Scintillation response of CdWO$_4$ scintillator for gamma-ray detection

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Abstract. At present, scintillation materials are playing a major role in medical radiation detection. They are being used for various scans including CT scan, PET scan and SPECT scan. In this work, the researchers studied the scintillation response of the CdWO$_4$ (CWO) crystal compared with the Bi$_4$Ge$_3$O$_{12}$ (BGO) crystal. The energy resolution and light yield values were tested using a photomultiplier tube (PMT) readout. The gamma source was aligned along the cylindrical axis of the crystal and the PMT. The energy spectra were then recorded using a PC-based multichannel analyser (MCA). From the results, it was found that the energy resolution of 6.5 % obtained from the CWO crystal was superior than that of 9.3 % obtained from the BGO crystal of 662 keV gamma-ray energy. The CWO crystal displayed about two times greater light yield than the BGO crystal. In the energy range from 32 keV to 1,408 keV, the degree of the light yield non-proportionality of 0.13 obtained from the CWO crystal was also more exceptional than that of 0.19 obtained from the BGO crystal. The photo-fraction of both crystals was also discussed.

1. Introduction

Nowadays, many kinds of radiation are widely utilised for non-destructive testing and inspection; such as, in geological exploration, industrial material analysis, medical imaging, and various other fields. A scintillation detector plays an essential role in these applications because humans cannot see radiation with the naked eye. This instrument is the combination of scintillation material and a photomultiplier tube (PMT), which is most commonly used for many practical applications. Moreover, research and development of new scintillation materials have been mainly initiated by the growing demand for high energy physics and modern medical imaging. During the last 20 years, new types of scintillation materials, in particular, inorganic scintillation crystals have been intensively studied, and some of them have been successfully developed for commercial production. Scintillation crystals have also been used as radiation detectors in many medical diagnostic instruments. In 2005, Mecher [1] reported that scintillation crystals were used in positron emission tomography (PET) of approximately 30 tonnes, X-ray computed tomography (X-ray CT) of approximately 22 tonnes, single photon emission tomography (SPECT) of approximately 10 tonnes, and high energy physics (HEP) research of approximately 20 tonnes. At present, the amount of usage in each category is several times higher. Furthermore, there are many positive reviews that have intensively studied the properties of these materials; such as, van Eijk...
Good scintillation crystals that are suitable for these applications should have the following qualities: high light yield, good energy resolution, good proportional response, fast decay time, high stopping power, minimal afterglow and non-hygroscopic. The relationship of the non-proportional response with the energy resolution of the scintillator was studied for many oxide-based crystals [5,6] and alkali halide crystal [7, 8]. In general, the scintillation response of the oxide-based crystal would improve as the energy of the photon increases whereas that of the alkali halide crystal would become deficient.

In this research article, the researchers chose to study the scintillation response of cadmium tungstate (CdWO$_4$ or CWO) crystals because there are very few studies that have conducted analyses in this aspect. The CWO scintillator is an inorganic single crystal, which is a non-hygroscopic material. Its effective atomic number and density is 66 and 7.9 g/cm$^3$, respectively. Moszynski et al [9] studied the scintillation properties and found that they showed an energy resolution of about 6.6 %, a light yield of about 27,000 ph/MeV, and photo-fraction of about 26 % of 662 keV gamma-ray energy.

### 2. Material and method

The CWO crystal with the proportions of 5 mm $\times$ 5 mm $\times$ 1 mm was supplied by Kinheng Crystal Material (Shanghai) Company Limited, Shanghai, People’s Republic of China. The crystal was examined to compare to the original form (bismuth germanate; Bi$_4$Ge$_3$O$_{12}$; BGO) of the same dimensions. Both crystals were supplied from the same company and grown by the Bridgman method. Each crystal was covered with white tape except the bottom that was used to connect to the window of the photomultiplier tube (Photonis XP5200B PMT). The gamma sources were positioned at a relative distance away from the crystal. When the gamma photons came to the crystal, the crystal changed the gamma photons into visible light photons. These lights entered the PMT and were converted into an electrical signal. This signal was amplified by the preamplifier and amplifier circuits and then entered the multi-channel analyser (MCA) [10] for analysis and recording.

### 3. Results and discussion

#### 3.1. Light yield and energy spectra

Figure 1 shows the energy spectra of the 662 keV gamma rays from the $^{137}$Cs source of both crystals. Energy resolution of about 6.5 % was obtained from the CWO crystal, which was superior than that of about 9.3 % obtained from the BGO. This was due to the higher light yield and lower intrinsic resolution for CWO (refer to table 1). The energy resolution of the tested CWO was comparable to that measured for the 5$\times$5$\times$3 mm$^3$ CWO sample by Moszynski et al [9]. The light yield of the CWO crystal was greater than that of the BGO crystal as seen by the position of the photo peak on the x-axis (channel number) (refer to figure 1). The photoelectron yield and energy resolution values are summarised in table 1. The photoelectron yield, expressed as the number of photoelectrons per MeV (phel/MeV) for each photo peak, was measured by the Bertolaccini method [11-12]. The photoelectron yield of 3,780 phel/MeV obtained from the CWO crystal was about two times greater than that of 1,890 phel/MeV obtained from the BGO crystal resulting in the better energy resolution value of the CWO crystal.

