TIMING PROPERTIES OF BGO SCINTILLATOR

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Light pulse shape, number of photoelectrons per energy unit and obtainable time resolution were studied with a 2 cm diameter and 3 cm high BGO scintillator coupled to an XP 2020 photomultiplier and compared with similar measurements on NaI(Tl) crystal.

The observed time resolution of the time spectrum, fwhm equal to 1.3 ns and fwtm equal to 3.5 ns measured with one BGO crystal in coincidence with a CsI scintillator for a 60Co source and the energy threshold set at 100 keV showed that BGO scintillator can easily be used in coincidence experiments.

Despite the low light yield, equivalent to 550 photoelectrons per 1 MeV, the time resolution of BGO crystal is only a factor of two worse than NaI(Tl) scintillator. It seems to be associated with the faster initial decay of the light pulse from the BGO crystal, as well as, with the very low afterglow which permits the BGO to work with the true triggering on the first photoelectron which is almost impossible in timing with NaI(Tl) scintillators.

The fast component, with a decay time constant equal to 60 ns preceding the known decay with the time constant equal to 300 ns, was found by observing the light pulse shape using the single photon method.

1. Introduction

A growing interest in possible applications of bismuth germanate (BGO) scintillators in different experiments, which very often require fast timing, prompted this detailed study of the time resolution obtainable with these crystals. BGO has the highest efficiency for γ-ray detection of all known detectors, 3 times that of NaI(Tl) crystal for 1 MeV γ-rays [1] thus making BGO scintillators very attractive in several applications. Recently, new positron tomography systems have been designed mainly employing BGO crystals as detectors of annihilation quanta [2,3].

The properties of a BGO scintillator have been studied by Nestor and Huang [1]. They have shown that the light response of the BGO crystal varied linearly with γ-ray energy, E, and that the energy resolution varied as $E^{-1/2}$. An 8% pulse height relative to NaI(Tl) crystal with 15% resolution has been observed under excitation by 662 keV γ-rays from a $^{137}$Cs source. The light pulse shape measured by means of the single photon method displayed a single exponential decay with a time constant of 0.3 μs beyond the first 50 ns of the decay.

The possibility of the application BGO crystals in coincidence measurements has been studied recently by Cho and Farukhi [4] with particular emphasis on the use of BGO in positron tomography. The measured time resolution, however, cannot be considered as an ultimate one. The fwhm of the time spectrum measured with two BGO crystals coupled to RCA 8575 photomultipliers was equal to 6.8 ns for 511 keV full energy peak accepted in the side channels. The fwhm of the time spectrum measured in the same conditions with NaI(Tl) crystals was equal to 3.4 ns, far larger than previously published values [5–8]. As the light yield of BGO crystals is below 10% of that produced by NaI(Tl) scintillator and the decay time is slightly longer than that of NaI(Tl) [1] a time resolution for 511 keV γ-rays can be expected, which is comparable with that measured with the NaI(Tl) crystals for γ-rays with energy equal to 30–50 keV, see refs. 6–8. Thus we can predict a time resolution for a BGO scintillator for 511 keV full energy peak in the range of 1 to 3 ns depending on the crystal size.

The aim of this work was to study the timing properties of the BGO scintillator in comparison with

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NaI(Tl) crystal. Light pulse shapes and numbers of photoelectrons per energy unit lost by γ-rays in the scintillators were measured as factors determining the time resolution obtainable with every scintillator. Time spectra measured with both the scintillators for the same range of light yield are discussed in terms of the Post and Schiff theory [9]. The importance of the very low afterglow of BGO scintillator in timing applications is pointed out.

