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**NUCLEAR
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Section A

Comparison of YAP and BGO for high-resolution PET detectors

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Abstract

The goal of this work was to evaluate the potential of small YAP : Ce crystals, especially designed for a high-resolution PET system. We directly compared the scintillator properties of $3 \times 3 \times 20 \text{ mm}^3$ crystals YAP with those of BGO. The light output, energy resolution, detection efficiency and timing properties for the irradiation using ^{137}Cs and ^{22}Na sources were investigated. Special consideration was given to the influence of the reflector coating on the light output as well as on the overall performance of the quality of the studied crystals. © 1998 Elsevier Science B.V. All rights reserved.

1. Introduction

Currently, most of the commercially available positron-emission tomography (PET) systems use BGO block detectors. These block detectors consist of many crystal elements coupled to a smaller number of photomultiplier tubes (PMTs) [1–3]. A modified Anger scheme is being used to identify the crystal of interaction. Thus, the spatial resolution of these detectors is limited – by the PMT size and the statistical fluctuations of photons emitted from BGO – to about 4 mm FWHM. However, a current trend in PET requires detector systems with 1–2 mm FWHM resolution, e.g. for studying the biodistribution or organ functions in small animals such as mice and rats [4].

A number of groups make attempts to develop high-resolution detectors based on small discrete crystals. One approach is to couple a crystal matrix to a position sensitive PMT [5,6], or to a multi-wire proportional chamber [7]. Another approach is to use small avalanche photodiodes coupled one-to-one to individual crystals [8]. Furthermore, significant progress is also expected by replacing BGO with recently proposed new inorganic scintillators as LSO [9,10], LuAP [11,12] or YAP [13,14]. Since, at present, only YAP crystals are commercially available, this scintillator has been used in first applied studies for animal tomographs [15,16]. The YAP : Ce (yttrium aluminum perovskite, YAlO_3) is characterized by a high light output of 18 000 photons/MeV and a short decay time constant of about 25 ns. A peak emission at 370 nm is in good agreement with the sensitivity of typical photomultipliers. Recently studied energy and time resolution of YAP, coupled to a XP2020Q

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photomultiplier, showed excellent properties reflected in 5.7% energy resolution for ^{137}Cs γ -rays [13]. However, its application in γ -spectroscopy is limited by a moderate detection efficiency because of the low atomic number of yttrium ($Z = 39$), and its moderate density of 5.37 g/cm^3 . For the same reason, a limitation of potential application of YAP in nuclear medicine to gamma cameras and PET systems can be expected.

The subject of this work is to evaluate the potential use of small YAP : Ce crystals for a high-resolution PET system. We directly compared the scintillator properties of $3 \times 3 \times 20 \text{ mm}^3$ crystals of YAP with those of BGO. The light output, energy resolution, detection efficiency at different energy thresholds and timing properties were studied. Hereby, the attenuation of the light in a long and narrow crystal, as well as the influence of the reflector coating on the light output, was given special consideration. For some YAP crystals, a strong attenuation of the light with increasing thickness of the crystal was reported [17]. This effect may limit the light output of the real crystal for PET application.

2. Experimental details

In all studies we used samples of YAP and BGO crystals with dimensions of $3 \times 3 \times 20 \text{ mm}^3$. The YAP crystals were grown and specially coated with an optical reflector (with exception of one $3 \times 3 \text{ mm}^2$ plane) by Preciosa Crytur Ltd. (Turnov, Czech Republic), while the BGO samples were delivered by Crismatec Corp. (Nemours, France). In order to study the quality of the optical reflector, the original coating was removed by washing the crystals in toluene. Then, the crystals were wrapped with white Teflon tape, a well-known optical reflector.

The measurements were performed with a Philips XP2020Q PMT. This PMT has a radiant photocathode sensitivity of 74 mA/W at 401 nm and works with the B voltage chain.

3. Result and discussion

3.1. Light output

In order to determine the light output of the crystals under study, the number of photoelectrons

per energy unit (phe/MeV) was measured by comparing the position of the 661.6 keV full-energy peak from a ^{137}Cs source with that of the single-photoelectron peak. First, the uncoated $3 \times 3 \text{ mm}^2$ plane of a crystal was optically coupled to the PMT (vertical geometry, cf. Fig. 1a). In this geometry, a very low number of photoelectrons of 1422 ± 21 phe/MeV for YAP and 115 ± 6 phe/MeV for BGO, respectively, was obtained. Then, the original coating was removed and the crystals were wrapped with Teflon tape (cf. Fig. 1b). The result of 2324 ± 30 phe/MeV for YAP and 238 ± 7 phe/MeV for BGO showed a significant increase of the number of photoelectrons. Furthermore, the same samples of crystals were wrapped with Teflon tape, and one $3 \times 20 \text{ mm}^2$ plane was optically coupled to the PMT (horizontal geometry, cf. Fig. 1c), in order to check the quality of the scintillator material. The measured number of photoelectrons of 3814 ± 38 phe/MeV for YAP and 985 ± 16 phe/MeV for BGO confirms the good quality of the crystals [18]. It should be emphasized, that an increase in crystal thickness by changing from horizontal to vertical geometry results in a much lower light attenuation for YAP (39%) compared to that for BGO (76%). This observation suggests that YAP crystals from Preciosa Crytur Ltd. do not exhibit the same strong parasitic absorption, observed in thicker samples previously.

