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Bismuth Germanate as a High-Energy Gamma-Ray Detector

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Introduction

For the past several years the majority of experiments that detected gamma-rays above 10.0 MeV involved large volume NaI detectors with anti-coincidence shields surrounding them.¹ These shields serve two purposes: first, they veto cosmic ray events, and second, they reject gamma-ray events that do not deposit their total energy in the crystal. Recently bismuth germanate ($\text{Bi}_2\text{Ge}_2\text{O}_{12}$), or BGO, scintillators have been developed with many properties that may make them an attractive alternative to NaI in many applications.^{2,3} In our particular experiment we detect gamma rays following high-energy neutron capture using a white neutron source. The requirements of our detector system are that it have good energy and time resolution, high efficiency, and low sensitivity to neutron backgrounds. Since we require an array of detectors to simultaneously measure the angular distribution of the radiation along with the excitation function, NaI detectors with anticoincidence shields seem impractical. We therefore decided to construct a detector system consisting of five 7.6-cm-long by 7.6-cm-diam-BGO scintillators spanning an angular range from 140 to 15 degrees in the reaction plane.

Table 1 lists some of the properties of BGO^{4,5} and the values for NaI for comparison. For our application the advantages of BGO are its high average atomic number and its large density. Both these factors contribute towards improving the detector efficiency. The disadvantages of BGO are its lower light output (1/10 of NaI), its high index of refraction ($n = 2.15$), and its longer wavelength at maximum light output. In addition large BGO crystals often contain trapped bubbles, which scatter the light. All these factors tend to limit the resolution of the scintillator.

Energy resolution

The energy resolution of a 7.6 by 7.6 cm cylindrical BGO crystal with no active shielding or collimation around it was measured in the energy range from 0.5 to 20 MeV. For these tests the crystal was coupled to a 9.0-cm-diam EMI 9531 photomultiplier tube (PMT) using Dow Corning Q2-3067 ($n = 1.48$) optical coupling grease. The resolution below 6 MeV was measured using radioactive sources. Figure 1 shows the pulse-height spectrum of the 4.43-MeV gamma-ray from a Pu-Be radioactive source. The single escape peak is approximately 40% of the full energy peak. Figure 2 shows the response of BGO for gamma rays of 15 MeV that was obtained using the $^{12}\text{C}(p,\gamma)$ reaction at $E_p = 14.3$ MeV. Figure 3 shows the response at 17.7 MeV that was obtained using the $^{12}\text{C}(t,\gamma)$ reaction at $E_t = 3.5$ MeV. A summary of the energy dependence of the energy resolution is plotted in Fig. 4. The value at 21 MeV was obtained from the $^3\text{H}(t,\gamma)$ reaction for tritons at 3.75 MeV. From 500 keV to 1.46 MeV the resolution was determined by fitting to a single gaussian. The resolution at 4.43 and 6.13 MeV were obtained by fitting the data with two gaussians corresponding to the full energy and the first escape peaks. In these cases the values given in the plot are for the full width at half maximum (FWHM) of the full energy peak only. Since the escape peaks are not resolved from the full peak energy for the points above 6 MeV, the total peak was fit to a single gaussian in this energy region. As seen from the figure, the percent of energy resolution up to 6 MeV decreases approximately inversely as the square root of the energy. This suggests that the energy resolution is limited by the statistics of the photons or the light output

Table 1
Properties of BGO and NaI

	BGO	NaI
Density (g/cm^3)	7.13	3.67
Relative light output	1.0-1.6	10.0
Index of refraction	2.15	1.85
Emission maximum (nm)	480	415
Hygroscopic	no	yes
Decay constant (μ)	300	230

Fig. 1. Pulse height spectrum of 4.43-MeV gamma ray from Pu-Be source using a 7.6 by 7.6 cm BGO crystal.

from the BGO crystal. Above 6 MeV the resolution is limited by the low-energy tail due to escape radiation. Presumably, if the detector had an active shield to reject escape radiation the resolution would be improved. Alternatively, if the detector was collimated so that only the central core of the detector was illuminated, the escape radiation would be absorbed in the crystal and the energy resolution would be improved. For comparison Fig. 4 also shows the energy resolution⁶ of a 25.4 by 25.4 cm collimated NaI detector that has an anticoincidence shield around it to reject escape radiation.