2. Experimental

All the studies were performed with a BGO crystal delivered by “Harshaw”. A 2 cm diameter and 3 cm high scintillator was coupled to an XP 2020 photomultiplier. The energy resolution measured for 662 keV γ-rays from a 137Cs source was equal to 15.5%. Fig. 1 presents the energy spectra of γ-rays from 137Cs, 22Na and 57Co sources. Note the very high peak-to-total ratio. For 662 keV γ-rays it was equal to 59% thus significantly higher than that observed for 3/4” × 3/4” NaI(Tl) crystals [10]. The NaI(Tl) crystal, 1/4” diameter and 1” high, was delivered by Quartz and Silice. A 7.7% energy resolution was measured for 662 keV γ-rays, coupling the scintillator to the XP 2020 photomultiplier.

Light pulse shapes from BGO and NaI(Tl) crystals were measured by means of the single photon method [1]. As the scintillators were coated with a diffuse reflector a separate scintillator technique was applied to the single photon method following ref. 12. The arrangement used in the experiment is shown in fig. 2. A reference signal was produced by a separate scintillation counter. A 2.3 cm diameter and 1.8 cm thick CsF crystal scintillator was coupled to the XP 2020 photomultiplier. It ensured both a high efficiency for γ-ray detection and the high time resolution of the reference counter [13]. The investigated scintillator was irradiated from the side by γ-rays from 22Na source. The time spectrum of coincidences between 511 keV annihilation quanta accepted in the side channel of the reference counter and single photons detected by C31024 photomultiplier was measured. Both the geometry and the 2 cm thick lead collimator at the C31024 photomultiplier photocathode enabled avoidance of false coincidences due to the detection of γ-rays in the photomultiplier window via the Cherenkov effect. A good pulse height resolution for single photoelectrons on the C31024 photomultiplier ensured true single photon detection. It was achieved by an adjustment of the solid angle under which light from the scintillator was viewed by the CsF photomultiplier. Moreover, a 50% wide energy window in the side channel was set at the maximum of the single photoelectron peak. The time spectra were measured with a typical slow-fast arrangement. The fwhm of the prompt time spectrum of the system measured with a LED light pulser was equal to 300 ps.

All the time resolution studies of BGO and NaI(Tl) crystals were performed with reference to the CsF scintillator coupled to the XP 2020 photomultiplier. Recent study [13] of the CsF crystals timing properties has shown a time resolution comparable with that measured before with plastic scintillators. A fast–fast timing system was used in the study with the energy selection done by arming discriminators inside the time pick-off units. A simple constant fraction discriminator, following ref. 14 was used with the CsF counter. For BGO and NaI(Tl) counters the same unit was modified into a leading-edge discriminator with a very low threshold. It ensured the possibility of triggering by the first photoelectron. The dead time of
the discriminator was increased to about 3 μs to avoid the multitriggering associated with the low number of photoelectrons and slow decay time of the pulses.

3. Results

3.1. Light pulse shape study

Fig. 3 presents a comparison of the light pulse shape from BGO and NaI(T1) crystals. Note the large difference in the decay shapes of the pulses. The main component of the BGO pulse decays with a time constant equal to 300 ns which agrees well with the previous measurement performed by Nestor and Huang [1]. The initial decay, however, is faster with a time constant equal to about 60 ns. The intensity of the fast component is only about 10% of the total light but it increases the pulse height by a factor of 1.5. In contrast, the faster decaying NaI(T1) light pulse with the very well known time constant of 230 ns has a much slower initial decay. This has been observed in several studies [7,15] but has not been considered in an interpretation of timing with NaI(T1) crystals except in ref. 7.

![Fig. 3. Comparison of the light pulse shapes from BGO and NaI(T1) crystals measured by means of the single photon method. Note the large difference in the initial decay of both the pulses.](image)

Fig. 4 presents the initial part of the BGO light pulse shape to observe rise time of the pulse.

