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A large area $LaBr_3$/NaI phoswich for hard X-ray astronomy

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ABSTRACT

In terms of energy resolution, temporal response to burst events, and thermal stability, lanthanum bromide doped with Ce is a much better choice than the traditional NaI(Tl) scintillator for hard X-ray astronomy. We present the test results of a phoswich detector with a diameter of 101.6 mm consisting of 6 mm thick $LaBr_3$:Ce and 40 mm thick NaI(Tl), which is the largest one of this type reported so far. The measured energy resolution is 10.6% at 60 keV, varying inversely proportional to the square root of the energy, and the energy nonlinearity is found to be less than 1%, as good as those of smaller phoswiches. The coupled scintillators and phototube also show excellent uniformity across the detecting surface, with a deviation of 0.7% on the pulse amplitude produced by 60 keV gamma-rays. Thanks to the large ratio of light decay times of NaI(Tl) and $LaBr_3$:Ce, 250 ns versus 16 ns, pulse shape discrimination is much easier for this combination than for NaI(Tl)/CsI(Na). As the light decay time of $LaBr_3$:Ce is about 15 times faster than that of NaI(Tl), this phoswich is more suitable for detection of bright, transient sources such as gamma-ray bursts and soft gamma-ray repeaters. The internal activity of lanthanum produces a count rate of about 6 counts s^{-1} at 37.5 keV in the detector. This peak could be used for in-flight spectral calibration and gain correction.

1. Introduction

The phoswich detector has the advantages of high photopeak efficiency and outstanding background rejection capability over a single scintillator. The most traditional configuration of a phoswich is a combination of NaI(Tl) and CsI(Na) crystals, with NaI being the sensitive volume and CsI for anti-coincidence. This has been widely used in hard X-ray and soft gamma-ray astronomy over the past decades, especially where large detecting area, fast timing, and/or low background are required, e.g., the Phoswich Detection System (PDS) [1] onboard BeppoSAX and the High Energy X-ray Timing Experiment [2] onboard the Rossi X-ray Timing Explorer. Phoswiches like NaI/CsI are also selected for use in future space missions such as the Hard X-ray Modulation Telescope [3] and the Space-based multi-band astronomical Variable Object Monitor [4]. Other types of phoswich are also in use, such as the GSO(Ce)/BGO hard X-ray detector on Suzaku [5,6]. Therefore, investigation of new, advanced phoswiches would be interesting in X-ray astronomy.

Multiple crystals with distinct light decay times coupling to a single photomultiplier tube (PMT) provide a simple and reliable readout configuration, in contrast to high-*Z* semiconductor arrays of the same effective area, and is thus suitable for observations where the need for large area is prior to that for position sensitivity. However, such a large format of detector in front of a single readout has a potential disadvantage that pulses pileup is more likely to occur given the same input flux density, which will limit the maximum count rate that one can measure with the detector [7]. The dead time of scintillators is limited by its light decay time. The best way to overcome this issue without complicating the system is to find new crystals with shorter decay times.

Recently, lanthanum bromide crystals doped with cerium ($LaBr_3$:Ce) has been extensively studied and used due to its excellent physical properties. The energy resolution of $LaBr_3$:Ce is found to be around 3% at 662 keV [8], which, versus 7% for NaI(Tl), is a great improvement and is even comparable to the resolution of semiconductor (e.g., CdZnTe) detectors typical of 1–2%. $LaBr_3$:Ce has a decay time as fast as 16 ns, more than 10 times shorter than that of NaI(Tl). Therefore, $LaBr_3$:Ce should be a better choice than NaI(Tl) for applications in hard X-ray astronomy as mentioned above. Also, its excellent thermal stability [9] and high tolerance to radiation damage [10,11] make it suitable and robust for space applications. Balloon flights for X-ray astronomy with a single $LaBr_3$:Ce crystal have been carried out [12].

Mazumdar et al. [13] reported characteristics of a phoswich assembly with $LaBr_3$:Ce and NaI(Tl), with a diameter of 3 in.

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(=76.2 mm). Manchanda [12] mentioned that a similar phoswich had been designed and under study. In this paper, we report on the test of a 4 in. (=101.6 mm) diameter $LaBr_3$:Ce/NaI(Tl) phoswich (Section 2), about its temporal and spectral characteristics, uniformity (Section 3), and internal radioactivity (Section 4). A brief discussion and summary of the results is presented in Section 5.

2. Detector

The phoswich consists of cylindrical $LaBr_3$:Ce and NaI(Tl) with a diameter of 101.6 mm. The $LaBr_3$:Ce is 6 mm thick and the NaI(Tl) is 40 mm thick. Such a design allows a full-energy detection efficiency of 20% up to 300 keV. The entrance is shielded by a 0.22 mm thick Be window above $LaBr_3$:Ce, which allows at least 90% throughput for photons above 6 keV. A PMT (Hamamatsu R877) that has a bialkali window of 127 mm in diameter and magnetic shield is mounted against the NaI(Tl). The whole detector was manufactured by the Saint-Gobain group corporate using their BrilLanCe 380 and NaI(Tl) crystals. Fig. 1 shows the schematic drawing of the phoswich detector.

The PMT was operated at a negative high voltage of -860 V. Signals output from the PMT anode were fed into a preamplifier with a discharge time scale of 100 ns. A pulse shape discrimination based on the front-rear-edge technique [14] was applied to distinguish from which crystal the signal arose. All the measurements were made at room temperature.

