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Geometry dependence of the light collection efficiency of BGO crystal scintillators read out by avalanche photo diodes

M. Sasano [a,*], H. Nishioka [a], S. Okuyama [a], K. Nakazawa [a], K. Makishima [a,b,c], S. Yamada [c], T. Yuasa [d], A. Okumura [e], J. Kataoka [f], Y. Fukazawa [g], Y. Hanabata [g], K. Hayashi [g]

[a] Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
[b] Research Center for the Early Universe, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
[c] RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
[d] ISAS/JAXA, 3-1-1 Yuinodai, Chuo, Sagamihara, Kanagawa 252-5210, Japan
[e] Solar-Terrestrial Environment Laboratory, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan
[f] Research Institute for Science and Engineering, Waseda University, 3-4-1, Okubo, Shinjuku, Tokyo 169-8555, Japan
[g] High Energy Astrophysics Group, Department of Physical Sciences, Hiroshima University, 1-3-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8526, Japan

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ABSTRACT

Light collection efficiency from BGO crystal scintillators of various sizes and shapes was measured by reading them using 1×1 cm^2 avalanche photo diodes. When the crystals have simple geometry, the light collection efficiency was found to depend on their size, shape and the read-out position through a rather well-defined empirical scaling relation. The light collection efficiency of tapered crystals was seen to depend on both the position of $\gamma-$ray irradiation, and the read-out position of the avalanche photo diodes. Using optical Monte-Carlo simulations, the relation was reproduced assuming plausible proper parameters for surface conditions and the attenuation length. This results were reproduced with a reasonable accuracy by optical Monte-Carlo simulations. Simple physical explanations are given to these geometrical effects.

1. Introduction

BGO ($Bi_4Ge_3O_{12}$), an inorganic scintillator material, is commercially available as crystals of relatively large size, e.g., 40 cm in length. With high specific gravity ($\sim$7.13 g cm^{-3}) and a large atomic number ($Z_{Bi} = 83$), BGO has a high stopping power against $\gamma-$rays. Together with good optical transparency, these makes BGO an attractive radiation detector material (including its use as an active shield), even though its light output is relatively low ($\sim$10–20% of that of NaI(Tl)). In fact, BGO scintillators have been utilized as active shields of various cosmic X-ray and $\gamma-$ray experiments, including the Hard X-ray Detector (HXD:[1,2]) onboard the cosmic X-ray satellite *Suzaku* [3].

Avalanche photodiodes (APDs: [4,5]) are a special type of photodiodes which have internal signal gain under high electric fields. Compared to photomultiplier tubes (PMTs), APDs have many advantages, particularly for space use, as a read out device for inorganic scintillators. The advantages of APDs include their small size, light weight, high mechanical strength, high quantum efficiency, and low power consumption.

As an active shield system for a space-borne radiation detector, BGO crystal scintillators coupled with APDs have thus many advantages. However, this combination has an obvious problem: BGO has high refractive index, $\sim$2.15, so that its critical angle is very small, such as $\theta_c = 28^\circ$ at its boundary with air, and 43° with glasses. Due to this property, many scintillation photons are trapped and travel long paths in a BGO crystal being totally reflected many times at its surface. If there were no parasitic absorption, the photons would eventually arrive at the readout device. However all scintillators have some undesired absorption, both in the bulk of the scintillator and at the surfaces. Therefore, photons which travel long paths are absorbed with high possibility. and eventually absorbed therein before they manage to arrive at the readout device. This problem would become more severe when we use APDs, because they usually have considerably smaller photon sensing areas than PMTs. Therefore, we investigated experimentally and numerically how the light output of BGO crystals depend on their sizes and shapes when they are read out by APDs with an active area of 1×1 cm^2 in size.

2. Experimental setup

2.1. BGO crystal samples

Fig. 1 shows BGO crystal samples which we employed in our measurements. Their geometrical parameters are summarized in

* Corresponding author. Tel.: +81 358414173.
E-mail address: sasano@juno.phys.s.u-tokyo.ac.jp (M. Sasano).

