

# Wide-band Gamma-Ray Burst Monitor

– GBM for the CALET Mission –

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## ABSTRACT

We are developing the gamma-ray burst monitor for the CALET (CALorimetric Electron Telescope) experiment which is proposed and studied (in phase A) to be a next experiment for the JEM/Exposure Facility of the ISS. The CALET GRB Monitor (CALET-GBM) is planned to measure wide-band energy spectra from GRB prompt emissions over nine decades in energy (from a few keV to a few TeV) together with the CALET Imaging Calorimeter (IMC) and the Total Absorption Calorimeter (TASC). To fulfill this requirement, we are planning to employ six LaBr<sub>3</sub>(Ce) crystals for the range from a few keV to about 1 MeV together with a thick BGO detector covering from several tens of keV to about 20 MeV. Since the light yield of LaBr<sub>3</sub>(Ce) is about twice as large as that of NaI(Tl), it is very attractive material. However it has not been yet used as a detector for long exposure in space. Therefore its radiation hardness and induced background due to trapped protons in the geomagnetic field are not fully understood. To evaluate its performance in high radiation environment in the ISS orbit, we carried out proton irradiation tests. Proton-induced radio-activation were measured from a few minutes after irradiation over a period longer than two months by a Germanium detector, and most of radioactive nuclei induced by protons are identified. We have manufactured a proto-type model, 3 inch in diameter  $\times$  0.5 inch thick with the entrance window of 220  $\mu$ m beryllium. In preliminary measurements, 6.4 keV Fe K $\alpha$  fluorescence line is clearly detectable. We can expect that the lower energy threshold can be around 4 keV or even lower.

KEY WORDS: Scintillation detectors, GRB, XRF, Gamma-rays, X-rays, Radiation-damage

## 1. introduction

Gamma-ray burst (GRB) is one of the biggest explosions in our universe. The total radiation energy release is estimated to be  $10^{51}$  erg, and more than 50% of the energy is usually emitted in the hard X-ray to the soft gamma-ray range (20-1000 keV). Although the long-GRBs were considered to be associated with the death of massive stars and related to Ic supernovae. However detailed physics remain unclear even the initial energy source "fireball" model. Well-studied energy range of GRBs by typical detectors is 15 keV  $\sim$  10 MeV. By extending it to the lower energy side, Ginga, Beppo-SAX, and HETE-2 brought us a discovery of X-ray rich GRBs (XRR) and X-ray flashes (XRF) whose emitted energy is dominant in not gamma-rays but more in X-rays (10 keV)[1]. In

the higher energy side than  $\sim$ 10 MeV, two important discoveries were made by CGRO/EGRET observations[2]. One is a presence of the delayed GeV emissions from the GRBs, and the other is a presence of the high energy excess component [3]. In order to understand the radiation mechanisms of the GRB prompt emissions, it is essential to study wide-band spectra and their variability over the keV to GeV band. For this purpose, we propose to have a gamma-ray burst monitor (GBM) in the CALET experiment[4] on the International Space Station (ISS).

## 2. Components of the CALET

### 2.1. IMaging Calorimeter and Total Absorption Calorimeter

The CALET (CALorimetric Electron Telescope) mission is aimed to study high energy electrons and gamma-rays. It is proposed for the second public advertisement of an experimental payload attached to the Japan Experimental Module/Exposure Facility of the ISS targeting the launch of 2013.

CALET main detector consists of an imaging calorimeter (IMC), total absorption calorimeter (TASC). The IMC is used for identification of the incident particle and energy measurement below 10 GeV, while the TASC is for total energy measurement above 10 GeV. The IMC consists of 17 layers of lead plates and scintillating fiber (SciFi) belts, and the dimension is about 90 cm  $\times$  90 cm. The readout for the SciFi is multi-anode photomultiplier tubes. The TASC is composed of 12 layers of BGO logs which has dimensions of 2.5 cm  $\times$  2.5 cm  $\times$  30 cm. There are 12 layers and 48 such logs in each layers, and has the size of 60 cm  $\times$  60 cm  $\times$  30 cm. Total weight of CALET instruments is  $\sim$  1450 kg and the effective geometrical factor is  $\sim$  7000 cm<sup>2</sup>sr. The schematic structure is shown in Fig.1.

