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THE RESPONSE OF A 5 cm × 20 cm BGO
CRYSTAL TO ELECTRONS IN THE 150 MeV TO 700 MeV RANGE

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ABSTRACT

A shower detector consisting of two optically coupled BGO crystals (5×10) cm each, was tested with an electron beam in the energy range from 150 to 700 MeV. The BGO resolution obtained for high-energy electromagnetic showers is found to be equivalent to that of NaI.

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1. INTRODUCTION

The detection of intermediate energy γ -rays and electrons (50-1000 MeV) with high efficiency and good energy and spatial resolution is dominated, as in current practice, by lead-glass or scintillators spectrometers, with NaI(Tl) as the mainstay. For the energy range considered here, the energy resolution of NaI(Tl) spectrometers is mostly determined by the fluctuations in energy leakage out of the crystal and the inhomogeneity of the thallium concentration. Good energy resolution was obtained so far by growing large monocrystals of NaI(Tl). However, several factors limit the usefulness of this type of approach. Firstly, for large crystals it is no longer possible to check the uniformity of response of the crystal. Secondly, in the case of an experiment with high multiplicity, or high background, the (volume dependent) counting rates result in pulse pile-up and photomultiplier-gain instabilities, both of which have a negative influence on the energy resolution.

Satisfactory spatial resolution has so far not been achieved with large monocrystals of NaI. A commonly used solution to these problems is to use a large detector composed of many modules. Here the energy resolution depends on the precision of the relative calibration and the energy losses in the inactive material between the modules. As far as the spatial resolution is concerned, several techniques¹⁾ have been developed for determining the entrance point and direction of a photon striking a modular spectrometer by comparing the distribution of energy in the group of affected modules. However, these techniques are confronted with difficulties in the case of overlapping electromagnetic showers, since the lateral expansion of a shower is proportional to the radiation length of the material used, and therefore high density or high-Z materials are preferred in order to keep small the limiting angle for resolving two photons.

Modular shower detectors of high energy and spatial resolution exist and are usually made from NaI(Tl). This material has the disadvantage of having relatively low density and of being highly hygroscopic. Such detectors have therefore to be housed in vacuum-tight vessels and are thus rather clumsy and of a fixed geometrical configuration.

The availability of large BGO crystals ($\text{Bi}_4\text{Ge}_3\text{O}_{12}$) now makes it possible to construct high-energy γ -ray modular detectors. BGO has good conversion and stopping power owing to the high atomic number of bismuth. The ratio of the radiation length of NaI relative to BGO ²⁾ is 2.3. This means a corresponding reduction in the linear dimensions for the same stopping effect and 12-fold volume reduction, significant in the move towards very high-energy particle detection. The BGO is mechanically and chemically durable and is non-hygroscopic, giving it an advantage over many other scintillators with respect to "canning" requirements and geometrical flexibility. In addition, the crystals can be worked mechanically without any special treatment. Finally BGO, in contrast to "impurity activated" scintillators such as NaI(Tl), is a "pure" scintillator and is therefore free from problems associated with non-uniform dopant distribution. The light emitted has been identified with the $^3\text{P}_1 \rightarrow ^1\text{S}_0$ electronic transition within the Bi^{3+} ions³⁾, and spans the wavelength interval from 350 to 650 nm with the maximum at 480 nm. At this wavelength the refractive index is 2.15. Some properties of BGO are listed in Table 1 together with those of NaI. The comparison shows that BGO is in some essential aspects superior to NaI. The relatively low light output is of minor importance for the high energetic electromagnetic showers.

Shower calorimeters of BGO crystals could thus be of much smaller geometrical sizes. The compactness together with the chemical and mechanical insensibility makes such detectors very versatile, flexible, and easy to handle. Therefore, a detector made from BGO crystals can fully exploit the advantages of the modular configuration in γ -ray spectroscopy. This work was undertaken to establish the suitability of BGO in a high-energy shower spectrometer.

2. MEASUREMENTS

The BGO detector was provided by Harshaw Chemie BV-Holland and consisted of two cylindrical BGO crystals with a diameter of 5 cm and a length of 10 cm each. The two crystals were optically coupled to a detector of total length 20 cm, corresponding to approximately 18 radiation lengths, and a diameter of 5 cm corresponding to 4.5 radiation lengths.

