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Letter to the Editor

BISMUTH GERMANATE SCINTILLATOR AS A FAST HIGH-ENERGY ION DETECTOR

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The pulse-height response and timing characteristics of bismuth germanate scintillator haven been determined for light and heavy ions (A ≤ 35, $E \lesssim 250$ MeV). Timing resolutions of ≤ 250 ps have been observed.

Bismuth germanate crystals [$Bi_4Ge_3O_{12}$ (BGO)] are now widely employed as high-Z γ-ray detectors [1]. Typical pulse-height resolutions for 1 MeV γ-rays are 10–15% (fwhm) with a time resolution of ca. 1.5 ns (fwhm). Much less is known about the response of BGO to energetic light and heavy-ions although data for electrons [2], neutrons [3], and low-energy ^{1,2,3}H ions [4] have been reported. As expected, both the relative pulse height resolution and the absolute timing resolution appear to improve with increasing energy, the former approaching a few percent, and the latter indicating $\Delta t < 2$ ns at high energies. No data have been reported for ions with $Z > 2$.

We have extended the response measurements of BGO to heavy ions ($Z \leq 17$, $E \lesssim 300$ MeV) and energetic light-ions (^{1,2,3}H, ^{4}He, $E \lesssim 150$ MeV). The latter and some of the former include timing information. The heavy-ion response data were obtained at the Brookhaven National Laboratory (BNL) tandem Van de Graaff accelerator using a magnetic spectrometer and the techniques described in ref. [5]. Timing information was obtained at the Argonne National Laboratory (ANL) superconducting heavy-ion linac using elastically scattered ^{28}Si ions $E \leq 250$ MeV with the linac rf used as a trigger signal ($\Delta t_{beam} \leq 150$ ps). The BGO crystal used for pulse-height response measurements was 25 mm thick by 19 mm diameter [6] mounted directly on an RCA 4517 photomultiplier tube (PMT) and covered with a thin, opaque evaporated aluminum coating (100 μg/cm^2). The response was measured relative to a ThC′ alpha-particle signal ($E_\alpha = 8.78$ MeV). The same crystal was also calibrated [4] at the University of Colorado cyclotron using a spectrometer with low-energy light ions ($E < 50$ MeV). This crystal along with a smaller crystal (15.9 mm diameter by 4.6 mm thick covered by a 4 μm aluminized mylar) was used at ANL for timing measurements.

The response determined for the 25 mm thick BGO crystal is shown in figs. 1 and 2. As with other scintillators [5], the light output is a function of A, Z and E and appears to saturate for highly ionizing particles. However, the relative response between various ions (Z)

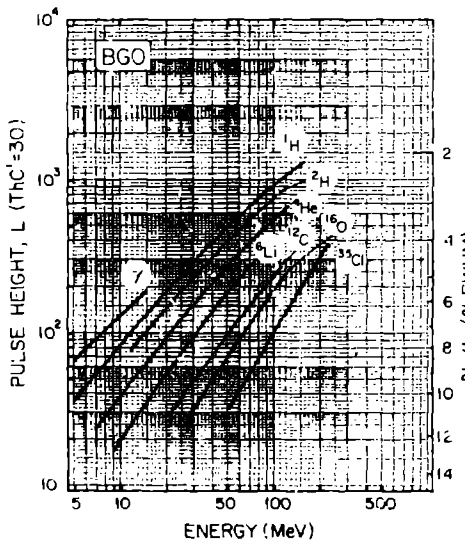

Fig. 1. Deduced light output of BGO, L, and typical pulse height resolution, $\delta L/L$, vs energy for the ions indicated (8.78 MeV ThC′ α-particles: $L \equiv 30$). The data were obtained from crystals 25 mm thick × 19 mm diameter and 150 mm thick × 51 mm diameter.

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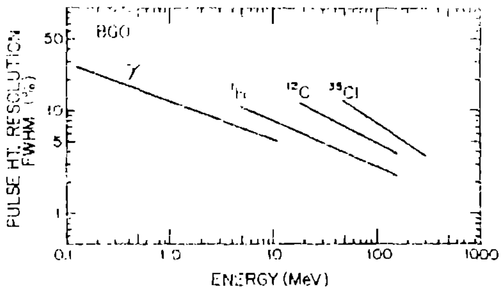

Fig. 2. Pulse-height resolution, $\delta L/L$, observed for various ions (fig. 1) compared with that observed for γ-rays [1,6].

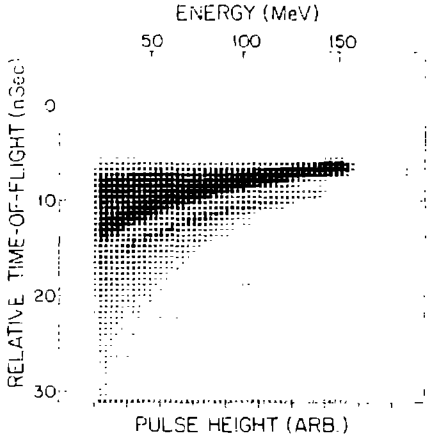

Fig. 3. Time-of-flight (BGO - rf) for a 1 m flight path vs light output for ^{1,2,3}H and ^{3,4}He particles from p + ^{9}Be, $\theta = 30°$, $E_p = 150$ MeV. The crystal was 51 mm diameter × 150 mm thick collimated to 20 mm diameter with 50 mm of lead.

differs from plastic and falls off faster with decreasing energy for BGO. Typical pulse-height resolutions ($\delta L/L$ – which is *not* necessarily the same as the energy resolution, although similar) are indicated in figs. 1 and 2. As expected $\delta L/L$ is related to the photon statistics with $\delta L/l \propto L^{-1/2}$, approaching a few percent for $E \geq 100$ MeV (fig. 1).