[4]

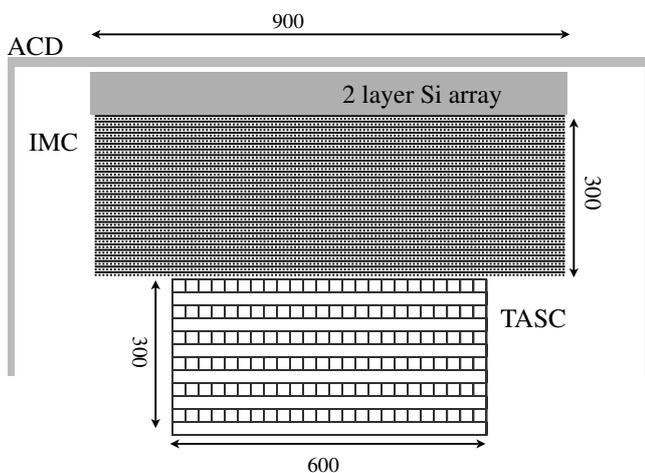


Fig. 1. image of CALET detectors.

The CALET is sensitive to electrons from 1 GeV to 20 TeV. With 3 years observation, CALET can observe about two thousands of galactic TeV electron events, and we can clearly identify local acceleration sites in the galaxy such as Vela from the energy spectrum and the anisotropy. Furthermore, the most exotic and interesting objective is a feature due to the decay of SUSY or Kaluza-Klein dark matter. The CALET also has sensitivity to gamma-rays from 20 MeV to several TeV, owing to the background rejection with the anti coincidence shield. The scientific target of the gamma-ray

observation is Galactic and extra-Galactic diffuse component, supernova remnants, pulsars, AGNs, and gamma-ray bursts.

### 2.2. Gamma-Ray Burst Monitor

The CALET-GBM is designed to see the energy band lower of the CALET calorimeters (20 MeV), fulfilling a observational band of nine decades from several keV  $\sim$  TeV together with the CALET IMC and TASC. The CALET-GBM employs two types of detector, Soft Gamma-ray Monitor (SGM) and Hard X-ray Monitors (HXM), shown in Fig.2). They consist of inorganic scintillators and photomultiplier tubes, it is basically same as Ginga/GBD, HETE-2/FREGATE and Suzaku/WAM. SGM consists of a 5 inch  $\phi$   $\times$  3 inch thick BGO crystal with a large stopping power, and sensitive from several tens of keV to 20 MeV. HXM consists of six 4 inch  $\phi$   $\times$  0.5 inch thick LaBr<sub>3</sub>(Ce) crystals to achieve excellent energy resolution.

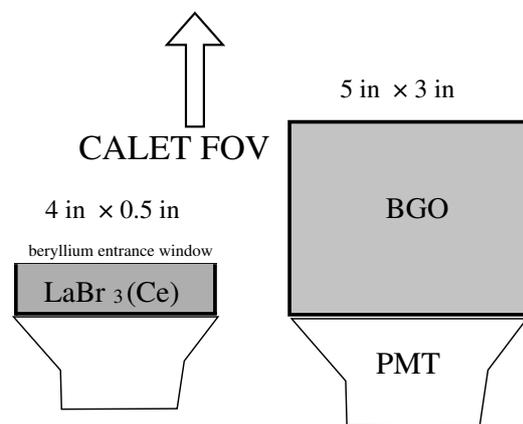


Fig. 2. image of CALET GBM

Because of deliquescent of LaBr<sub>3</sub>(Ce) crystal, the airtight housing is required. In order to have a sensitivity for X-rays, we will use 220  $\mu$ m beryllium for the entrance window. All the detectors are co-aligned with CALET calorimeters to get a high sensitivity for the FOV events. Current characteristics of SGM and HXM are summarized in Table1, and effective area of them are shown in Fig.3.

### 2.3. scientific objectives of the GBM together with the CALET IMC and the TASC

The CALET-GBM is expected to observe in total 100 events per year assuming logN-logP distributions from the BATSE catalog. The FOV events will be expected to be 40 per year, while out of FOV events could be 60 events per year. More detailed background study is necessary taking mass distribution around CALET into account.

The scientific objectives are as below.

Table 1. Current Design of the CALET-GBM.

