Bismuth Germanate as a Potential Scintillation Detector in Positron Cameras

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Timing and energy resolutions of the bismuth germanate ($Bi_4Ge_3O_{12}$) scintillation crystals were studied, with particular respect to a positron-camera application. In comparison with the NaI(Tl) system, the detection efficiency for annihilation radiation is more than triple, and coincidence detection efficiency is more than ten times as good. This paper explores the properties of the new scintillator material and their bearing on the spatial resolution and the efficiency of coincidence detection in positron cameras with stationary ring detectors.

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Radionuclide tomography using positron emitters makes possible the performance of dynamic studies in addition to anatomic delineation of the patient (*1,2*). Clinical acceptance of these systems has been limited partly due to the poor spatial resolutions of these scanners compared with the currently available transmission CT scanners (*3*). An attempt has been made to obtain high spatial resolution by the use of many small crystals [e.g., 288 NaI(*Tl*) crystals 8 mm wide] in a stationary close-packed ring (*4*). When the size of the crystals is reduced, however, there is increased probability that an incident photon will interact in more than one crystal, and the coincident detection efficiency is reduced by the rejection of such events. The spatial resolution in ring systems (*1,2,4*) is limited basically by the crystal size, both in terms of coincidence-detector pair resolution (40% of the crystal-to-crystal distance) and sampling. Our experience with the UCLA CRTAPC system (*1,2*) indicates the near-optimum crystal size for this instrument to be 2 cm (diameter) × 3.8 cm (length). Crystals that are narrower than this may improve resolution only near the center of the ring. Gamma emissions that are off-axis can penetrate several crystals before interacting, which decreases spatial resolution. Because of these fundamental difficulties with NaI(*Tl*) detectors, we have searched for scintillators that have a better stopping power and have good enough light output and scintillation-decay characteristics to make them suitable for positron-camera applications. Among the high-Z scintillators, bismuth germanate (BGO) seems to fulfill the necessary requirements (*5*).

In this paper we report the results of a study comparing BGO with NaI(*Tl*) for positron-camera applications, in particular to ring systems, and the possibility of constructing a stationary ring positron camera having a spatial resolution in the neighborhood of 3-mm FWHM.

EFFICIENCY

The detector efficiency plays a crucial part in the spatial resolution of a ring positron camera. The *true detection efficiency* of the detector includes its ability to discriminate against the photons due to Compton scattering in the subject. This contribution for a NaI(*Tl*) detector of 2 cm (diameter) × 3.8 cm (length) is illustrated in Fig. 1A. The lower spectrum is recorded with no scattering medium present other than air, while the upper one includes 11.5 cm of water as a scattering medium. Clearly, at least 50% of all counts (the ordinate is linear) are due to Compton-scattered photons arriving at the crystal face, and these counts would contribute to erroneous coding. This contribution can be reduced by setting

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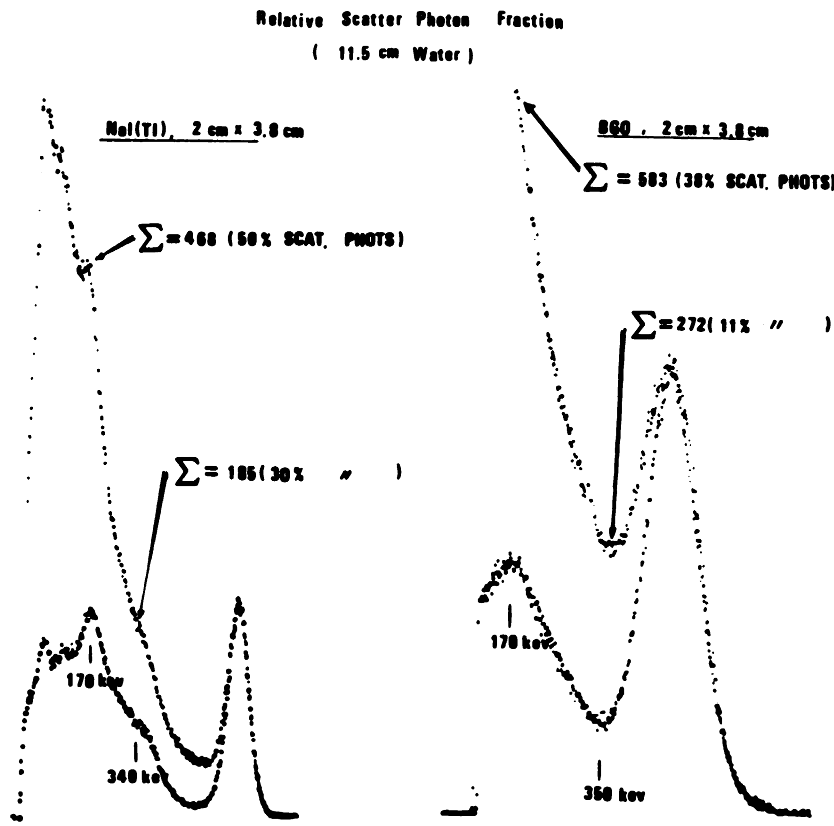

