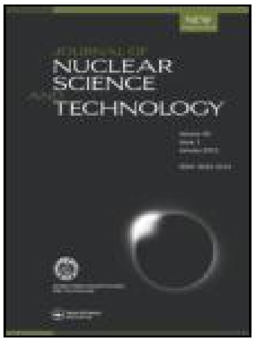

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Large Size $CdWO_4$ Crystal for Energetic X- and γ-Ray Detection

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A Large size of Φ70 mm × 71 mm (2.1 kg) $CdWO_4$ crystal with excellent quality was studied for the energy response of the crystal to the γ-rays. The large crystal was coupled with a green-extended Photomultiplier tube (PMT) and tested at room temperature. We measured light yield and energy resolution of the crystal using various radioactive sources. The energy resolutions of the $CdWO_4$ crystal were obtained to be 9.5 % and 5.3% for 662 keV and 2614 keV, respectively. Linearity of the crystal in different γ-ray energy was also measured. In the environmental background spectrum, well defined peaks of 1461 keV by ^{40}K decay and 2614 keV by ^{208}Tl decay were identified. A simulation study with GEANT4 package was performed for the efficiency comparison with commonly used NaI(Tl) crystal scintillators. The study showed that the $CdWO_4$ crystal is the promising candidate for the boarder control and energetic X-and γ-ray detection equipment.

KEYWORDS: $CdWO_4$, scintillation properties, efficiency, energy resolution, number of photoelectron, linearity

I. Introduction

Scintillation detectors are widely used in the detection and spectroscopy of X-rays or γ-rays at room temperature. The detectors are commonly used in nuclear and high-energy physics, medical imaging, diffraction, non-destructive testing, homeland security, geological exploration, and astrophysics [1)].

Important requirements for the scintillation crystals used in these applications include high light output, high stopping power, fast response, low cost, good energy resolution, good linearity, and minimal afterglow. These all requirements can not be met by any of the commercially available scintillators and it should be application specific to choose the best scintillation crystal.

During the last decay high-Z crystal scintillators have been developed for medical imaging such as computer tomography (CT) or positron emission tomography (PET). They include BGO, GSO, LSO and $CdWO_4$ and others, whose distinguished property is high detection efficiency for X- and γ-rays, as well as excellent operational characteristics. These scintillators can be used for medical imaging, radiation detection and board control applications.

Cadmium tungstate ($CdWO_4$, CWO) crystal is one of the candidate for such application since it has high effective Z number, high density, higher light yield than BGO, and very low afterglow [2)]. Radiation hardness of CWO crystal is as high as 10^5 rad. Because of such advantage, CWO scintillator is being used extensively in X-ray CT [2)]. The main characteristics of $CdWO_4$ crystal are summarized in **Table 1**. Large CWO crystal can be used for the board control, γ-ray spectrometer for well logging [3)], planetary lander missions [4)], and γ-rays detection for radiation monitoring [5)]. S. Ph. Burachas et al. reported 13.8% energy resolution at the energy of 662 keV with a Φ54 mm × 95 mm (1.7 kg) crystal [6)].

We report a study of response to the γ-ray of a large Φ70 mm × 71 mm (2.1 kg) CWO crystal with an excellent quality. Also a simulation study with GEANT4 package was done for the efficiency comparison with commonly used NaI(Tl) crystal scintillator.

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Table. 1 Properties of $CdWO_4$ crystal scintillator [2)].

Properties and characteristics [units]	Value
Effective atomic number	64
Density [g/cm3]	7.9
Melting point [K]	1598
Cleavage plane	<010>
Mohs' hardness	4-4.5
Hygroscopicity	No
Luminescence maximum [nm]	470/540
Index of refraction	2.3
Average decay time [□s]	5 and 20
Light yield [% of NaI(Tl)]	25-40
Afterglow after 3 ms [%]	0.1
Radiation hardness [rad]	10^5

II. Experiment

A 7.0 cm diameter by 7.1 cm thick cylindrical CWO scintillation crystal (2.1 kg) as shown in **Fig. 1** was prepared for the test. The CWO was produced by Novosbisk, Russia and it is so transparent that quality of crystal is better than previously studied one[5),6)] which showed a slight color suggesting self-absorption of the light. The CWO was wrapped with the Teflon followed by the black tape. The crystal is attached with a 3 inch Photomultiplier tube (PMT) with RbCs photocathode (Electron tube). The RbCs photocathode enhances quantum efficiency in the green wavelength region and gives more photoelectron yield for the CWO crystal than a normal bialkali PMT. The high voltage of -1350 V was applied to the PMT.