	HXM	SGM
Scintillator Crystal	LaBr <sub>3</sub> (Ce)	BGO
Number of Detector	6	1
Diameter (inch)	4	5
Thickness (inch)	0.5	3
Geometrical Area (cm <sup>2</sup> )	486	127
Energy Range (keV)	~7-600	~100-20000
Energy resolution (662keV)	~3%	11%
Weight (kg)	6.9	7.5

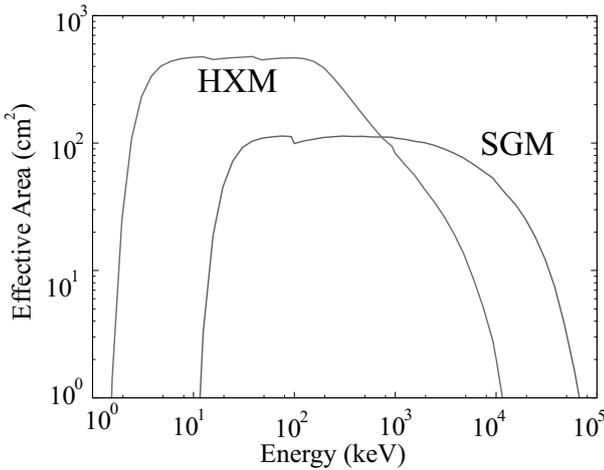


Fig. 3. Effective area of a SGM and six HXMs.

- Gamma-ray bursts (GRBs)
  - search for the spectral cutoff which reflects electron acceleration in the shock.
  - origin of the high energy excess (10 MeV) from the possible synchrotron emissions.
  - origin of delayed GeV emissions.
  - Ep distribution based on wide band  $\nu F\nu$  spectra.
  - broadband time-variability study such as pulse widths and lags
  - search for possible emission/absorption line features.
- Soft gamma-ray repeaters (SGRs)
  - a detailed study of the broadband spectrum.
  - for flares with various intensities(short to giant).
  - origin of the non-thermal hard tail above 100 keV.
- Solar Flares
- hard X-ray transients from NS or BH system.

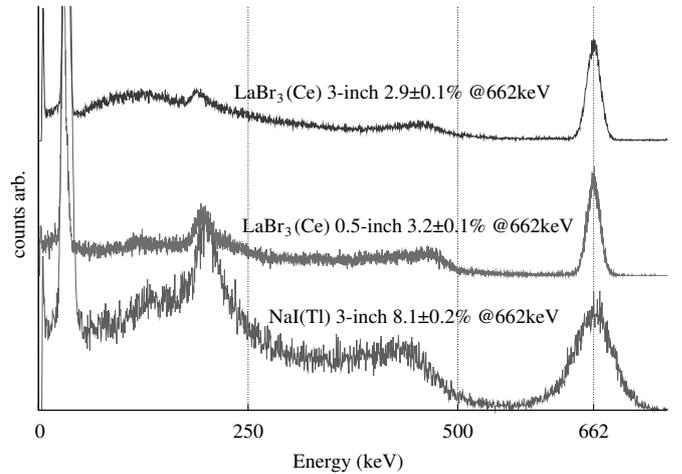
### 3. Evaluation of LaBr<sub>3</sub>(Ce) scintillator

The LaBr<sub>3</sub>(Ce) with a high light output, therefore an excellent energy resolution, a fast decay time and a high thermal stability[5] is very attractive material for our detector, nevertheless has not been used in space so far. Hence, we are studying its

- basic performances such as energy resolution
- basic performances and uniformity in larger 3 inch  $\phi$  crystal
- lower energy threshold of the detector with a thin beryllium window
- intrinsic backgrounds
- radiation hardness for gamma-rays and protons
- proton induced background

#### 3.1. performance

We have tested commercially available LaBr<sub>3</sub>(Ce) crystal of 0.5 inch  $\times$  0.5 inch thick. The crystal is covered by aluminum housing and light-guide glass, and it is coupled by the photomultiplier tube through the glass. Signals from a charge sensitive pre-amplifier are processed in a shaping amplifier, then recorded in a pulse-height analyzer.

Fig. 4. <sup>137</sup>Cs 662 keV spectrum of LaBr<sub>3</sub>(Ce) crystal in comparing with NaI(Tl).

FWHM energy resolution of 662 keV gamma-rays from <sup>137</sup>Cs was measured, 3.2% $\pm$ 0.1% with LaBr<sub>3</sub>(Ce) while 8.2%  $\pm$  0.2% with NaI(Tl) (Fig.4).