FIG. 1. Relative scattered-photon fractions observed with NaI(*Tl*) and BGO, with and without scatter medium. Crystal size used in both is 2-cm diam × 3.8-cm length.

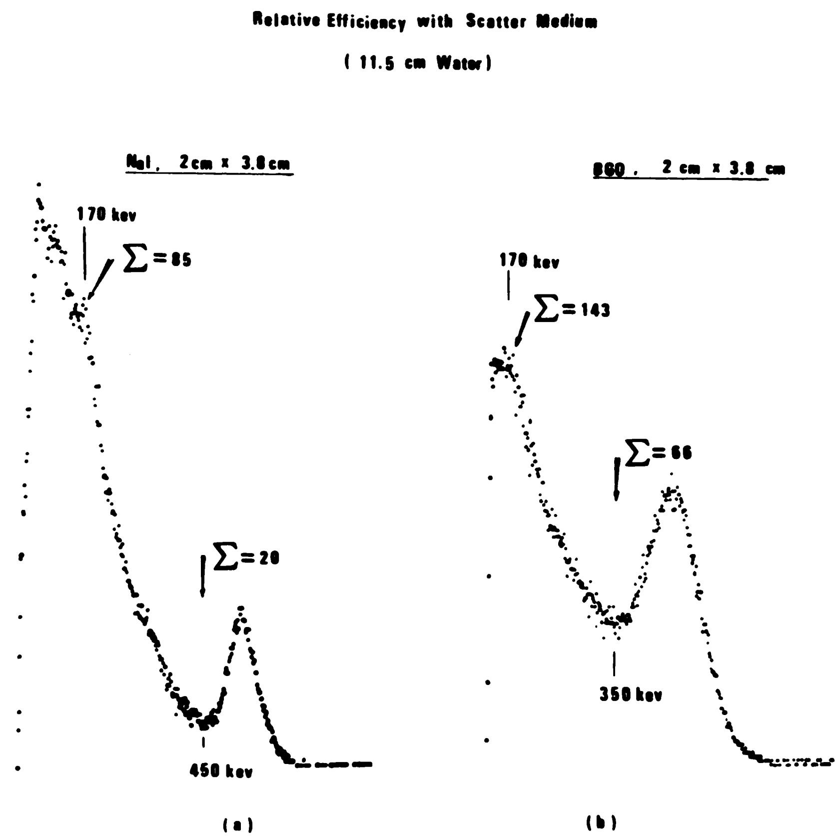

FIG. 2. Relative counts (same source intensity, distance, and counting time) of NaI(*Tl*) and BGO with a scattering medium of 11.5 cm water. With photopeak counts alone, the count ratio for BGO to NaI(*Tl*) is ~3.3.

the low-level energy discrimination (E_L) at approximately 450 keV, thus using only the full-absorption peak. In doing so, one faces the problem of too few counts, since the photofraction is rather small about 24% of the counts above E_L-170 keV (see Fig. 2A). The 2- × 3.8-cm NaI(*Tl*) crystal is considered relatively large for a stationary ring positron-camera system. The crystal should really be narrower in order to improve the spatial resolution, but the dilemma then faced is that with the reduction in crystal size there is a proportionate decrease in the total-absorption efficiency and an increase in the escape of Compton photons scattered within the crystal. Hence, this size represents a compromise between resolution and efficiency, and with this choice of crystal dimensions the spatial resolution is limited to 10-mm FWHM.