![Fig. 4. Initial part of the BGO light pulse shape to observe rise time of the pulse.](image)

3.2. Photoelectron yield

The number of photoelectrons per energy unit produced by the BGO and NaI(T1) scintillators in the XP 2020 photomultiplier was determined by a method described by Bertolaccini et al. [17]. The number is measured directly by a comparison of the position of the mean value of the single photoelectron pulse height distribution which determines the gain of the photomultiplier and the characteristic point in the energy spectrum of the detected γ-rays. To reduce the dynamic range of the pulse height between pulses due to the light from scintillator and single photoelectrons, the photoelectrons yield was determined for γ-rays with low energies. For the BGO scintillator it was done with a $^{57}$Co source for 122 keV γ-rays full energy peak and for the NaI(T1) crystal with $^{137}$Cs source for 31.6 keV K X-rays peak.

Table I contains data on the photoelectron yield of the BGO and NaI(T1) scintillators measured in the course of this work and that of the CsF crystal taken from ref. 13, determined, however, with the same photomultiplier.
Table 1

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>N/MeV</th>
</tr>
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<tbody>
<tr>
<td>BGO</td>
<td>550</td>
</tr>
<tr>
<td>NaI(Tl)</td>
<td>9000</td>
</tr>
<tr>
<td>CsF b)</td>
<td>450–540</td>
</tr>
</tbody>
</table>

a) Measured with an XP 2020 photomultiplier.
b) See ref. 13.

It is interesting to note that the energy resolution of the BGO crystal is determined mainly by the statistics of photoelectrons. The calculated value equal to 14.2% for 662 keV is close to the measured value equal to 15.5%. It reflects the high homogeneity of the crystal and the weak self-absorption of the light. The above conclusion seems to be of importance considering an application of the BGO scintillator in an anticompton arrangement with a Ge(Li) detector.

3.3. Time resolution study

The time resolution obtainable with slowly decaying scintillators such as NaI(Tl) and BGO is limited primarily by the statistics of photoelectron production. The time resolution imposed by this effect alone was calculated by Post and Schiff [9]. The time spread of the light collection process in scintillators and the transit time jitter of photomultipliers impairs the time resolution of the measured spectra. It was proved [6–8], however, that the slope of the time spectra measured with NaI(Tl) crystals for energies below 100 keV can be discussed in terms of the Post and Schiff theory. Particularly, for triggering by the first photoelectron it is equal to

\[ T_{1/2} = 0.693\tau/N, \]

where: \( T_{1/2} \) is the slope of the time spectrum; \( \tau \) is the decay time constant of the scintillator; and \( N \) is the number of photoelectrons.

A comparison of time resolution measured for the same energy lost in BGO and NaI(Tl) crystals by γ-rays seems to be of some use as a test of the timing properties of both the crystals. An expected difference in the time resolutions is associated mainly with the large difference in the light yield. Therefore, the primary comparison presented below was performed for a similar range of light level as produced by both the scintillators. Thus, the time resolution measured for high energy γ-rays detected by BGO was compared with that measured for X-rays detected by

![Fig. 5. Time spectra measured with the BGO crystal in coincidence with CsF scintillator for full energy peaks from \( ^{60}\text{Co} \) (1.175 and 1.33 MeV) and \( ^{22}\text{Na} \) (511 keV) sources.](image)

![Fig. 6. Time spectrum measured with NaI(Tl) scintillator for 31.6 keV K X-rays from \( ^{137}\text{Cs} \). Note that the studied sample of NaI(Tl) crystal produces for 31.6 keV energy the same number of photoelectrons as does BGO crystal for 511 keV.](image)
NaI(Tl) crystal. It was found particularly that the NaI(Tl) crystal tested excited by 31.6 keV K X-rays from a $^{137}$Cs source produce the same number of photoelectrons as the BGO scintillator excited by 511 keV annihilation radiation.