The current technology of LaBr<sub>3</sub>(Ce) crystal growth is capable of being scaled up to 200 mm diameter crystals[6]. We obtained larger 3 inch diameter  $\times$  0.5 inch thickness LaBr<sub>3</sub>(Ce) single crystal as a proto-type of CALET-GBM, which has a 220 $\mu$ m beryllium entrance

window for a sensitivity to the lower energy. We tested it using 662 keV gamma-ray from  $^{137}\text{Cs}$  and 14.4 keV, 122 keV, 136.5 keV gamma-ray, and 6.4 keV Fe-K $\alpha$  from  $^{57}\text{Co}$  for the lower energy. In the experiment, energy resolution at 662 keV was  $2.9\% \pm 0.1\%$ : comparable to smaller crystals (2.8~3.2% typically).

For the lower energy, down to 6.4 keV X-ray were can be seen (Fig5). The achieved lower energy threshold was less than 4 keV. We expect that the lower energy threshold can be around 4 keV or even lower.

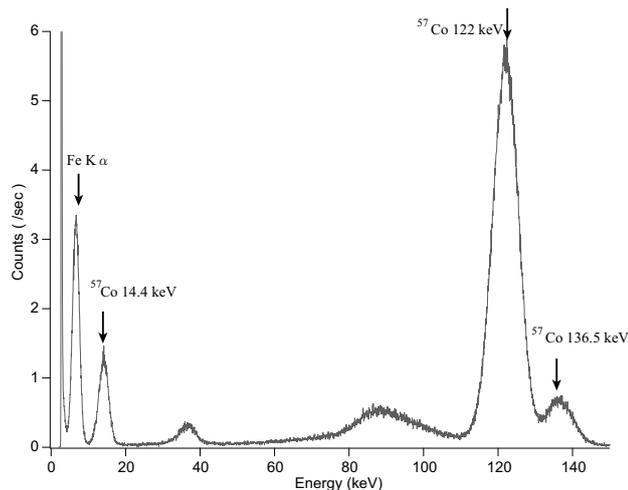


Fig. 5.  $^{57}\text{Co}$  spectrum taken by of the 3 inch  $\phi$  detector with a beryllium entrance window. The energy resolution was quite excellent. 6.4 keV Fe K $\alpha$  X-ray and 14.4 keV  $^{57}\text{Co}$  gamma-ray were clearly resolved.

Naturally occurring lanthanum includes 0.09% of  $^{138}\text{La}$ , which has a  $1.05 \times 10^{11}$  yr half-life and two different decay schemes shown Fig.6. 66.4% are EC (Electron Capture) decay with a 1435.6 keV gamma-ray and the rest with the broadening ratio of 33.6% are  $\beta^-$  decay emitting 788.7 keV gamma-ray and  $\beta^-$  particle ( $\beta_{max}=254$  keV).

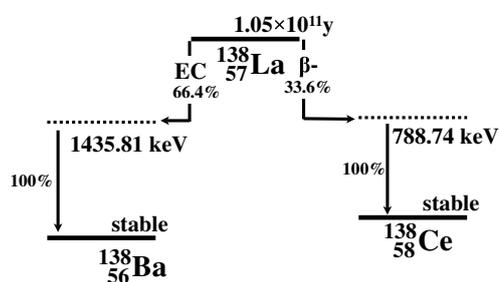


Fig. 6. Decay scheme of  $^{138}\text{La}$ , which has EC decay and  $\beta^-$  decay.

Measured spectrum using 3 inch  $\phi \times 0.5$  inch thick crystal and Photomultiplier Tube is shown in Fig.7. There are broad component of  $\beta$  particle under 254 keV and sum of 788.7 keV gamma-ray and  $\beta$  component, and

1436 keV line are interfered with  $^{40}\text{K}$  1460.8 keV gamma-ray from the room background. Above 1435.6 keV peak, you can see broad triple peak caused by alpha particles due to  $^{227}\text{Ac}$  contamination. The count rate of its intrinsic background was  $\sim 1.2\text{-}1.3$  counts  $\text{s}^{-1} \text{cm}^{-3}$ .

