A Thermal-Neutron Detector with a Phoswich System of LiCaAlF$_6$ and BGO Crystal Scintillators onboard PoGOLite


Abstract—To measure the flux of atmospheric neutrons and study the neutron contribution to the background of the main detector of the PoGOLite (Polarized Gamma-ray Observer) balloon-borne experiment, a thermal-neutron detector with a phoswich system of LiCaAlF$_6$ (Eu) and BGO crystal scintillators is developed. The performance to separate thermal-neutron events from those of gamma-rays and charged particles is validated with $^{252}$Cf on ground. The detector is attached to the PoGOLite instrument and is launched in 2011 from the Esrange facility in the North of Sweden. Although the emission wavelength of the LiCaAlF$_6$ (Ce) is $\sim$ 300 nm and overlaps with the absorption wavelength of the BGO, the phoswich capability of the LiCaAlF$_6$ (Ce) with the BGO is also confirmed with installing a waveform shifter.

Index Terms—Neutron detector, Li-composed crystal scintillator (LiCaAlF$_6$), Phoswich detector, PoGOLite, X-ray and gamma-ray polarimeter, Balloon experiment

I. INTRODUCTION

DEMAND of efficient neutron detectors is increasing in many fields of science, medical and industrial applications. In hard X-ray and soft gamma-ray astrophysics, recent detectors reach low background levels with active shields which consist of scintillators (e.g., CsI or BGO) and output anti-coincidence signals. After the rejection of the backgrounds caused by charged particles and gammas, the remaining background signals are mainly occupied by interaction with neutrons [1]. Then, neutron detectors, particularly in a solid-state form, are needed to reduce the background further.

Li-Composed inorganic scintillators are recently investigated and revealed to have good capabilities of crystal growth (size as large as several cm), high light yield (several 1000 – 10000 photons/neutron) and good transparency without any hygroscopy (e.g., [2]). Additionally, the development of neutron detectors for astrophysical applications is one of the new areas, and we have developed phoswich detectors consisting of LiCaAlF$_6$ (LiCAF) with Eu- or Ce-doping and BGO crystal scintillators, which can be sensitive for thermal neutrons through the neutron-capture process of $^6$Li in the LiCAF and reject events of charged particles and gamma-rays by the surrounding BGO shield (see also [3]). The LiCAF (Eu) has the higher light yield (30000 photons/neutron) than that of the LiCAF (Ce) (3500 photons/neutron), while the LiCAF (Ce) shows the faster decay-time constant (40 ns) compared with that of the LiCAF (Eu) (1600 ns) (e.g., [4], [5]). The phoswich neutron detector with the LiCAF (Eu) and BGO combination has already been installed in the PoGOLite balloon-borne experiment, whose pathfinder flight is scheduled in 2011, to measure the flux of atmospheric neutrons in real time during the flight. This paper summarizes the performance of the phoswich detectors validated with $^{252}$Cf source on ground.

II. EXPERIMENTAL SETUP

We developed two thermal-neutron phoswich detectors. One consists of one LiCAF (Eu 2%; $^6$Li with 50% concentration) scintillator for the main neutron-detection part, and two BGO crystals, which are the same as those used in the main gamma-ray detector of the PoGOLite, covering the top and bottom of the LiCAF as the shield parts. The other is a test detector with one LiCAF (Ce 2%; $^6$Li with 95% concentration) and one BGO coupled with a wavelength shifter (BC-499-09), to study the phoswich capability of this combination. The emission wavelength of the LiCAF (Ce 2%) is $\sim$ 300 nm, and partially
Fig. 1. LiCAF (Eu 2%), LiCAF (Ce 2%) and BGO crystals consist of thermal-neutron phoswich detectors.

overlaps with the absorption wavelength of the BGO (< 300 nm). After installing the wavelength shifter, the LiCAF (Ce) emission is shifted from ~ 300 nm to ~ 400 nm and is not affected by the BGO.