Fig. 5 present the time spectra measured with a BGO crystal in the stop channel and a CsF crystal in the start channel. The 511 keV and both 1.175 MeV and 1.33 MeV full energy peaks from $^{22}$Na and $^{60}$Co sources, respectively, were accepted in the side channels of both the counters. Fig. 6 shows the time spectrum measured with the NaI(Tl) crystal in the stop channel detecting 31.6 keV K X-rays from a $^{137}$Cs source in coincidence with K-electron conversion detected in NE 111 plastic scintillator. Note the better time resolution and the faster slope of the time spectrum as measured with the BGO crystal for 511 keV $\gamma$-rays than that observed with the NaI(Tl) scintillator. As any influence of the reference counter on the time spectra can be ignored in both cases, it seems to reflect a difference in the light pulse shape presented in section 3.1.

It is difficult, however, to use eq. (1) to discuss quantitatively the slopes of the measured time spectra. The decays of both the pulses are complex and do not exhibit a single decay time constant as is assumed in the theory presented by Post and Schiff [9]. Therefore, the problem was reversed and the so-called “effective decay times” of the BGO and NaI(Tl) pulses were calculated. It will represent the mean rate of photoelectron production seen by a timing unit. Rewriting eq. (1) as follows:

$$\tau_{ef} = N T_{1/2}/0.693,$$

we can calculate the effective decay time constant for both measurements performed with BGO for $^{22}$Na and $^{60}$Co sources, see fig. 5, as 250 ns and 260 ns, respectively. For NaI(Tl) we can find a value equal to 312 ns. This confirms the discussion concerning the speed of the light pulses from BGO and NaI(Tl) scintillators as given in section 3.1.

Fig. 7 presents the time spectrum measured with the BGO crystal for a $^{60}$Co source with the energy threshold set at 100 keV. The main peak of the spectrum with a fwhm equal to 1.3 ns is followed by a late tail with a mean slope of $T_{1/2} = 1.5$ ns associated with the low energy events. Full widths at $1/10$ and $1/100$ marked on the spectrum equal to 3.5 ns and 9 ns, respectively are quite good for a lot of coincidence experiments. Note that the above measurement was performed with a BGO crystal having an efficiency for $\gamma$-ray detection comparable with that of a $3" \times 3"$ NaI(Tl) scintillator.

Data on the time resolution measured with the BGO and NaI(Tl) scintillators for different ranges of $\gamma$-ray energy are collected in the table 2. For measurements with a large dynamic range of energy values of fwtm are given too.

Relatively good time resolutions of the BGO crystal in comparison with those of the NaI(Tl) scintillator are also associated with the first photoelectron triggering used which in turn is practically very limited for NaI(Tl) crystals. A very high number of single photoelectron and even multielectron pulses are produced by the phosphorescence of NaI(Tl) scin-

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>BGO fwhm (ns)</th>
<th>BGO fwtm (ns)</th>
<th>NaI(Tl) fwhm (ns)</th>
<th>NaI(Tl) fwtm (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{60}$Co</td>
<td>1.05</td>
<td>1.3</td>
<td>0.8</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>&gt;1000</td>
<td>1.9</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>$^{22}$Na</td>
<td>2.1</td>
<td>4.4</td>
<td>0.9</td>
<td>2.0</td>
</tr>
</tbody>
</table>

$^a$ Measured in coincidence with CsF scintillator in the reference counter.
4. Conclusions

The present study has shown that BGO scintillator can easily be used in coincidence experiments. Despite the fact that the light yield of the BGO crystal was equal only to 6% of that measured for NaI(Tl) scintillator, the time resolutions were worse by only a factor of two. This seems to be associated with a faster initial decay of the light pulse from BGO crystal, as well as, with a very low afterglow of the BGO, which permits it to work with true triggering on the first photoelectron, which in turn is almost impossible in timing with NaI(Tl) scintillators.

The fast component with a decay time constant equal to 60 ns preceding the well-known decay with a time constant equal to 300 ns was found by observing the light pulse shape using the single photon method.

The fact that the energy resolution of BGO crystal is determined mainly by photoelectron statistics suggests that the crystal exhibits a high homogeneity and weak light self-absorption. Thus large volume BGO scintillators may easily be used in different applications, e.g. an anticompton Ge(Li) spectrometer.

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References