| Crystal | Photoelectron yield [phel/MeV] | Energy resolution [%] |
|---------|-------------------------------|----------------------|
| CWO     | 3,780 ± 380                   | 6.51 ± 0.48          |
| BGO     | 1,890 ± 190                   | 9.30 ± 0.47          |
3.2. Non-proportionality of light yield

The non-proportionality of the light yield is defined as the ratio of the light yield at any energy to the light yield at 662 keV energy. The light yield of the CWO crystal at 32 keV decreased by 26 % from 100 % at 662 keV while the light yield of the BGO crystal at 32 keV decreased by 43 % from 100 % at 662 keV (refer to figure 2). In order to gain some understanding, Dorenbos [13] presented the degree of the non-proportionality of the light yield (σnp) for comparison. The σnp of the CWO crystal was 0.13 and the BGO crystal was 0.19. The σnp of the BGO crystal was comparable to that measured for the
15×15×4 mm³ BGO sample by Phunpueok et al. [14]. The researchers of the current study found that the $\sigma_{np}$ of the BGO crystal was more deficient than the CWO crystal. These values were clearly consistent with the results shown in figure 2. The better proportionality of the light yield of the CWO crystal was one of the key reasons behind its better intrinsic resolution [15].

3.3. Energy resolution

Energy resolution is the ability to distinguish the radiation energy entering a radiation detector. The energy resolution ($\Delta E/E$) of a full energy peak measured with a scintillation crystal connected to a PMT can be displayed as equation 1 [8].

$$ (\Delta E/E)^2 = \delta_{st}^2 + \delta_p^2 + \delta_{sc}^2 $$

where $\delta_{st}$ is the statistical contribution of the PMT to the resolution; $\delta_p$ is the transfer resolution between the crystal to the PMT, and $\delta_{sc}$ is the intrinsic resolution. The PMT resolution can be displayed as equation 2.

$$ \delta_{st} = 2.355 \times 1/N^{1/2} \times (1 + \varepsilon)^{1/2} $$

where $N$ is the number of photoelectrons produced at the photocathode in the PMT, and $\varepsilon$ is the electron multiplier gain variance in the PMT. The $\varepsilon$ of the XP5200B PMT is 0.1. The intrinsic resolution is associated with the light yield non-proportionality of the crystal [8,15], and many effects; such as, the uniform of the tape covering the crystal and homogeneities in the crystal. The transfer resolution has very little value compared to other components of the energy resolution that can be ignored. Thus, $\delta_{sc}$ can be written as equation 3:

$$ \delta_{sc}^2 = (\Delta E/E)^2 - \delta_{st}^2. $$

![Figure 3. The energy resolution of the CWO and BGO crystals.](image)

Figures 3 and 4 show energy resolution and intrinsic resolution of both crystals, respectively. From figure 3, it can be seen that the energy resolution of the CWO crystal was superior than that of the BGO crystal throughout the energy range from 32 to 1,408 keV. The energy resolution values tended to decrease when the energy of the radiation increased. In figure 4, the intrinsic resolution values of the
CWO crystal were more improved than that of the BGO crystal in the energy range from 32 to 245 keV. In a high energy range (511 to 1,408 keV), the intrinsic resolution values of the CWO crystal are slightly better than that of the BGO crystal. To better understand the energy resolution of both crystals, the contribution of various components to the energy resolution are summarised in table 2. The N (the number of photoelectrons produced in the photocathode in the PMT) could be obtained by using the Bertolaccini method [11,12]. The $\Delta E/E$ was estimated from the energy spectra, the $\delta_{st}$ was determined by using equation 2, and the $\delta_{sc}$ was calculated using equation 3. The $\sigma_{np}$ could be obtained by using the Dorenbos method [13]. As seen in column 2 of table 2, the researchers found that the CWO crystal could emit twice the amount of light photons than the BGO crystal (3,778 vs. 1,889). This resulted in the PMT resolution of the CWO crystal being superior than the BGO crystal (5.77 % vs. 8.16 %). Additionally, the CWO crystal had a notable intrinsic resolution than the BGO crystal (3.02 % vs. 4.47 %) resulting in the energy resolution of the CWO crystal being clearly better than the BGO crystal. For the $\sigma_{np}$, the CWO crystal also displayed a superior value than the BGO crystal (0.13 vs. 0.19). This demonstrated that these $\sigma_{np}$ were strongly correlated to the intrinsic resolution and the energy resolution.