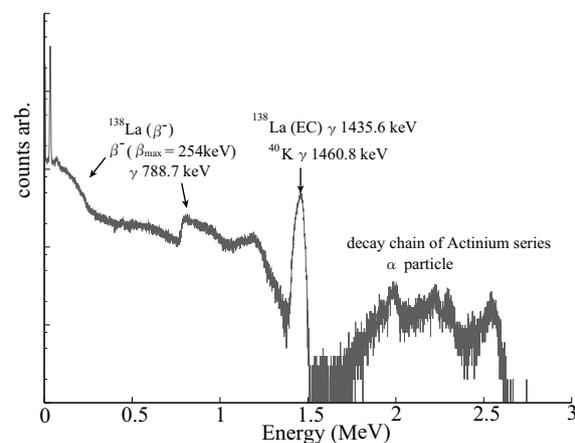


Fig. 7. Measured intrinsic background of 3 inch  $\phi \times 0.5$  inch thick crystal and PMT. It is caused by naturally occurring radioactive  $^{138}\text{La}$  and contaminated  $^{227}\text{Ac}$ .

### 3.2. degradation by radiation damage

The International Space Station rotates around the Earth sixteen times a day, and passes through the South Atlantic Anomaly at a half of its passages. The proton dose in the ISS orbit is estimated to be  $10^9 \text{ cm}^{-2}$  per year. In such a radiation environment, degradation of properties of the detector by radiation damage is not negligible, and the induced background is considerably higher than that on the ground. Thus investigations for its radiation hardness and possible induced background is necessary. We carried out proton irradiation test on December 2007 at the Wakasa-Wan Energy Research Center, Fukui, Japan. We investigated degradation of its gain and energy resolution after irradiation by protons with their kinetic energy 140 MeV as a function of their dose ranging from  $10^5$  to  $10^{11}$  protons  $\text{cm}^{-2}$ . By irradiation of  $10^{11}$  protons  $\text{cm}^{-2}$  (corresponding to about 100 years on ISS orbit), the energy resolution degraded from 3% to 4% and the light yield looked to have decreased by 30% (Fig.8). However, for a few  $10^9$  protons  $\text{cm}^{-2}$  that corresponds to the flux on the actual duration of the mission, there were little degradations.

We noticed that the light-guide glass and/or  $\text{LaBr}_3(\text{Ce})$  crystal was colored slightly in reddish-brown after  $10^{11}$  protons  $\text{cm}^{-2}$  irradiation. So, we tested glass itself and measured permeability in optical  $\sim$  near-UV range. Permeability spectrum was taken by a spectrometer Hamamatsu C10082CAH and light source L10290. The spectrum is shown in Fig.9, in 380 nm (peak wavelength of  $\text{LaBr}_3(\text{Ce})$  fluorescence) permeability was de-

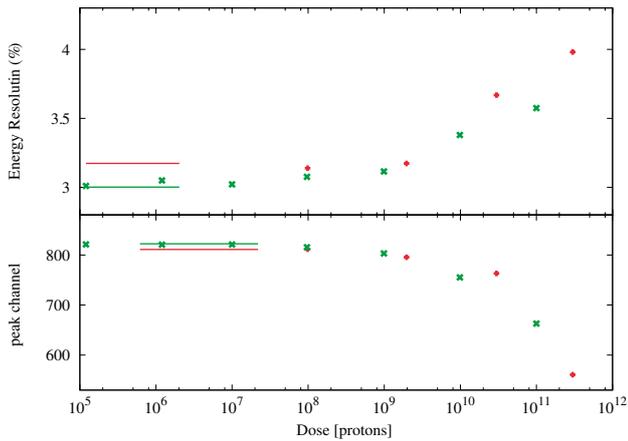


Fig. 8. Energy Resolution and peak channel using  $^{137}\text{Cs}$  source was measured as a function of their dose. As a result,  $10^9 \sim 10^{10} \text{ cm}^{-2}$  caused a degradation. The lines shows a properties of before irradiation.

creased more than 70 %. The result shows that the color centre induced in the glass by the irradiation caused a degradation, nevertheless it is not clear if the  $\text{LaBr}_3(\text{Ce})$  degraded or not. So, we need a little more investigations doing well with its deliquescence.