Special attention was paid to the light reflectors, so that for a given γ -energy the light output arriving at the photocathode was independent of the interaction point. Although BGO is free of non-uniformity problems, it can trap air bubbles during its growth, and this may well influence the light transmission. The uniformity of the light transmission was measured with a collimated Cs source (661 keV), and the fluctuation was less than $\pm 1\%$ except for the region where the two crystals were glued together. Figure 1 shows the pulse height and the resolution of the detector as a function of the source position on the crystal surface. The energy resolution $\Delta E/E$ was between 14 and 15%.

The performance of the BGO detector was tested in an electron beam at the CERN Proton Synchrotron (PS), for energies ranging from 150 to 700 MeV.

The experimental set-up consisted of the BGO detector and eight lead-glass counters ($8 \times 8 \times 40$) cm³ each (Fig. 2). The beam was defined by a set of plastic scintillation counters. A small counter centred in front of the BGO detector determined the beam size to be ~ 1 cm². A TOF counter system was used in order to separate pions from electrons up to 300 MeV/c momentum. For higher energies, the electrons could be separated from pions because of the different energies deposited in the BGO crystal (Fig. 3).

Above ~ 1 MeV the total counting rates of the BGO detector were continuously monitored and kept at the same level of 10^4 counts per second in all measurements.

The over-all stability and in-beam resolution of the BGO detector were continuously checked with a ¹³⁷Cs source.

The experimental resolution of the BGO crystal (FWHM) as well as the results from Monte Carlo simulations for different energies is shown in Fig. 4. Owing to the small lateral size of the BGO detector used, the energy resolution is determined by the energy leakage out of the crystal.

Because of the small diameter of the BGO detector, the radially escaping part of the electromagnetic shower was rather high. The lead-glass counters (Fig. 2) surrounding the BGO crystal were used in order to select those showers which develop strongly in the forward direction. In order to select such showers, only

events which deposit a rather small fraction f of the incident energy in the lead glasses were accepted, which means that: $E_{\text{Pb-glass}}/E_{\text{BGO}} \leq f$. This constraint condition automatically rejects showers having large lateral dimensions. The resolution of the BGO detector for events which deposited in the lead glasses an energy less than 4% of the incident energy, is shown in Fig. 4. It corresponds in first approximation to the best resolution achieved in these tests. The energy dependence of the FWHM can be expressed by: $\text{FWHM} = (5.5 \pm 0.2)\%/\sqrt{E}$ (GeV).

However, because of the limited resolution and efficiency of the lead-glass for the low-energy tails of the electromagnetic showers, plus the fluctuations allowed by the constraint $f \leq 4\%$ in defining the escaping energy, and because of the momentum spread of the beam, $\Delta p/p = \pm 1.5\%$, the intrinsic resolution of the BGO is certainly better than that shown in Fig. 4.

3. RESULTS

The use of BGO crystals brings about a substantial improvement in the spectroscopy of highly energetic gammas, mainly because of the short radiation length and the mechanical and chemical ruggedness, and in particular the non-hygroscopicity of these crystals.

Although the light output of BGO is inferior to that of NaI(Tl), this is not a disadvantage for highly energetic showers. According to our measurements and to EGS shower calculations²⁾, the energy resolution has turned out to be equivalent to that of NaI.

This provides the possibility of constructing large modular BGO detectors in a much easier and flexible way than NaI systems, providing, in addition, a better spatial resolution for high-energy gammas. This detector shows considerable promise for application in high-energy spectroscopy.

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Table 1

Characteristics of BGO in comparison to NaI(Tl)*)

	BGO	NaI(Tl)
Wavelength of maximum emission (nm)	480	410
Decay constant (ns)	300	230
Scintillation cut-off wavelength (nm)	350	320
Index of refraction at wavelength of maximum emission	2.15	1.85
Density (g/cm ³)	7.13	3.67
Radiation length (cm)	1.12	2.59
Hygroscopic	No	Yes
Relative light output	10	100
Afterglow at 3 ms	0.005%	0.5-5%
LT temperature coefficient of light output (%/°C) at 25 °C	1.0-1.5 Negative	0.22-0.9 Positive

*) Harshaw Chemie technical papers (unpublished)

Figure captions

- Fig. 1 : The BGO uniformity of the light transmission and the energy resolution along the BGO surface.
- Fig. 2 : The experimental set-up. The BGO diameter is 5 cm and its length 20 cm. The triangle shown in front of the BGO crystal is the plastic scintillator defining the beam size.
- Fig. 3 : The BGO spectrum for 400 MeV/c beam momentum.
- Fig. 4 : The energy dependence of the BGO resolution. For comparison, the resolution of a lead-glass block is shown ($\times$).

Fig. 1

Fig. 2

Fig. 3

Fig. 4