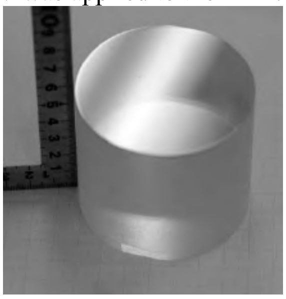

Fig. 1 Φ70 mm × 71 mm of $CdWO_4$ produced by Novosbisk

A 25 MHz USB2 based Flash Analog to Digital Converter (FADC) board was used for the analog signal digitization [7]. An analog signal from the PMT attached to the CWO is connected into the analog input of the FADC board via an ORTEC 576 shaping amplifier. A software threshold setting was applied to trigger an event by a self-trigger algorithm on Field Programmable Gate Array (FPGA) chip of the FADC board. The FADC output was recorded into the personal computer and the recorded data were analyzed with a C++ data analysis program. **Fig. 2** shows a schematic diagram of the experimental setup for the radiation measurement.

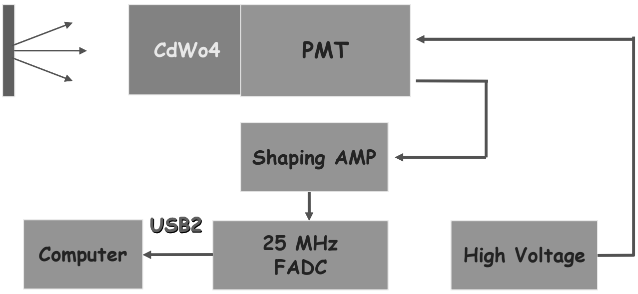

Fig. 2 A Schematic diagram of data acquisition system (DAQ).

For the cross checking purpose, signals from the PMT were also amplified using a home-made amplifier with a low noise and high slew rate. The output signals were then fed into a 400 MHz FADC (flash analog-to-digital converter) [7]. The trigger was formed in the FPGA (field programmable gate array) chip on the FADC board. The FADC was located in the VERSA module eurocard bus (VME) crate and was read out by using a Linux operating PC through the VME-USB2 interface. The module is designed to sample the pulse every 2.5 ns for duration up to 32 μs so that one can fully reconstruct each pulse as shown in **Fig. 3**. We investigated scintillation characteristics of the crystal using single photoelectron (SPE) counting method in 24 μs window since the trigger point is set to be 8 μs. In SPE counting method, it needs to identify SPE signal to reduce the effect coming from the noise to improve energy resolution because the information for the scintillation light from the detector is included only in the SPE signal. We used a clustering algorithm to identify SPEs. If decay time of scintillator is long, the SPE counting method is useful for the characterization of the scintillator [8].

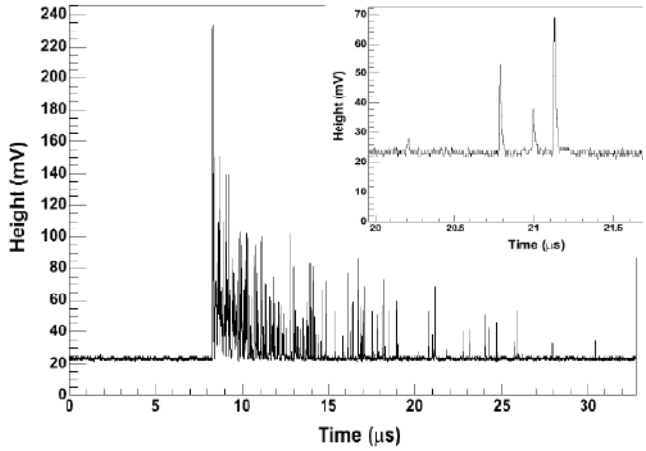

Fig. 3 Typical pulse spectra of the CWO by 400 MHz FADC and SPEs are also shown.

III. Results and Discussion

1. Number of Photoelectron

As described in previous section, SPE can be identified by using a 400 MHz FADC and a clustering algorithm. The number of photoelectrons per keV can be obtained by counting each peak in one event since single photoelectrons are clearly separated one another at low energy as shown in **Fig. 3**. That is, a low energy event can be identified as a set of single photoelectrons above a threshold cut within a timing window of 24 μs. As shown in **Fig. 4**, average number of photoelectons per keV was obtained with low energy events after calibration with 662 keV γ-rays from a ^{137}Cs radioactive source. The average number of photoelectrons of the CWO crystal is obtained to be 2.4 photoelectrons/keV. Taking account only statistical fluctuation, 6.4% of energy resolution could be obtained with 662 keV γ-rays.