Finally, high-energy ^{1,2,3}H and ^{3,4}He ions were detected from the reactions ^{1,2}H + p, ^{9}Be + p and ^{12}C + p at $E_p = 150$ MeV using the Indiana University Cyclotron Facility (IUCF) with a hermetically sealed 51 mm diameter by 150 mm thick BGO in-line assembly [6] with a fast PMT (RCA 8850), located at a 3.1 mm thick aluminum window ($\theta = 30°$) outside a large scattering chamber. The detector, situated one meter from the target, was collimated to $\leqslant 2$ cm diameter by 5 cm of lead. The IUCF beam is known to have a narrow time-width, typically $\Delta t_{beam} \lesssim 400$ ps at $E_p = 150$ MeV. Thus, the BGO timing could be initially measured with respect to a cyclotron rf trigger. These measurements indicated a BGO time resolution $\lesssim 600$ ps for $E_p = 150$ MeV and permitted a direct separation of ^{1,2}H and ^{4}He using the BGO and rf timing signals. A two-dimensional spectrum of light output versus particle time-of-flight (TOF) is shown in fig. 3. The background observed below the main particle groups (at constant TOF) is attributed to nuclear reactions in the crystal (ca. 10%) and is similar to that observed for NaI(Tl).

Particle spectra, gated from the two-dimensional spectrum, are shown in figs. 4 and 5. The response data are included in fig. 1. The best pulse-height resolution for this detector was ca. 1.5% fwhm at $E_p \approx 150$ MeV (^{12}C + p, fig. 2). The resolution appears to be better than that observed for other particles at comparable energies [1–3] and comparable to that of large NaI crystals [7]. (Since BGO is extremely sensitive to γ-rays, the resolution depends on the γ-ray background. The measurements reported here were done at low beam intensities and count rates.)

Particle TOF spectra, gated by light output (energy)

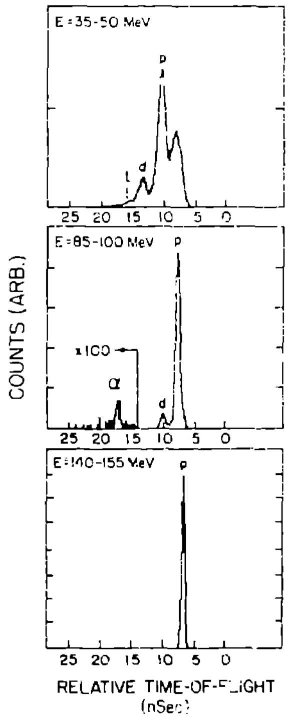

Fig. 4. Projected time-of-flight spectra (fig. 3) for gates set on the energy regions indicated.

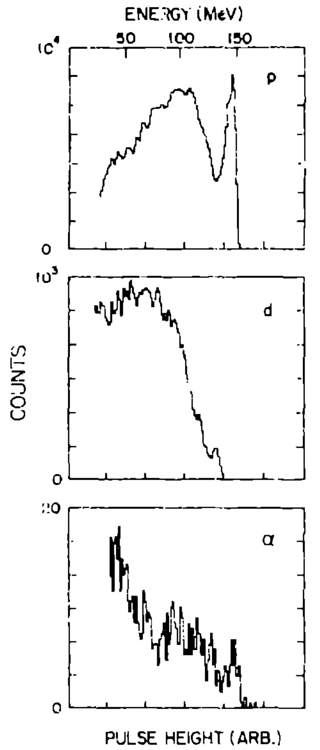

Fig. 5. Proton (*top*), deuteron (*middle*), and alpha-particle spectra (*bottom*) obtained by gating on TOF vs light output (fig. 3). (Some levels are unresolved doublets or broadened by kinematic effects.)

are shown in fig. 4. The time resolution appears to degrade with decreasing light output, even after removing the time-spread due to the energy width of the gating bin.

Since the timing resolution observed was quite good (≤ 0.5 ns fwhm), further tests were done by inserting a small NE 102 plastic scintillator (2 cm diameter) coupled to an RCA 8575 PMT directly in front of the BGO crystal behind the lead collimator. Both the BGO (PMT anode-signal rise-time ≈ 8 ns) and the plastic scintillator (PMT anode-signal rise-time ≈ 3 ns) anode outputs were sent to a constant-fraction discriminator and then a time-to-analog signal converter which could be gated by the BGO light output (i.e., particle energy). In this manner timing resolutions of ≤ 400 ps (fwhm) were observed for $E_p \geq 100$ MeV. A similar improvement in timing for energetic protons has been observed in NaI crystals [7]. Tests at ANL using a 240 MeV ^{28}Si beam and a small crystal (4.6 mm thick) indicated a BGO timing resolution (after removing the 240 ps beam time spread) of less than 250 ps (fwhm). It appears that BGO will be useful in fast timing applications for both light and heavy ions with $\Delta t = 250$–600 ps (fwhm), depending on the crystal geometry, light output, PMT, etc. An advantage of BGO relative to plastic is that due to its high density (7.1 g/cm^3), a smaller crystal can be used which minimizes the time dispersion due to geometrical effects. Also, it is less sensitive to fast neutrons.

Thus with sufficient incident energy (i.e. high light output) BGO is capable of modest pulse-height resolution and fast timing, the latter approaching that of plastic and superior to NaI(Tl). The inferior timing resolution reported [1] at low energies (ca. 1.5 ns) is likely the result of poor photon statistics due to the low light output of BGO (10% of NaI), rather than the intrinsic limitations of BGO. Timing and pulse-height resolution better than that reported here is likely at higher energies and with a more careful selection of the PMT, crystal geometry, etc. Also, Cherenkov light may become important as $\beta = v/c \to 1$ since $n = 2.1$ for BGO.

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