Fig. 2. Pulse height spectrum of 15-MeV-gamma ray from $^{12}\text{C}(p,\gamma)$ reaction at $E_p=14.3$ MeV using a 7.6 by 7.6 cm BGO crystal.

Fig. 3. Pulse height spectrum of 17.7-MeV-gamma ray in 7.6 by 7.6 cm BGO using the $^{12}\text{C}(p,\gamma)$ reaction at $E_p = 1.5$ MeV.

Fig. 4. Full width at half maximum of gamma-ray peaks as function of energy. The solid dots are for a 7.6 by 7.6 cm unshielded and uncollimated BGO crystal. The dashed line is for a 25.4 cm by 25.4 NaI crystal with an active anticoincidence shield collimated to the back face of the detector (Ref. 6).

Absolute efficiency

The absolute efficiency of a 7.6 by 7.6 cm cylindrical BGO crystal with an active anticoincidence shielding or collimation was measured at 15 MeV using the $^{12}\text{C}(p,\gamma)$ reaction and a thick carbon target.⁸ The distance from the target to the center of the BGO crystal was 45 cm. If we use this distance to calculate the solid angle of the detector, we obtain an absolute efficiency of 46% when the peak is fitted to a gaussian line shape. If the peak is integrated to include more of the escape radiation the absolute efficiency is increased to 48%.

For comparison we have measured the absolute efficiency of a 25.4-cm long by 15.2-cm diam actively shielded NaI detector that was collimated to 10 cm at the front face. When we include singles and double-escape radiation, we obtain an absolute efficiency of 43% for the NaI detector.

Time resolution

The time resolution in the gamma ray energy range from 1 to 20 MeV was measured by observing the microstructure of the 800-MeV Proton beam from the Los Alamos Meson Physics Facility (LAMPF) linear accelerator. Each 3.5 ns long macropulse contains micropulses that are less than 100 ps wide and separated by 5 ns. Similar tests were previously reported⁹ using a 7.6-cm-long and 5.1-cm-diam BGO detector coupled to an RCA BA50 PMT. In the present tests the 7.6 by 7.6 cm BGO crystal was coupled to a 12.7-cm-diam Hamamatsu R 1250 PMT. The rise time of the PMT is given as approximately 2.1 ns. The start pulse for the

time-to-amplitude converter (TAC) was obtained from a beam pickoff located in front of the target. We derived the stop pulse for the TAC from the anode output pulse of the PMT using a constant fraction timing discriminator to minimize timing walk. The data were acquired into a 512 by 512 channel two-dimensional array of gamma-ray energy vs time from the start pulse to the gamma-ray event. The time spectra for various energy bins were subsequently projected from the array, fitted to gaussians, and their FWHM were obtained. Figure 5 shows the time spectrum for gamma-ray energies between 10 and 20 MeV. Figure 6 shows a plot of the time resolution (FWHM) as a function of gamma-ray energy for the 7.6 by 7.6 cm BGO as well as the results of Ref. 9. The energy dependence of the time

Fig. 5. Time spectrum of the microstructure of the LAMPF beam for gamma-ray energies between 10 and 20 MeV in a 7.6 by 7.6 cm BGO crystal. The time peaks are separated by 5 ns.

resolution for Ref. 9 decreases approximately inversely as the square root of the energy, while the results with the 7.6 by 7.6 cm BGO are constant with energy suggesting that the time resolution in this case is dominated by factors other than the light intensity.

Discussion

In evaluating the performance of BGO relative to NaI, several additional factors should be considered. Because BGO is more efficient than NaI for the same volume, the same sensitivity can be obtained with a smaller detector. A smaller detector can often be placed closer to a target and achieve a larger solid angle. Since the efficiencies of a 25.4-cm-thick NaI and a 7.6-cm-thick BGO are similar, the count rate in a BGO detector can be greater due to the larger possible solid angle. In addition, since BGO detectors are compact, anticoincidence ray shielding is less important. In cases where a BGO detector does not need

Fig. 6. Full width at half maximum of time peaks as function of energy. The solid circles represent a 7.6 by 7.6 cm BGO coupled to a Hamamatsu R-1250 PHT, the closed circles represent a 7.6-cm-long by 5.1-cm-diam BGO coupled to an RCA 8850 PHT (Ref 9).

an active shield its associated electronics are considerably simpler and less expensive.