**Figure 4.** The intrinsic resolution of the CWO and BGO crystals.

**Table 2.** Analysis of the 662 keV energy resolution for the CWO and BGO crystals.

| Crystal | Photoelectron [N] | $\Delta E/E$ [%] | $\delta_{st}$ [%] | $\delta_{sc}$ [%] | $\sigma_{np}$ |
|---------|-------------------|-----------------|-----------------|-----------------|-------------|
| CWO     | 3,780 ± 380       | 6.51 ± 0.48     | 5.77 ± 0.29     | 3.02 ± 0.15     | 0.13        |
| BGO     | 1,890 ± 190       | 9.30 ± 0.47     | 8.16 ± 0.41     | 4.47 ± 0.22     | 0.19        |

3.4. Photo-fraction

The photoelectric fraction or photo-fraction is defined as the ratio between the area under the photo peak to the area under the entire spectrum. The photo-fraction is the property that is used to tell the ability to stop high energy radiation. This is the high stopping power property of the crystal. The photo-fractions for both crystals are presented in table 3. The second column gives $Z_{eff}$, the effective atomic number of the crystal. The third column shows $\rho$, the density of the crystal. For a comparison, the cross-sectional ratio ($\sigma$-ratio) for the photoelectric effect to the total one calculated using the WinXCom programme [16] was also provided. The data showed that the photo-fraction of the BGO crystal was much higher.
than that of the CWO crystal in the same trend with the cross-sectional ratio obtained from the WinXCom programme. In general, the photo-fraction would be proportional to the product of $\rho$ and $Z_{\text{eff}}^5$. Although the density of the CWO crystal was more than the BGO crystal (7.90 vs. 7.13 g/cm$^3$), the influence of the effective atomic number was greater because of the fifth power. The $Z_{\text{eff}}$ value of the BGO crystal was more than the CWO crystal (74 vs. 66) resulting in the superior photo-fraction of the BGO crystal.

### Table 3. Photo-fraction for the CWO and BGO crystals at 662 keV gamma energy.

| Crystal | $Z_{\text{eff}}$ | $\rho$ [g/cm$^3$] | Photo-fraction [%] | $\sigma$-ratio [%] |
|---------|-----------------|------------------|-------------------|-----------------|
| CWO     | 66              | 7.90             | 17.93             | 21.70           |
| BGO     | 74              | 7.13             | 24.10             | 32.35           |

4. Conclusion

From all the experimental results, the researchers found that although the ability of the CWO crystal for detecting high-energy radiation was slightly less than the BGO crystal, the light yield of the CWO was almost two times higher than that of the BGO crystal. In addition, the intrinsic resolution of the CWO was better resulting in a superior energy resolution. Therefore, this crystal would be interesting to replace the old BGO crystal in modern medical imaging for diagnostics; such as, a PET scan and SPECT scan.

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References

[1] Melcher C L 2005 Nucl. Instrum. Methods Phys. Res. A 537 6
[2] van Eijk C W E 2001 Nucl. Instrum. Methods Phys. Res. A 460 1
[3] Moszynski M 2003 Nucl. Instrum. Methods Phys. Res. A 505 101
[4] Lecoq P, Annenkov A, Gektin A, Korzhik M and Pedrini C 2006 Inorganic Scintillators for Detector Systems (Netherlands: Springer)
[5] Sysoeva E P, Zelenskaya O V and Sysoeva E V 1996 IEEE Trans. Nucl. Sci. 43 1282
[6] Moszynski M, Balcerzyk M, Czarnacki W, Kapusta M, Klamra W, Syntfeld A and Szawlowski M 2004 IEEE Trans. Nucl. Sci. 51 1074
[7] Valentine J D, Rooney B D and Li J 1998 IEEE Trans. Nucl. Sci. 45 512
[8] Moszynski M, Zalipska J, Balcerzyk M, Kapusta M, Mengeshe W and Valentine J D 2002 Nucl. Instrum. Methods Phys. Res. A 484 259
[9] Moszynski M, Balcerzyk M, Kapusta M, Syntfeld A, Wolski D, Pausch G, Stein J and Schotanus P 2005 IEEE Trans. Nucl. Sci. 52 3124
[10] Guzik Z, Borsuk S, Traczyk K and Plominski M 2006 IEEE Trans. Nucl. Sci. 53 231
[11] Bertolaccini M, Cova S and Bussolatti C 1968 Proc. Nuclear Electronics Symp (Versailles, France) 62 211
[12] Moszynski M, Kapusta M, Mayhugh M, Wolski D and Flyckt S O 1997 IEEE Trans. Nucl. Sci. 44 1052
[13] Dorenbos P 2002 Nucl. Instrum. Methods Phys. Res. A 486 208.
[14] Phunpueok A, Chewpraditkul W, Limsuwan P and Wanarak C 2012 Nucl. Instrum. Methods Phys. Res. B 286 76
[15] Dorenbos P, de Haas J T M and van Eijk C W E 1995 IEEE Trans. Nucl. Sci. 42 2190
[16] Gerward L, Guilbert H, Iensen K B and Levring H 2004 Radiat. Phys. Chem. 71 653