3.2. Energy resolution

Fig. 1 shows the energy spectra of the YAP and BGO crystals irradiated with 661.6 keV γ -rays from a ^{137}Cs source for vertical and horizontal geometries. Note the excellent energy resolution of the YAP crystal for both geometries. In the case of BGO, the energy resolution is much worse, particularly for the vertical geometry. The reason for that is a dramatic reduction of light yield of the crystal.

Fig. 2 presents the energy spectra of γ -rays from an ^{22}Na source, measured for vertical geometry with an originally coated YAP and BGO crystal, respectively. Again, a very good energy resolution for the YAP crystal is observed, which is superior to that for the BGO crystal. For the YAP crystal, a lower number of photoelectrons corresponding to

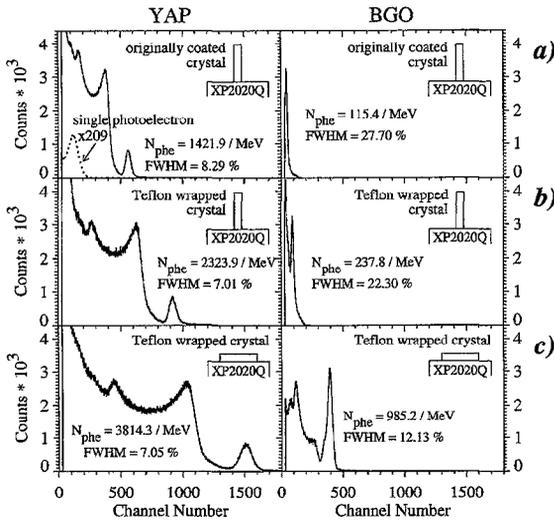


Fig. 1. Pulse height spectra of a ¹³⁷Cs source measured with YAP and BGO for different geometries and optical reflectors. For all measurements a single photoelectron spectrum comparable to that shown in (a, left) has been obtained.

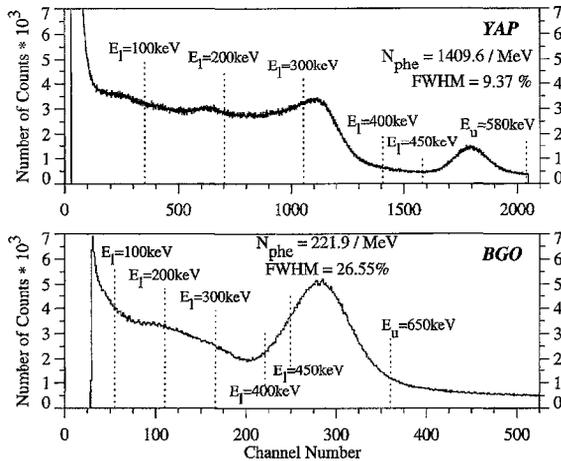


Fig. 2. Pulse height spectra of an ²²Na source measured with YAP and BGO for vertical geometry and the use of the original coating as optical reflector. The spectra displayed are limited to the 511 keV full-energy peak.

511 keV γ -rays results in a deterioration of energy resolution, compared to that for 661.6 keV (cf. Fig. 1a). In contrast to YAP results, an improved energy resolution was measured with the BGO

crystal for the 511 keV γ -rays. This improved energy resolution is caused by twice the light output of the BGO crystal used for the measurement with 511 keV γ -rays in comparison with the light yield of the sample irradiated with photons of 661.6 keV.

3.3. Time resolution

The timing properties of YAP and BGO were tested for the same crystals, which had been used for measuring the energy resolution with an ²²Na source. For this purpose, the 3 × 3 mm² crystal plane was coupled optically to the XP2020Q PMT (vertical geometry). The reference counter consisted of a 25 mm in diameter and 12 mm high BaF₂ crystal coupled to a second XP2020Q PMT. For the YAP crystal, the anode signal of PMT was sent to a constant fraction discriminator (CFD). Due to the low number of photoelectrons corresponding to about 120 phe/511 keV, in the case of BGO the anode signal was sent to an integrating preamplifier with an integration time of about 200 ns, following Ref. [19]. This method allows the selection of an energy threshold in the CFD for both scintillators. The measurements were performed for 511 keV annihilation quanta from an ²²Na source.