Improvements in resolution and efficiency can be achieved by choosing a scintillator having an inherently better photofraction than NaI(*Tl*)—so that one can utilize the photopeak to discriminate against tissue-scattered photons and yet maintain a high enough detection efficiency. In Fig. 3 the spectra for bismuth germanate (BGO) and NaI(*Tl*) are compared for identical crystal sizes, the same source strengths, and the same source-to-crystal geometry (NaI in Fig. 3A and BGO in 3B). The photofractions for the two scintillators are compared in Table 1. The spectra for BGO with 11.5 cm of water as a scattering medium are shown in Figs. 1B and 2B. Table 2 illustrates the relative advantage of BGO over NaI(*Tl*) *re* photofraction gain with a scattering medium. Whether with or without a scattering medium, BGO photopeak efficiency is at least three times that of NaI(*Tl*).

Since the tissue-scatter contribution to coincidence counting is a problem, we have compared this contribution at two settings of the low-level discriminator (see Table 3). Obviously, the lowest scatter

TABLE 1. PHOTOFRACTIONS FOR NaI(*Tl*) AND BGO*

E_L	100 keV	170 keV	350 keV
NaI(*Tl*)	2681 counts f = 0.27	1860 counts f = 0.39	723
BGO	4167 counts f = 0.60	3596 counts f = 0.70	2506
Counts BGO / Counts NaI(*Tl*)	1.55	1.93	3.47

* 2-cm diam × 3.8-cm length.

TABLE 2. PHOTOFRACTIONS OF BGO AND NaI(*Tl*) WITH 11.5 cm OF WATER SCATTERING MEDIUM

	NaI(*Tl*)	BGO	BGO/NaI
Counts in photopeak	20	66	3.3
Counts above 170 keV	85	143	1.7
Photofraction $\frac{a}{b}$	24%	46%	

TABLE 3. SCATTER-PHOTON CONTRIBUTION AT TWO E_L SETTINGS

E_L	170 keV	Photopeak	Photopeak fraction at E_L = 170 keV
NaI(*Tl*)	50%	11%	24%
BGO	38%	11%	46%

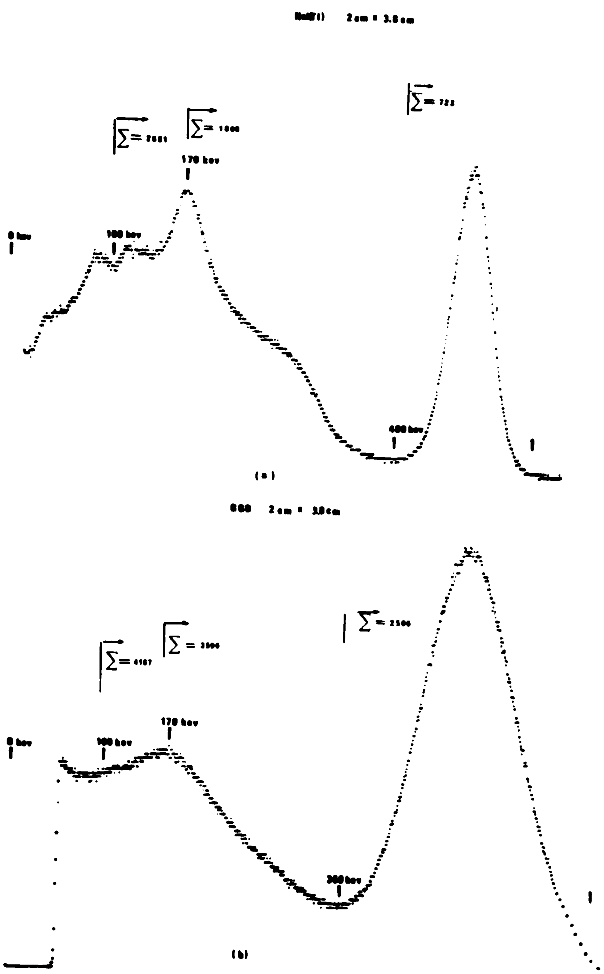

FIG. 3. Relative counts with several energy threshold settings. Σ indicates the total counts above the threshold indicated.