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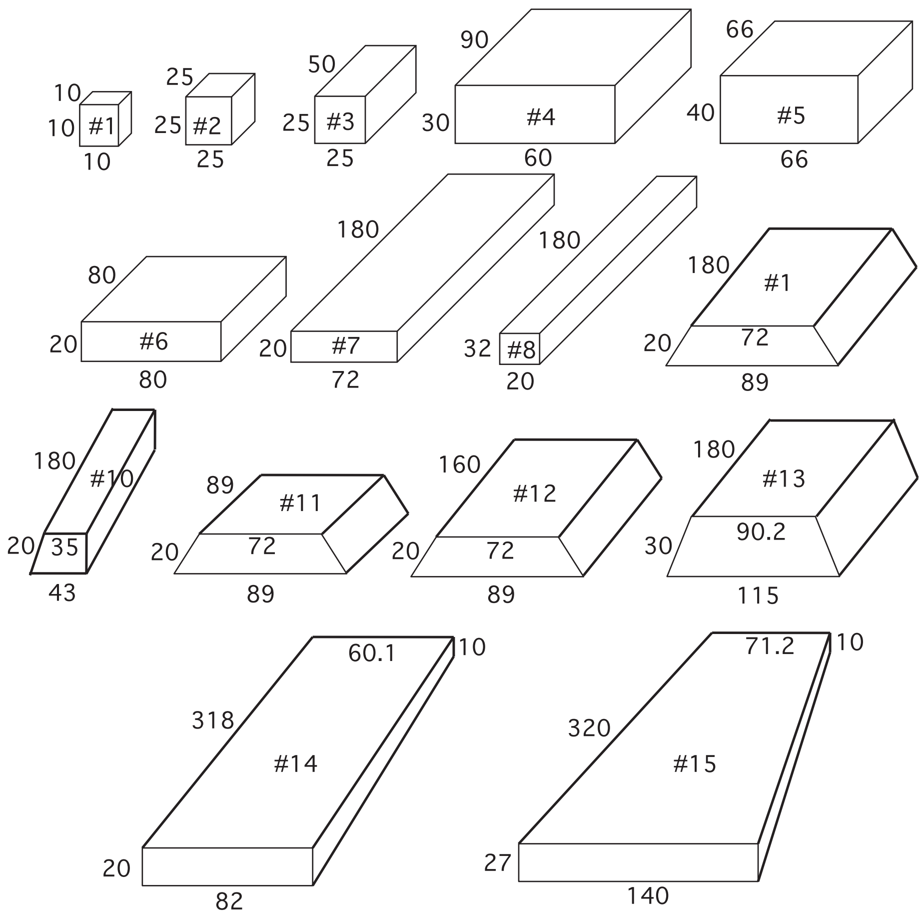

Fig. 1. BGO crystal samples used in the present paper. Units are in mm.

Table 1. They were all manufactured by Nikolaev Institute of Inorganic Chemistry in Russia, as part of our developments of two space-borne instruments, the Hard X-ray Imager and the Soft Gamma-ray Detector, both to be onboard the 6th Japanese X-ray Astronomy satellite *ASTRO-H* (scheduled for launch in 2014; [6]). Among them, #1–#8 are rectangular crystals, and #9–#14 are non-rectangular ones. Especially, #14 has a large size. All these crystals have polished surfaces. We measured their light outputs with an APD which was attached on the smallest surface of each crystal. In addition, the rectangular samples were read out from other sides as well.

Although these samples were taken from different ingots, their systematic difference in the intrinsic light yield (i.e., the number of scintillator photons per deposited radiation energy) is considered to be less than 10% normally. In other words, any difference in the output pulse height among these crystals can be attributed mainly to their differences in the light collection efficiency. Actually, we measured several crystals of the same dimensions made from different ingots, and usually obtained similar light outputs within a typically scatter by $\pm 10\%$.

2.2. APDs

In the present experiment, we employed a Si-type APD of S8664-1010 series made by Hamamatsu photonics, having an entrance window with an area of 1×1 cm^2, made of epoxy resin. Their basic parameters are essentially identical, and are summarized in Table 2. Their quantum efficiency is ~80% around the wavelengths emitted by BGO (peak at ~480 nm). Fig. 2 shows V–I (voltage–current) and gain curves of one of them, obtained at

Table 1
Sizes and shapes of BGO crystal samples.

Sample	Geometry (cm × cm × cm)
#1	1.0 × 1.0 × 1.0
#2	2.5 × 2.5 × 2.5
#3	2.5 × 2.5 × 5.0
#4	3.0 × 6.0 × 9.0
#5	4.0 × 6.6 × 6.6
#6	2.0 × 8.0 × 8.0
#7	2.0 × 7.2 × 18
#8	2.0 × 3.2 × 18
#9	2.0 × 7.2 (8.9) × 18
#10	2.0 × 3.5 (4.3) × 18
#11	2.0 × 7.2 (8.9) × 8.9
#12	2.0 × 7.2 (8.9) × 16
#13	3.0 × 9.02 (11.5) × 13.2
#14	2.0(1.0) × 8.2 (6.01) × 31.8

Table 2
Parameters of Si-type APDs of S8664-1010 series made by Hamamatsu photonics.

Surface area	1×1 cm^2
Window	Epoxy resin
Dark current (gain=50, +20 °C)	~10 nA
Break-down voltage (+25 °C)	460 V
Bias voltage (gain=50, +20 °C)	414 V
Capacitance (gain=50, +25 °C)	~270 pF
Quantum efficiency	~80% (480 nm)