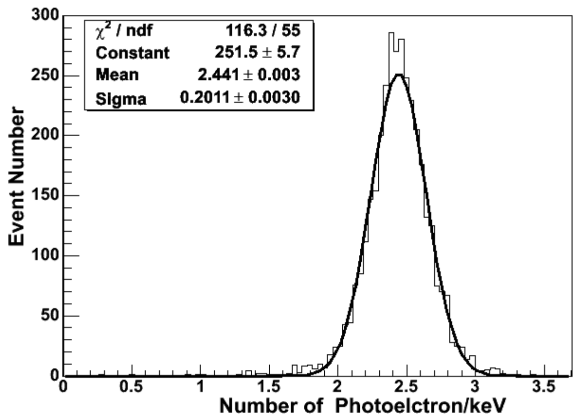

Fig. 4 Number of photoelectron per keV for the CWO crystal.

2. Energy Resolution

The energy response of CWO crystal to γ-rays from ^{137}Cs, ^{22}Na, ^{60}Co radioactive source and natural KCl, thorium oxide powders were used for the energy resolution determination. These results were obtained with a shaping time of 10 μs. The Gaussian fit was applied each identified γ-ray peak and energy resolution is determined by the fitted mean value.

The **Fig. 5** shows the energy resolution of CWO crystal from 511 keV to 2614 keV. The resolution of 9.5% and 5.2% is obtained with 662 keV and 2614 keV γ– rays, respectively. These results are better than previously reported one with similar size of crystal by S. Ph. Burachas et al [6].

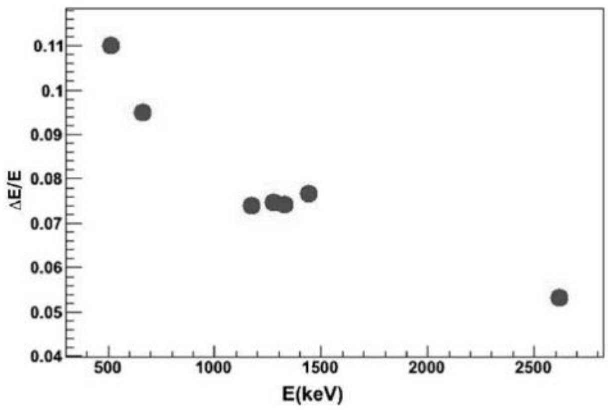

Fig. 5 Energy resolution of the CWO crystal with various γ-ray sources.

3. Linearity

The CWO crystal was irradiated with various radioactive sources with the energy range from 88 keV to 2614 keV for the linearity study. Each γ-ray peak is identified with a Gaussian fit. As shown in **Fig. 6**, the energy response of CWO crystal to γ-ray is linear in the energy range from 100 keV to 2600 keV.

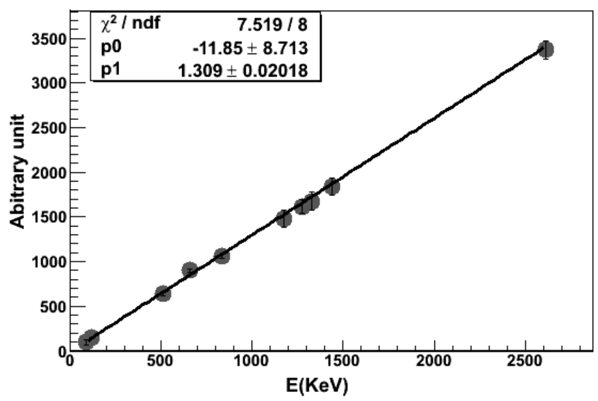

Fig. 6 Linearity distribution of CWO with various γ-ray sources. The solid line shows the linear fit to data.

4. Efficiency Comparison between CWO and NaI(Tl)

A Monte Carlo simulation was performed to compare full peak efficiencies of γ-ray between CWO and NaI(Tl) crystal in the energy range from 0 to 10000 keV. The GEANT4 package with low energy model was used for the simulation[9].

The size of CWO and NaI(Tl) crystals are assumed to be a 7.0 cm diameter by 7.1 cm thick cylindrical shape and each γ-ray is entered in the center of the crystals. The full peak efficiencies are estimated with total energy deposition in the crystal. The efficiency curves of CWO and NaI(Tl) are shown in **Fig. 7**. The full peak efficiencies of the crystals at low energy are not 100% because of backscattering and X-ray emission. Since effective atomic number of CWO crystal is higher than NaI(Tl), full peak efficiencies of CWO at high energy is expect to be much higher than NaI(Tl). The simulation study shows that CWO full peak efficiencies is about 3 and 10 times higher than that of NaI(Tl) in the energy of 2600 keV and 10000 keV, respectively.