For example, in a recent experiment the 17-MeV gamma ray from the $^{12}\text{C}(t,\gamma)$ reaction was detected with both our usual 24.5-cm-long by 15-cm diam NaI detector and a 7.6 by 7.6 cm BGO. Because of the massive active and passive shielding surrounding the NaI detector its distance to the target could not be less than 100 cm, while the distance to the BGO detector was 40 cm and could have been even closer. The product of efficiency and solid angle for the NaI was 0.003 and for the BGO detector 0.01. Since we plan to investigate this reaction with a polarized tritium beam, we will be limited by beam current and will need as much sensitivity as possible. In this case the BGO detector would be at least three times more sensitive than NaI.

In many experiments that detect high-energy gamma rays, the detector is also subject to large neutron fluxes. These neutron fluxes may create backgrounds in the energy region of interest and may also add to the overall count rate in the detector. The calculated cross section for thermal neutron capture in NaI is 2.7×10^{-2} barns/gram, while the cross section in BGO is only 1.4×10^{-2} barns/gram. This factor of 8 reduction in cross section for BGO may significantly reduce backgrounds and the requirements for shielding.

At present the major disadvantage of BGO relative to NaI is its poorer energy resolution. The poor energy resolution in the gamma-ray energy range below 10 MeV is mostly a result of the reduced light output. The reduced light output is due to two factors: (1) the self-absorption of light within the crystal, and (2) the difficulty of coupling the light out of the crystal to a PMT.

Debenzo and Riba¹⁰ measured an attenuation length of 20 cm in a relatively clear sample of BGO. Saxman¹¹ measured an attenuation length of 10

cm in a 7.6-cm-long sample of BGO. With such a small attenuation length it is difficult to attain good resolution in large BGO scintillators for two reasons. First, the overall intensity of the light incident on the photocathode of the PMT is reduced, and second, there is a variation in pulse-height when different regions of the crystal are illuminated. We measured a pulse-height variation of 2% between the front and back of a 7.6 by 7.6 cm BGO using a ^{22}Na source. The effect of self-absorption of light may be reduced if several PMTs view the crystal, or if the surfaces of the crystal are properly graded.

The problem of coupling the light from the crystal to a PMT is basically due to the large index of refraction of BGO. A Monte-Carlo calculation for a 7.6 by 7.6 cm BGO predicts that approximately 40% of the light is trapped within the crystal. This result is in good agreement with the more sophisticated calculations of Derenzo and Riles,¹⁰ which include scattering from bubbles and self-absorption. Derenzo and Riles¹⁰ proposed that more light could be coupled to a PMT if the outside surfaces of the crystal were properly shaped. We are presently investigating two other schemes to improve the light coupling to the PMT. If the output surface of the BGO crystal were coated with a graded index of refraction antireflection coating, this might improve the light transmission. Another method is to couple the BGO to the PMT using a lens. A Monte-Carlo calculation predicts that if a spherical lens with a radius of curvature equal to one half the length of the crystal is used, then up to 95% of the light could be transmitted. Such a lens could be cut into the BGO itself or, to minimize loss of material, the lens could be of the Fresnel type.

The energy resolution above 10 MeV is dominated by the low-energy γ tailing due to escape radiation. This effect may be reduced by surrounding the BGO with an active anticoincidence shield to reject events that do not deposit their entire energy in the crystal. Drake et al.¹ reported an energy resolution of 1.5% at 22 MeV for a 7.6 by 7.6 cm BGO using an anticoincidence shield. This technique, however, usually involves some loss in efficiency.

In summary, BGO scintillators presently provide an attractive alternative to NaI in many applications because of their large efficiencies. It is possible that with further improvements in manufacturing techniques and better methods of light coupling, the resolution may also be improved to equal or exceed that of NaI.

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