3. Temporal and spectral responses

The decay time of $LaBr_3$:Ce is 16 ns versus 250 ns for NaI(Tl). Distinct pulse widths are expected for energy deposits in the two crystals. Fig. 2 shows the pulse width spectrum from signals obtained by irradiating the phoswich with an ^{241}Am source. The spectrum is characterized by two well separated peaks, one centered at 157 ns and the other at 439 ns, corresponding to energy deposits in $LaBr_3$:Ce and NaI(Tl), respectively. This is consistent with previous results obtained from a smaller $LaBr_3$:Ce/NaI(Tl) phoswich [13]. Energy deposits in $LaBr_3$:Ce can then be identified by screening pulse widths. For comparison, we also presented a similar measurement with a NaI(Tl)/CsI(Na) phoswich of similar size [15], see the dashed curve in Fig. 2.

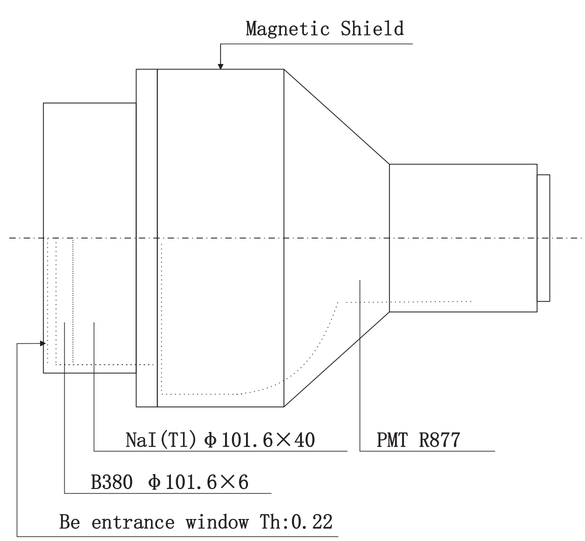

Fig. 1. Schematic drawing of the $LaBr_3$:Ce/NaI(Tl) phoswich.

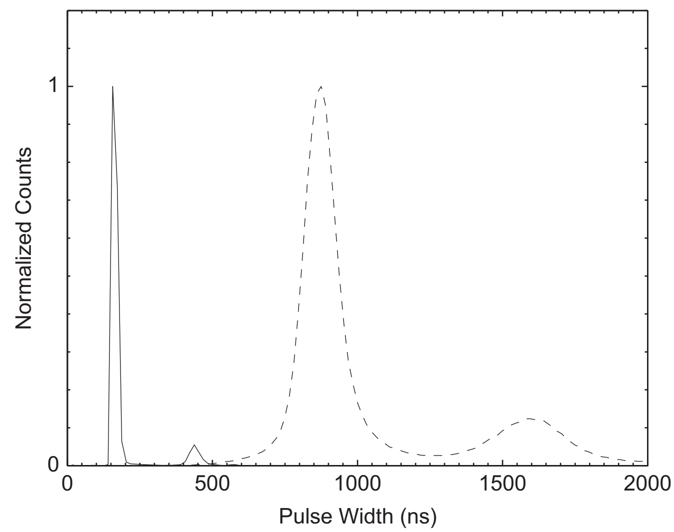

Fig. 2. Pulse width spectrum measured with the $LaBr_3$:Ce/NaI(Tl) and NaI(Tl)/CsI(Na) phoswiches and with an ^{241}Am source. The solid line is for $LaBr_3$:Ce/NaI(Tl), where the left peak corresponds to events from the $LaBr_3$:Ce crystal and the right peak is for NaI(Tl). The dashed line is for NaI(Tl)/CsI(Na), where the left peak is for NaI(Tl) and the right is for Cs(Tl). Each curve is normalized to unity at the peak.

To investigate linearity of such a large phoswich, a variety of radioactive sources were used. Fig. 3 shows energy spectra of ^{241}Am, ^{152}Eu, ^{137}Cs, and lead irradiated by ^{137}Cs, measured with the detector. Only events with a pulse width in the $LaBr_3$:Ce peak are selected. We fitted each photopeak with a Gaussian function, plus a polynomial component accounting for the continuum if necessary. The measured energy resolution in full width at half maximum (FWHM) is 5.1, 6.0, 6.3, 7.4, and 9.1 keV, respectively, at 32.1 keV (Ba Kα from ^{137}Cs), 39.9 keV (Sm Kα from ^{152}Eu), 59.5 keV (^{241}Am), 74.2 keV (Pb Kα), and 121.8 keV (^{152}Eu). This is nearly a factor of two better than the resolution of NaI(Tl)/CsI(Na) phoswich of a comparable size [1,16].

With five photopeaks over the energy range of 30–130 keV, the nonlinearity of the phoswich detector was measured to be less than 1%, see Fig. 4A. The fractional energy resolution versus energy is shown in Fig. 4B; a $E^{-0.5}$ function can adequately fit the curve, with $\chi^2 = 3.8$ and 4 degrees of freedom. The best-fit fractional energy resolution is $\mathrm{FWHM}/E = 0.88(E/\mathrm{keV})^{-0.5}$. This is consistent with the results obtained from a relatively smaller single $LaBr_3$:Ce scintillator [12].

The uniformity of spectral responses across the detecting surface is an important property of large area detectors. For scintillators, differences on light yielding, transmission, reflection, and collection at various spots may contribute to the nonuniformity. A poor uniformity would greatly degrade the spectral resolution of large area detectors. Here we only focus on the overall uniformity of whole system. We selected 21 positions evenly across the detecting surface, and exposed them to an ^{241}Am source with a single hole collimator of 5 mm in diameter. The channel centroids of the photopeak from 59.54 keV gamma-rays at each position are shown in Fig. 5. The peak centroids have a fractional standard deviation of 0.7% over the surface.

4. Internal radioactivity

^{138}La is a natural radioisotope of lanthanum with a half-life of 1.02×10^{11} year. It decays to ^{138}Ba by electron capture with a chance of 66.4%, or ^{138}Ce by electron emission with a chance of