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Event localization in bulk scintillator crystals using coded apertures

K.P. Ziock [a,b,*], J.B. Braverman [b], L. Fabris [a], M.J. Harrison [a], D. Hornback [a], J. Newby [a]

[a] Oak Ridge National Laboratory, Oak Ridge, TN, USA
[b] Department of Physics and Astronomy, University of Tennessee, Knoxville, TN, USA

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ABSTRACT

The localization of radiation interactions in bulk scintillators is generally limited by the size of the light distribution at the readout surface of the crystal/light-pipe system. By finding the centroid of the light spot, which is typically of order centimeters across, practical single-event localization is limited to $\sim$2 mm/cm of crystal thickness. Similar resolution can also be achieved for the depth of interaction by measuring the size of the light spot. Through the use of near-field coded-aperture techniques applied to the scintillation light, light transport simulations show that for 3-cm-thick crystals, more than a five-fold improvement (millimeter spatial resolution) can be achieved both laterally and in event depth. At the core of the technique is the requirement to resolve the shadow from an optical mask placed in the scintillation light path between the crystal and the readout. In this paper, experimental results are presented that demonstrate the overall concept using a 1D shadow mask, a thin-scintillator crystal and a light pipe of varying thickness to emulate a 2.2-cm-thick crystal. Spatial resolutions of $\sim$1 mm in both depth and transverse to the readout face are obtained over most of the crystal depth.

1. Introduction

Gamma-ray detectors based on inorganic scintillator crystals are widely used throughout the radiation detection community. Their useful balance of energy resolution, stopping power, and cost per unit volume has made them essential to a broad range of fields such as fundamental physics, high-energy astrophysics, homeland security, and nuclear medicine. In many of these applications, one is interested in both the energy of the gamma radiation and its interaction location within the detector. Several approaches have been developed to measure the latter. The most straightforward approach is to place a series of readout devices on one or multiple surfaces of a bulk crystal and look at how the light is shared between them. The location of each interaction is estimated using some form of centroiding algorithm with the spatial resolution limited by the size of the light spot at the readout surface divided by the square root of the number of detected scintillation photons. Anger cameras [1] are the primary example of this approach, and they can achieve a spatial resolution of a few millimeters along the instrumented face [2]. The problem with the centroiding approach is that the size of the light spot is of order the distance that the event occurs from the readout surface, and so the ability to locate the event is limited ($\sim$2 mm/cm of crystal thickness at 500 keV).

One means to improve spatial resolution is to subdivide the crystal to restrict the spread of the light to a single small “crystalet.” Using this approach, one can achieve better spatial resolution ($<$1 mm). However, if the crystalets are too small, then they will “leak” energy to neighboring locations due to finite electron ranges, *K*-escape peaks, and Compton scatter. Further, to provide good stopping power and maintain good spatial resolution requires crystalets with a high aspect ratio. This tends to limit energy resolution since fewer of the scintillation photons created in events far from the readout surface are detected.

When one requires the location of an event in all three dimensions, the problem becomes even harder. In detectors that use bulk crystals, one can determine the depth of an event by measuring the size of the light spot at the readout. This provides a resolution similar to that of an event's lateral location. In segmented systems with high aspect crystalets, one can instrument both ends of the crystalet and use light sharing (or even light arrival time for larger bar pixels). The thickness of such an assembly will be limited by the acceptable light loss from multiple reflections along the crystalet. In small systems ($\sim$1 cm^3), sub-millimeter spatial resolution can be achieved, but with a significant increase in the system complexity [3].

We report the first experimental results of a new approach that promises to provide the spatial resolution achievable with a pixelated system in a bulk scintillator. The technique is shown schematically in Fig. 1. It uses a coded-aperture shadow mask [4] in the light pipe that connects the scintillator crystal to a position-sensitive readout device. The shadow mask encodes the event location in all three dimensions, allowing one to locate events within the crystal. For the location parallel to the readout surface, standard coded-aperture cross-correlation calculations are used [4]. To determine the depth of an event, the approach takes advantage of the fact that the mask pattern projected on the readout device is

* Corresponding author at: Oak Ridge National Laboratory, Oak Ridge, TN, USA.

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magnified, with the amount of magnification determined by the depth of the event within the crystal. By sequentially reconstructing an event at different depths (magnifications), one can *a posteriori* “vary the focus” of the system and look for the sharpest image. Extensive light-transport simulations have been conducted and indicate that voxel sizes of order a cubic millimeter can be achieved at energies as low as several hundred keV in 3-cm-thick scintillators [5,6]. For the first measurements reported here, a 1D coded aperture was used to provide 2D event reconstructions—depth and one dimension lateral to the readout surface.

2. Experimental design

A photograph and schematic of the hardware used for the experiment are shown in Fig. 2. In the experiment a thin scintillator crystal [1-mm-thick NaI(Tl), index of refraction $n=1.85$] is mounted to a quartz light pipe ($n=1.458$) that contains the shadow mask. Additional light pipe below the mask connects to the readout. Changing the amount of light pipe between the crystal and the mask provides a means of emulating a thick crystal with events located at different known depths.