As shown in Figure 1, the shape of each crystal is hexagonal with 16 mm on a side (diameter of 32 mm), and the thicknesses are 5 mm for the LiCAF (Eu), 26 mm for the LiCAF (Ce), and 40 mm for the BGOs. The LiCAF and BGO crystals are grown by Tokuyama Corporation and the Nikolaev Institute of Inorganic Chemistry, respectively. The wavelength shifter also has the same hexagonal shape with 1-mm thickness. Since the cross section of the thermal-neutron capture of $^6\text{Li}$ is 940 barn and the current LiCAF crystal (density of 2.99 g cm$^{-3}$) is composed of $^6\text{Li}$ with 50% concentration, the 5-mm thickness is sufficient to capture thermal neutrons with the efficiency of ~ 90%. The LiCAF, BGOs and wavelength shifter were attached with the optical grease (OKEN 6262A), and the scintillators were painted with BaSO$_4$ for the reflector.

Through the bottom of the BGO, light yields of both LiCAF and BGO crystals were read out by Hamamatsu photomultipliers (R7899 for LiCAF (Eu) and R6231 for LiCAF (Ce)).

Figure 2 summarizes configuration of the setups measured in this paper. Before coupled with the LiCAF scintillators, we first measured the BGO response to $^{252}\text{Cf}$ in the polyethylene shield for thermal-neutron and gamma-ray source (Figure 2 (a) and (d)). Then, the main setups of the LiCAF phoswich detector were tested ((b) and (e)). Finally, with installing the 2.5-mm thick Cd plate to reduce the thermal neutron flux, the detection of the thermal neutrons were confirmed ((c) and (f)).

For the LiCAF (Eu) detector which is actually used for the neutron monitor onboard PoGOLite, we simultaneously irradiated $^{137}\text{Cs}$ source for additional gamma-ray background.

To distinguish the photomultiplier signals from the LiCAF scintillators and BGOs, we measured the shapes of dynode waveforms output from a preamplifier. The data acquisition system is based on a SpaceWire-based architecture flash ADC [6]. Figure 3 shows the obtained waveforms from the LiCAF (Eu), LiCAF (Ce) and BGO crystals irradiated by $^{252}\text{Cf}$ source. Since their decay-time constants are $\tau \sim 1600 \text{ ns}$, $\sim 40 \text{ ns}$ and $\sim 300 \text{ ns}$, respectively, we changed the ADC sampling rate of 6.25 MHz (1 clock = 160 ns) for the combination of the LiCAF (Eu) phoswich detector, and 37.5 MHz (= 26.7 ns) for the LiCAF (Ce) one. In both combinations, the larger $\tau$ value results in the slower rise time in the preamplifier output.

Figure 2. Measurement Setups for the LiCAF (Eu) from (a) to (c) and the LiCAF (Ce) from (d) to (f). (a) only two BGO crystals. (b) phoswich configuration of the LiCAF (Eu) covered with top and bottom BGOs. (c) the same as (b) but with a 2.5-mm thick Cd plate to reduce thermal neutron flux. (d) only one BGO. (e) phoswich configuration of the LiCAF (Ce) and BGO coupled with the wavelength shifter. (f) the same as (e) but with the 2.5-mm thick Cd. The setups from (a) to (c) were irradiated by $^{252}\text{Cf}$ and $^{137}\text{Cs}$ sources, simultaneously, while those from (d) to (f) were only by $^{252}\text{Cf}$.

III. DATA ANALYSIS AND RESULTS

A. LiCAF (Eu) and BGO phoswich detector

For each waveform obtained in each configuration of Figure 2, we calculated “fast” and “slow” pulse heights with extracting the highest values of PH[$t+4$] - PH[$t$] and PH[$t+15$] - PH[$t$], respectively, where PH[$t$] is the ADC output sampled at the clock $t$ (0–49 clocks). Figure 4 shows “fast”-“slow” diagrams of the three measurements for the LiCAF (Eu) phoswich detector (Figure 2 (a), (b) and (c)).