Typical time spectra measured with YAP and BGO for the energy threshold set at 300 keV are presented in Fig. 3. It can be seen that YAP achieved a time resolution (530 ps) one order of magnitude better than BGO (7.6 ns). The tail observed on the start side of the spectrum for YAP corresponds to the lifetime of the positron. It is registered with the reference BaF₂ detector when an accidental stop signal, caused by the detection of 1275 keV γ -ray in the YAP, occurs. Also, a fast spike on the start side of the BGO time spectrum was observed. This spike was identified as being generated by Cherenkov radiation, which itself was produced by secondary electrons in the glass window of the PMT. Note the large area of the whole photo-cathode as compared to the small surface of 3 × 3 mm² crystal. A low number of photoelectrons from BGO crystal, produced within the decay time of light pulse (300 ns), makes the peak value easily comparable to the peak of the weaker, but much faster, Cherenkov light. The set of timing results is presented in Table 1.

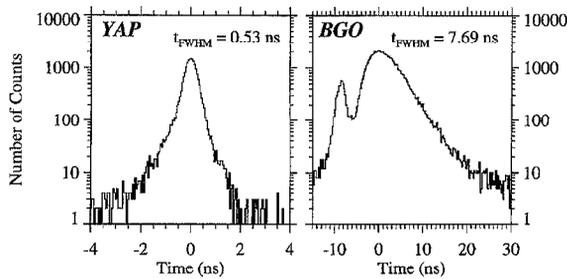


Fig. 3. Comparison of time spectra measured with YAP and BGO crystals for 511 keV annihilation quanta of an ^{22}Na source and a lower-energy threshold set at 300 keV.

3.4. Detection efficiency

The detection efficiency has a very important role in human PET diagnostics. Thus, detection efficiency of both crystals for 511 keV annihilation quanta was considered as an essential factor. The energy spectra of γ -rays from an ^{22}Na source were recorded by a multichannel analyser and the number of counts within a given energy window ($E_l \leq E \leq E_u$, cf. Fig. 2) was calculated. Measurements were performed using same geometry for

both scintillator materials. Relative values of their efficiencies are presented in Table 2. It can be seen that in the case of YAP crystals the efficiency for 511 keV γ -rays detection is three times lower than that of BGO, as measured at the lower-energy threshold of 200 keV. The reason hereof is the low atomic number of yttrium ($Z = 39$) and the moderate density of YAP. In our opinion, the lower detection efficiency seriously limits a future PET application of the YAP crystal to that of imaging small animals, where achieving best possible spatial resolution is of main importance. A further limitation of the YAP crystal in PET application is Compton scattering of γ -quanta, which are easily detectable in neighbouring crystals of a future multi-crystal block detector. This effect will deteriorate the spatial resolution of the PET system. In order to reduce this effect, one has to use a rather high threshold – at least 300 keV, or even higher. This will, however, reduce the detection efficiency of the system even further. Additional studies are required to investigate this effect. It is possible, that LSO or LuAP crystals will be commercially available in the near future and also, that they will be better suited for PET application.

Table 1

Comparison of the time resolution for 511 keV γ -rays as a function of the lower-energy threshold

Energy threshold (keV)	150	200	300
Time resolution (FWHM) (ns)			
BGO	9.57 ± 0.18	8.82 ± 0.28	7.69 ± 0.22
YAP	0.62 ± 0.03	0.59 ± 0.03	0.53 ± 0.04

Table 2

Comparison of the relative detection efficiency for 511 keV γ -rays as a function of the lower-energy threshold

Energy threshold (keV)	0	100	200	300	400	450
Number of registered events						
BGO	15026	13271	10564	8269	6620	5489
YAP	8834	5420	3643	1946	776	621
BGO/YAP	1.70	2.45	2.90	4.25	8.52	8.83

Table 3
Main crystal parameters for 511 keV γ -rays

	BGO	YAP
Photoelectron yield (phe/MeV)	222 ± 3	1409 ± 13
Energy resolution (FWHM) (%)	26.6 ± 0.4	9.4 ± 0.1
Time resolution (FWHM) (ns)		
$E_{\text{lower threshold}} = 300 \text{ keV}$	7.7 ± 0.2	0.5 ± 0.1
Relative detection efficiency		
$E_{\text{lower threshold}} = 0 \text{ keV}$	19.4 ± 0.3	11.4 ± 0.2
$E_{\text{lower threshold}} = 400 \text{ keV}$	8.5 ± 0.1	1.0 ± 0.1

4. Summary and conclusions

The subject of our investigations was the impact of using YAP : Ce instead of BGO on the design of a new high-resolution PET scanner. The main crystal parameters measured in this study are presented in Table 3. They confirm that the YAP crystal is a fast scintillator with a high light output. However, the expected advantages of YAP based PET detectors over BGO associated with higher light yield are not fully employed due to the low detection efficiency. The YAP crystal can be applied only in the animal PET. The reason hereof is the necessity to use higher radioactive doses than those required for BGO. Also, note that replacing the rather expensive optical reflector coating provided by the manufacturer with white Teflon tape improves the properties of the crystals.

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