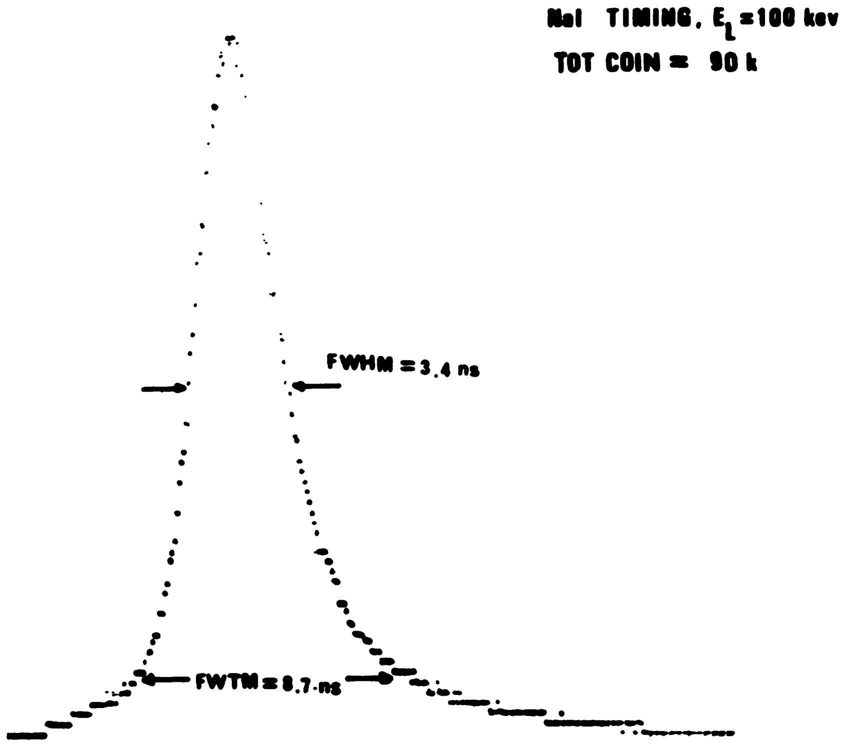

FIG. 4. Typical timing spectrum for NaI(*Tl*)–NaI(*Tl*) crystals (2-cm diam × 3.8-cm length). NaI(*Tl*)-plastic scintillator (= NE 111) timing spectrum measured was ~2.5 nsec.

contribution is achieved by selecting only the photopeak counts for data processing (only 11% contribution in either case) and with this selection the BGO detector provides at least three times the efficiency of NaI(*Tl*). Since coincidence detection efficiency is proportional to the square of the single-crystal efficiency, this translates into a gain of 10–12 in coincidence detection efficiency.

The 50% tissue-scatter contributions for NaI(*Tl*) are too high, and the corresponding size (2-cm diam × 3.8-cm length) is too large for a high-resolution stationary-ring positron camera. Reduction in crystal size would only tend to increase this scatter contribution while reducing the photopeak counts; hence the suggested way out of this dilemma is to use BGO whereby one could reduce the crystal size, use the photopeak only, and yet have acceptable counting efficiency, providing the timing resolution is acceptable.

TIMING

Timing is the ultimate limiting factor for true-to-random coincidence ratio, so a careful study has been made comparing the timing resolution of BGO and NaI(*Tl*) in positron-camera applications. Braunsfurth and Körner (*6*) report a time jitter distribution with a FWHM of 1.3 nsec for 511-keV photon pairs in NaI(*Tl*). The time resolution in NaI(*Tl*) depends upon the same random fluctuations that determine the photopeak energy resolution, and for the 2- × 3.8-cm crystal considered for this study the timing spectra for a NaI(*Tl*) pair is shown in Fig. 4, where FWHM = 3.8 nsec and FWTM = 8.7 nsec.

Figure 5 shows that in our samples of BGO (2 × 3.8 cm) the timing resolution for a pair appears to be a factor of two worse: 6.8 and 14.5 nsec for FWHM and FWTM. In both cases, Ortec constant-fraction discriminators and RCA 8575 photomultipliers were employed, and the electronic setup for timing measurements was the familiar fast–slow system described in Ref. 7. Given present-day electronic components and circuitry, coincidence resolving times of 10–20 nsec seem well within acceptable limits.

DISCUSSION

Improvement in spatial resolution with an acceptable coincidence counting efficiency for stationary ring positron cameras with NaI(*Tl*) detectors seems to be at an impasse. For reasons stated earlier, the 2-cm diam appears to be the best compromise for systems such as the UCLA CRTAPC.