When comparing the results with/without the LiCAF (Eu) scintillator, there are clearly two branches corresponding to the LiCAF (Eu) and BGO emission in Figure 4 (b), while there is only one from the BGO in (a). Since the decay-time constant of the LiCAF (Eu) is slower than that of the BGO, the LiCAF branch appears steeper, namely the “slow” pulse height becomes higher than the “fast” one. The vertical and horizontal
Fig. 3. Examples of waveforms output from a preamplifier. (Top) LiCAF (Eu 2%) and BGO with the ADC sampling rate of 6.25 MHz (1 clock = 160 ns). (Bottom) LiCAF (Ce 2%) and BGO with that of 37.5 MHz (= 26.7 ns). They are excited with thermal-neutron capture and gamma-ray from $^{252}$Cf source.

lines around the 2750 channel are caused by ADC-saturated events with large pulse heights. Figure 4 (c) is obtained with the Cd shield to reduce the thermal neutron flux from $^{252}$Cf. The number of the events peaking around (“fast”, “slow”) = (1300, 1800) decreases significantly compared with that in the setup (b), and they are considered to come from the neutron-capture process by the LiCAF.

To check the effect of Pulse Shape Discrimination (PSD), we compare spectra before and after the event selection of the LiCAF (Eu) branch in Figure 4 (b). As shown in Figure 5, there are several features in the spectrum before the selection, including all the events detected by both LiCAF (Eu) and BGO; the 662 keV gamma-ray peak ($^{137}$Cs), 1462 keV gamma-ray peak ($^{40}$K from environmental background) and gamma-ray continuum ($^{252}$Cf and $^{137}$Cs) detected by the BGO, and the neutron capture peak ($^{252}$Cf) by the LiCAF (Eu). After selecting only the LiCAF (Eu) branch with the condition of (“slow” < 1.5 × “fast”), the peak of the thermal-neutron capture events obtained by the LiCAF (Eu) is clearly separated and remains without any change, while the gamma-ray signals decrease by 1–2 orders of magnitude. When additionally plotting the LiCAF-branch spectrum of the setup (c) with the Cd shield, the peak around the 1800 channel becomes smaller according to the decrease of the thermal-neutron flux, while the continuum keeps almost the same counts. This results confirms that the peak comes from the neutron-capture events.

The LiCAF (Eu) energy resolution of the neutron-capture peak is 8.4%. The LiCAF (Eu) pulse height with this phoswich configuration decreases to ~ 70% of that of the single crystal measurement (only the LiCAF (Eu) is attached to the photomultiplier).

Since the BGO scintillator is sensitive to not only gamma-rays but also charged particles, we suppose that this phoswich system can discard background caused by them and choose only the thermal-neutron signals detected by the LiCAF (Eu) during the POGOLite flight at the attitude of ~ 40 km.

B. LiCAF (Ce) and BGO phoswich detector

We performed the same analysis for the datasets of the LiCAF (Ce) and BGO phoswich detector (the measurement setups of (d), (e) and (f)). Figure 6 shows the obtained “fast”-“slow” diagrams. Since the decay-time constant of the LiCAF (Ce) (40 ns) is faster than that of the BGO (300 ns), the LiCAF (Ce) events locate at the flatter branch and the BGO signals are at the steeper one, and the two branches are also clearly separated for this scintillator combination. The peak around (“fast”, “slow”) = (200, 250) represents the events of the thermal-neutron capture by the LiCAF (Ce), and decreases with the installation of the Cd shield (the setup (f)).

There are some events at the line of “fast” = “slow”, which are thought to come from signals of the wavelength shifter, since the events have the faster decay and the higher pulse heights than those of the LiCAF (Ce). Indeed, the “fast” = “slow” events are not observed when only the LiCAF (Ce) scintillator was irradiated without attaching the BGO and wavelength shifter.

With selecting the events in the LiCAF (Ce) branch with the condition of (“slow” < 1.5 × “fast”), we plot spectra in Figure 7. The obtained results are the same as those of the above LiCAF (Eu). Since the continuum comes form gamma-ray events detected mainly by the BGO, the neutron-capture peak at the 250 “slow” channel remains after the PSD selection, and the peak becomes smaller according to the thermal-neutron flux with the Cd plate. The energy resolution of the LiCAF (Ce) peak is 19%.

