the detection efficiency. In the following the measurements of time and energy resolution are described together with the Monte Carlo simulations.

3.1. Timing measurements

The time response of each crystal was characterized by coincidence measurements against a well-tested reference detector, consisting on a BaF_2 crystal coupled to a Photonis XP2020-URQ photomultiplier tube (PMT), whose time resolution had been measured earlier by the use of three identical BaF_2 crystals with equal response [10]. Timing measurements were carried out with an identical set up as the one described in [12]. The crystals under test were coupled to Hamamatsu R9779 PMTs and the negative anode signal from the PMT was fed into an ORTEC 935 Constant Fraction Discrimination (CFD), whose output was used as the stop signal in a ORTEC 567 Time to Amplitude Converter (TAC) that was started by the reference detector signal. The positive signal from the last dynode was preamplified, shaped and used for the energy measurements. The TAC and energy signals were digitized in three ADCs and list-mode data were stored and analyzed.

Since the time resolution is sensitive to certain set up parameters including the external CFD delay and the CFD zero-crossing value (Z), we have optimized them by a fine tune following the procedure described in [12]. Regarding CFD external delays, we have explored a wide range ranging from 1.0 ns to 20.0 ns, with especial attention to the short values region (from 1.2 ns to 2.0 ns), where the best time resolution is normally achieved for this type of detectors. In this study we have also evaluated the detector time walk as a function of the energy, intending to obtain a smooth behavior without compromise of the time resolution. Additionally the detectors stability against variations in the high voltage was assessed as well.

The time characterization was carried out at ^{60}Co and at ^{22}Na (511 keV) energies. Timing data were processed off-line and analyzed with the SORTM software [19]. The analysis comprises three important steps: identification and correction of possible time shifts, selection of the energy gates, and sorting of the final time spectrum with the chosen energy conditions.

For the ^{60}Co source, energy gates are set at the 1173-keV full-energy peak (FEP) on the BaF_2 detector and at the coincident 1332-keV FEP on the $LaBr_3(Ce)$ detector, and vice versa. Next, the two sorted time spectra are added together. The final coincidence resolution time (CRT) for ^{60}Co is given as the full width at half maximum (FWHM) of the summed time peak. For the ^{22}Na source narrow gates are set at the FWHM of the 511-keV peak, generating only one time spectrum. The $LaBr_3(Ce)$ individual time resolution is extracted by de-convoluting the BaF_2 contribution of 85 ± 2 ps at ^{60}Co energies and 125 ± 2 ps at 511 keV (^{22}Na), measured in this work. The resolutions given below refer to individual $LaBr_3(Ce)$ FWHM time resolutions after de-convolution. All steps of the sorting procedure are explained in more detail in [10,19].