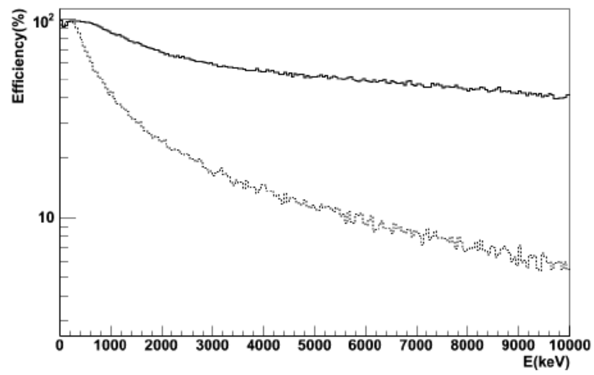

Fig. 7 Efficiency curve of γ-ray by GEANT4 simulation for a) CWO (solid histogram) and b) NaI(Tl) (dashed histogram.

For the full peak efficiency comparison between CWO and NaI(Tl) crystal, similar size of NaI(Tl) crystal was used with 2 inch bi-alkali PMT and 2 μs pulse shaping time. Both CWO and NaI(Tl) was irradiated with natural thorium oxide powder and pulse height spectra are recorded. **Fig. 8** shows energy spectra of the CWO and the NaI(Tl) normalized at low energy. Several γ-ray peaks produced by ^{232}Th decay chain are identified. It confirmed that the full peak efficiency of CWO crystal at 2614 keV is about 3 times higher than that of NaI(Tl) crystal.

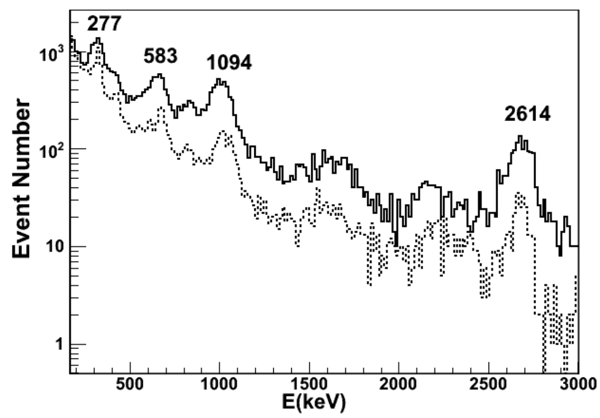

Fig. 8 Pulse height spectra by natural Thorium oxide powder for a) CWO (solid histogram) and b) NaI(Tl) (dashed histogram)

5. Background Energy Spectra of the CWO

The natural background in the experimental hall was measured with the CWO crystal. The energy of recorded pulse height spectrum was calibrated with the energy of 662 keV γ-rays from ^{137}Cs radioactive source. As shown in **Fig. 9**, 511 keV annihilation peak, 583 keV by ^{208}Tl, 1461 keV by ^{40}K and 2614 keV by ^{208}Tl are clearly identified.

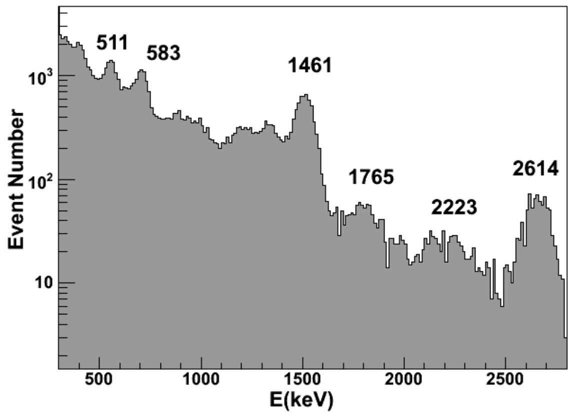

Fig. 9 Background energy spectrum of the CWO crystal.

IV. Conclusions

In this work, we described a study of 7.0 cm diameter by 7.1 cm thick cylindrical CWO scintillation crystal coupled with 3 inch green extended PMT. We determined good energy resolution of 9.5% for 662 keV γ-rays by ^{137}Cs and 5.2% for 2614 keV γ-rays by ^{208}Tl decay, respectively. These values were obtained with a shaping time of 10 μs. The number of photoelectron per keV is obtained to be 2.4 with 400 MHz FADC. Good energy linearity was obtained from 100 keV to 2600 keV.

We also demonstrated in this study the advantages of the large CWO crystal as efficient energetic X-ray or γ-ray detection and compared its efficiency with the NaI(Tl) crystal. The environmental background energy spectra for the CWO crystal show the capability of high energy γ-ray tagging such as 2614 keV produced by ^{208}Tl decay.

The large excellent quality of CWO scintillation crystal studied here confirmed the high efficiency for γ-rays detection and the high potential of CWO crystals for application of the border monitoring equipment and energetic X- and γ-ray detection.

Acknowledgement

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