We measured the LiCAF (Ce) pulse heights at the conditions of (1) the LiCAF (Ce) single scintillator, (2) LiCAF (Ce) with the wavelength shifter, and (3) the current phoswich configuration. The peak ratio of each measurement is obtained as (1) : (2) : (3) = 1 : 1.3 : 1.1. Then, with attaching the wavelength shifter from (1) to (2), the pulse height of the photomultiplier output increases by 30%. This effect is considered that the emission wavelength of the shifter (400 nm) matches the quantum efficiency of the photomultiplier better than the original LiCAF (Ce) emission (300 nm), overwhelming the loss of the conversion inefficiency of the LiCAF (Ce) emission through the shifter. As a result, even after the decrease between (2) and (3) is 20% similar to that of the above LiCAF (Eu) and BGO phoswich detectors, the final photomultiplier output (3) has the comparable or 10%-higher
pulse height than the original (1). Therefore, the installation of the wavelength shifter can avoid the absorption of the LiCAF (Ce) emission by the BGO, and also have the possibility to increase the detector performance.

IV. Conclusion

From the above results, we have validated the performances of the two phoswich detectors with the LiCAF (Eu) or (Ce) and BGO scintillators, where the gamma-ray events are detected/shielded by the surrounding BGOs, and the thermal neutrons are captured by the LiCAF. Since the decay-time constants among scintillators are several times different, the branches in the “fast”-“slow” diagram are clearly separated in both detectors, and the events by the neutron-capture process in the LiCAF branch are identified almost purely. Since the BGO is also sensitive to charged particles, we think such phoswich detectors can work even during space orbits or balloon flights, where the background rate is high by gamma-rays and charged particles.

For the case of the LiCAF (Ce), the shorter emission wavelength of 300 nm is converted to 400 nm through the wavelength shifter, to avoid the absorption by the BGO. This result also reveals that the photomultiplier output has the even higher pulse height because of the better matching of the quantum efficiency after the shift.

The PoGOLite detector has 15-cm thick polyethylene shield to reduce the background caused by the interaction with atmospheric neutrons, and thermal neutrons are supposed to exist around the detector. To detect such thermal neutrons and measure the flux, we have installed the LiCAF (Eu) and BGO phoswich detector developed here onboard PoGOLite. The pathfinder flight is scheduled in 2011 from the Esrange facility in the North of Sweden.

References

Fig. 4. “fast”–“slow” diagrams of the LiCAF (Eu) and BGO phoswich detector with irradiation of $^{252}$Cf and $^{137}$Cs, corresponding to the measurement setups in Figure 2 (a), (b) and (c), respectively. The steeper branch represents signals from the LiCAF (Eu), while the flatter one does those from the BGO.

Fig. 5. Spectra of the LiCAF (Eu) and BGO phoswich detector with irradiation of $^{252}$Cf and $^{137}$Cs sources. (Top) the spectrum of the setup (b) before the PSD selection. All the events detected by both LiCAF (Eu) and BGO are included. (Middle) the same as the top one but after the PSD selection of only the LiCAF (Eu) branch (i.e., the BGO signals are discarded). There is a clear single peak of the neutron-capture events at $\sim 1800$ ADC “slow” channel. (Bottom) the same as the middle but for the setup (c), where the number of the neutron-capture events decreases following the decrease of thermal-neutron flux by the Cd shield. The feature around 2750 channel is caused by ADC saturation due to large pulse-height events.
Fig. 6. The same as Figure 4 but for the LiCAF (Ce) and BGO phoswich detector, corresponding to the setups of Figure 2 (d), (e) and (f), respectively. The flatter branch represent signals from the LiCAF (Ce), while the slower one does those from the BGO.

Fig. 7. The same as Figure 5 but for the LiCAF (Ce) phoswich detector.