The consideration of BGO for the detector raises the possibility of reducing the crystal size to improve spatial resolution and yet maintain usable efficiency even while using the photopeak alone to discriminate against tissue scatter. Thus, it may be feasible to construct a positron camera with BGO detectors (6–7-mm width) with spatial resolutions in the neighbor-

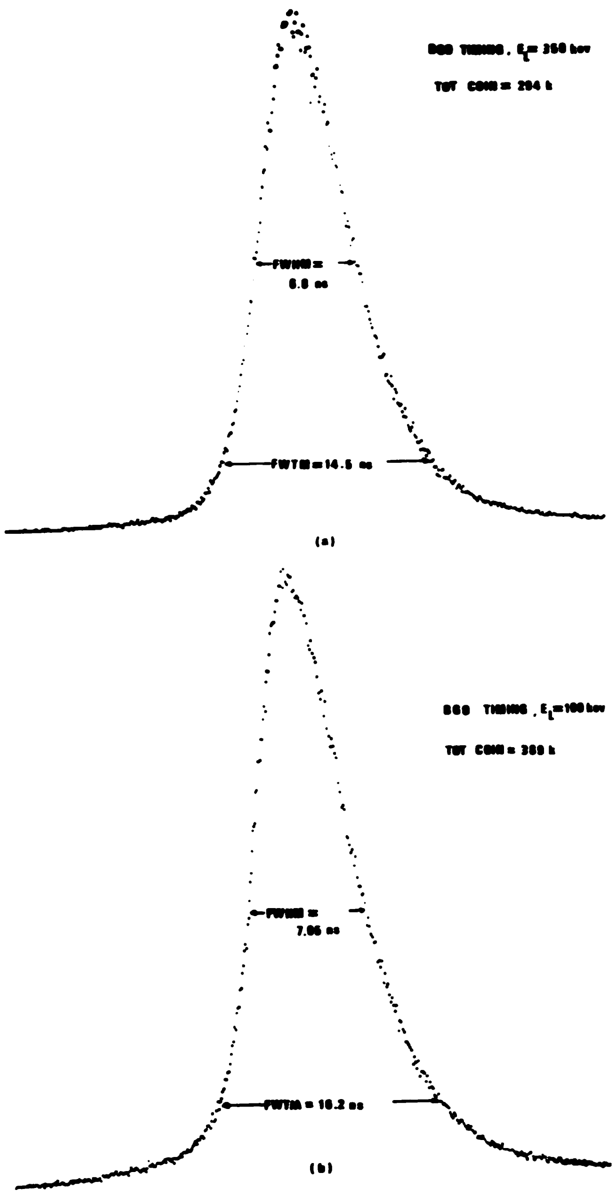

FIG. 5. BGO–BGO timing spectra measured with two different energy windows. FWHM and FWTH appear about a factor two worse than with NaI. Performance, however, is still well within the acceptable limit for practical coincidence resolving time.

hood of 3-mm FWHM and yet to have nearly the same individual detector efficiency as is provided in the CRTAPC system. This would increase the total efficiency proportionately and would make the instrument competitive in resolution with the present-day CT transmission scanners.

The scintillation properties of bismuth germanate and its merits as a high-Z scintillator have been discussed by Nestor and Huang (*5*). Compared to NaI(*Tl*), BGO has a higher photoelectric cross section, twice the density (7.13 g/cc), a comparable scintillation decay constant (0.3 μsec), and is relatively inert and nonhygroscopic. It is evident that with these properties, BGO should be a very useful detector for many nuclear medicine applications. BGO offers three times the detection efficiency of NaI(*Tl*), with acceptable timing characteristics. Since the introduction of BGO is relatively new, its low light output (8–10% compared to NaI(*Tl*) at 662 keV) reflects the current state-of-the-art in material purification and growth of bismuth germanate. It may be speculated that with continuing demand for this scintillator, a better understanding of the manufacturing problems would lead to a material with higher light output and a consequent improvement in energy and time resolution.

The data reported on efficiency and timing characteristics of BGO have not been available heretofore, and with the current interest in this scintillator for computer-assisted tomographic applications, these data become timely and useful.

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