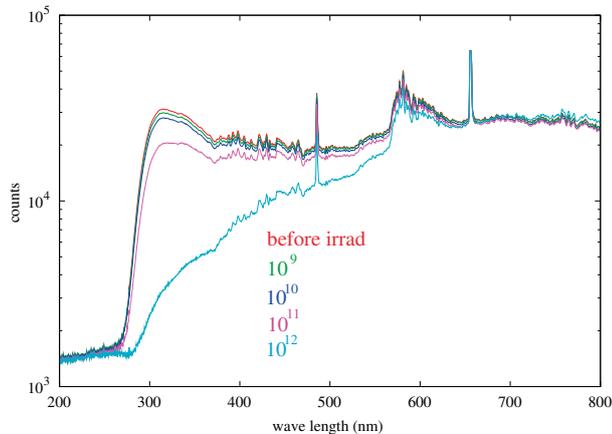


Fig. 9. Measured spectrum , with a dose of  $10^9, 10^{10}, 10^{11}$  and  $10^{12}$  protons  $\text{cm}^{-2}$ . The structure (such as the peak in 485 nm, 655 nm) reflects a characteristics of the light source.

### 3.3. proton-induced background

The nuclei with short lifetime of several minutes and long life-time of years gives different effects on the background. Proton-induced radioactive gamma-rays were monitored soon after irradiation by an external Germanium detector.

- $3 \times 10^9$  and  $3 \times 10^{10}$  protons  $\text{cm}^{-2}$  with kinetic energy 140 MeV were irradiated to each of two crystals.
- induced gamma-rays were investigated from a few minutes after irradiation for both one.

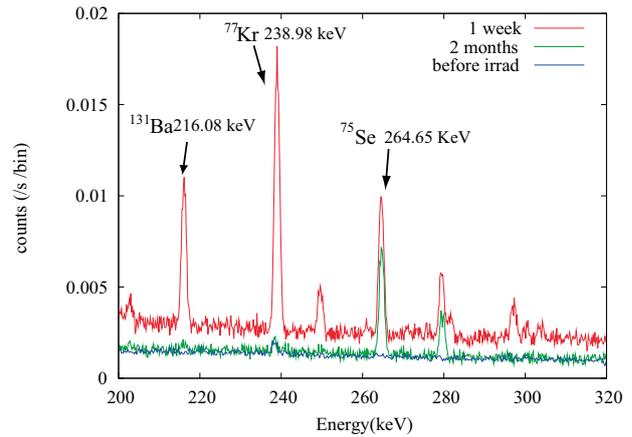


Fig. 10. Radio-activated background spectrum (partial) measured by Germanium detector: before irradiation, 1 week after proton beam irradiation, and after 2 months.

- especially for  $3 \times 10^{10}$  one, the measurement was continued for a longer period than two months.

Table 2. Summary of identified nuclei

5 min~1 hour	$^{74m}\text{Br}, ^{77m}\text{Br}, ^{77}\text{Kr}, ^{130}\text{La}, ^{131}\text{La}$ and more (lifetime:several minutes to a few hours)
1 week	$^{75}\text{Se}(119 \text{ d}), ^{77}\text{Br}(57 \text{ h}), ^{131}\text{Ba}(11.5 \text{ d})$
2 months	$^{75}\text{Se}(119 \text{ d})$

By the analysis on the data, most of radio-active nuclei induced by proton beam were identified. An example of proton induced background spectrum measured by the Germanium detector is shown in Fig.10, and the list of identified radio-active source is summarized in Table2. Considering the long-term background,  $^{75}\text{Se}$  that has a 119 day half-life is dominant.

### 4. conclusion

The CALET experiment will provide an unique capability for detecting GRBs on a wide band, with the gamma-ray burst monitor(CALET-GBM).The GBM in currently designed to have a sensitivity in the energy range from 7keV to 20 MeV, covering  $>2$  str. all the sky.

We have been investigating new scintillator:  $\text{LaBr}_3(\text{Ce})$  that has higher light output, better energy resolution and faster decay-time than  $\text{NaI}(\text{Tl})$ . We are testing its basic performance, radiation hardness and induced background anticipated on the ISS orbit,  $\text{LaBr}_3(\text{Ce})$  shows excellent performances as we expected. Although  $\text{LaBr}_3(\text{Ce})$  has several times as higher naturally occurring background as other inorganic scintillators.It is not

a considerable problem for our purpose: not pointing observation but burst monitoring.

#### Acknowledgments

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