The experiment used three Hamamatsu 9500 multi-anode photomultiplier (MAP) tubes [7] arranged side by side. All of the anodes perpendicular to the three-tube axis were connected to form readout strips. This MAP array was used below a shadow mask based on multiple repetitions of a rank-7, 1D modified uniformly redundant array (MURA) coded aperture [8]. To localize the radiation to a given region of the crystal, a tungsten collimator was used. This provided a beam ~1.2 mm in diameter at the crystal surface. Connections between optical elements were made using optical coupling compound ($n=1.465$) [9].

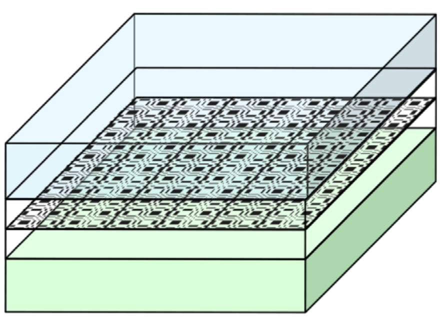

Fig. 1. Detector concept. An optical coded-aperture shadow mask is positioned in the light pipe connecting a bulk scintillator crystal with a position-sensitive photosensor.

2.1. Crystal thickness

The maximum displacement of the thin crystal in the experiments was 14.7 mm. Because the angular divergence of the light cloud increases when transitioning into the quartz (index of refraction ~1.5) from the higher index scintillator (~1.8), a smaller thickness of quartz generates the same spread as a greater thickness of scintillator crystal. To obtain the conversion factor between event depths in a bulk scintillator and the thin-crystal-quartz-light-pipe analog, we ran light transport simulations using GEANT4 [10] similar to those reported earlier [5,6]. In the simulations, a scintillation event was modeled by launching 40,000 photons at the top of the apparatus shown in Fig. 2. The photons were launched randomly in all directions. (Note that the top and sides of the optical system are painted black, and any photons hitting those surfaces were removed from the transport simulations.) The locations where photons reached the photocathode of the MAPs were recorded and mapped to the anode structure used in the experiment. These events were then imaged as described in Section 3.1.3 below to determine the event depth. For systems with different optical thicknesses, two configurations were run, one with a thin NaI(Tl) crystal with a quartz light pipe, and one where the light pipe was replaced by a material with the same refractive index as that of NaI. The results are plotted in Fig. 3 and show a linear relationship with a slope of 0.63. This factor is used in Table 1 to relate the real geometry to the emulated event location within a thick crystal. It indicates that the 15-mm-thick light pipe is comparable to a 22.5-mm-thick crystal.

2.2. Readout system

The design of the experiment was dominated by the 64 channels of readout available to perform the work. The data acquisition system comprised four, 250 MHz digitizers [11] in a VME crate read out using a personal computer. Due to noise and signal reflection issues when the digitizers were configured to run in a high-input impedance mode, the 50 Ω mode was used. To drive this the output of each row of anodes was sent through a Phillips 776, times 10 amplifier [12] before being passed to the digitizers. Residual baseline noise around 1 MHz meant that simply integrating the total charge received during the decay period of the scintillator light (a 3200-ns integration window was used) yielded poor energy resolution. To overcome this a modified peaklet analysis procedure was implemented. After a trigger was received (based on the signal from the last dynode of the center MAP), the 3200-ns-wide inspection window was opened for each channel. The signal recorded during the window was searched for the many small (single or a few) photoelectron pulses (peaklets) that arrived in each channel. The signal was integrated for those times

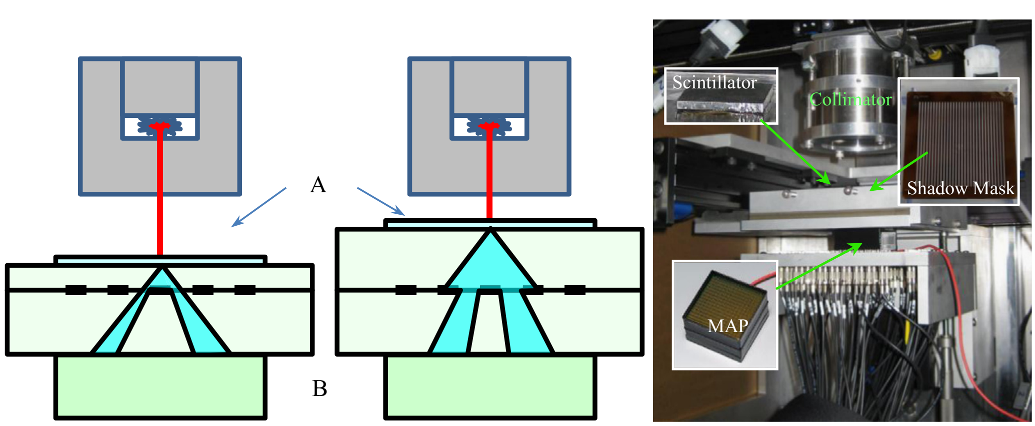

Fig. 2. Schematics of the experimental layout (left, center). A thin crystal (A) is placed on top of the light pipe/mask assembly. Scintillation light is detected by the MAP (B). The amount of light pipe between the mask and the crystal can be varied to emulate events at different locations within a thick crystal. Events at the bottom (left) generate a mask shadow with a greater magnification at the MAP compared to an event at the top of the crystal. The experimental hardware is shown on the right.