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Optimization of light collection from crystal scintillators for cryogenic experiments

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ABSTRACT

High light collection efficiency is an important requirement in any application of scintillation detectors. The purpose of this study is to investigate the possibility for improving this parameter in cryogenic scintillation bolometers, which can be considered as promising detectors in experiments investigating neutrinoless double beta decay and dark matter. Energy resolutions and relative pulse amplitudes of scintillation detectors using $ZnWO_4$ scintillation crystals of different shapes (cylinder ⌀ 20 × 20 mm and hexagonal prism with diagonal 20 mm and height 20 mm), reflector materials and shapes, optical contact and surface properties (polished and diffused) were measured at room temperature. Propagation of optical photons in these experimental conditions was simulated using Geant4 and ZEMAX codes. The results of the simulations are found to be in good agreement with each other and with direct measurements of the crystals. This could be applied to optimize the geometry of scintillation detectors used in the cryogenic experiments.

1. Introduction

Cryogenic scintillators are a promising detector component to search for dark matter and neutrinoless double beta (2β) decay due to excellent energy resolution, particle discrimination ability, and low energy threshold [1,2]. They also offer the important possibility of using compounds with a choice of different nuclei. For instance, the CRESST collaboration already uses low-temperature $CaWO_4$ scintillating bolometers to search for weakly interacting massive particles (WIMP) [3,4] while several experiments are in preparation to search for dark matter and 2β decay. In particular, the goal of the EURECA project [5] is to build a ton-scale cryogenic detector to investigate WIMP-nucleon scattering. The aim of a number of R&D projects is to build 2β decay experiments for the exploration of neutrino mass hierarchy scenarios using $CdWO_4$ [6,7], $CaMoO_4$ [8], ZnSe [9–11], and $ZnMoO_4$ [12–14] crystal scintillators.

The design and optimization of detectors for the next generation of cryogenic experiments require not only knowledge on the physics of conversion of high-energy quanta to visible photons but also an understanding of the mechanism of light transport in the crystal. Given that less than half of the photons generated in a scintillation crystal reach the photodetector [15–17] it is apparent that the efficiency of light collection has a significant effect on the overall performance of a detection module. Maximizing the light collection is of particular importance for dark matter experiments where a low energy threshold is needed for separation of nuclear recoil events (effect) from gamma/beta events (background) as this eventually defines the experiment's sensitivity [3,4]. In 2β experiments the light collection is crucial for achieving effective pulse-shape discrimination, in particular for random coincidence events, which were recently recognized as one of the problematic sources of background in bolometric detectors, especially when the search involves the isotope ^{100}Mo that has a particularly fast two neutrino double beta decay rate [18,19]. When designing detection modules for such applications it is important to understand and control the factors that influence overall light collection. Therefore, the aim of this work is to investigate how the light collection of scintillation detectors is dependent on the particular choice of the experimental setup, i.e. scintillator shape, surface condition, wrapping, optical contact and reflector.

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In this work we studied the performance of $ZnWO_4$ scintillation detectors using experimental and simulation approaches. The choice of the scintillator was motivated by the fact that it is a promising target for dark matter and/or 2β decay experiments due to high light output, very low level of radioactive contamination and its composition (presence of zinc and tungsten nuclei containing potentially 2β active isotopes) [20–25]. Moreover zinc tungstate has optical properties very similar to those of other representatives of the ABO_4 (A=Ca, Zn, Cd; B=Mo, W) family of heavy inorganic scintillators which are considered as attractive complementary targets for cryogenic rare event searches [26]. Therefore, the results on the optimization of the light collection efficiency for this material can be applicable to other cryogenic scintillating bolometers. We measured the dependence of energy resolution and relative pulse amplitude of $ZnWO_4$ scintillation detectors on the crystal shape (hexagonal and cylindrical), design and material of a reflector, type of optical contact with the photodetector, and optical condition of the crystal scintillator surface (polished and diffuse). These results are discussed in the first part of this paper. In the second part we present results of modeling. Two different Monte Carlo techniques were used to simulate the light transport in the scintillator–detector assembly: Geant4 and ZEMAX. Such an approach offered the advantage for cross-examination of the modeling results and their validation – all too often a stumbling-block of simulations.

2. Materials, measurements and results

Two $ZnWO_4$ crystal scintillators were produced from one $ZnWO_4$ crystal ingot in the Institute of Scintillation Materials (Kharkiv, Ukraine). This was done to ensure as much as possible identical optical properties of the two samples used in the tests. The first crystal was of cylindrical shape with diameter 20 mm and height 20 mm. The second crystal was in the form of a hexagonal prism with the larger diagonal 20 mm and height 20 mm. The measurements of the transmittance spectra using a spectrophotometer Shimadzu, UV-3600 evidence that both samples have very similar optical properties (see Fig. 1).

The measurements of the energy resolution and the relative pulse amplitude with radioactive sources were carried out using a 3″ photomultiplier (PMT) Philips XP2412. The positions of the γ sources (^{137}Cs and ^{207}Bi) were chosen to provide a counting rate less than 250 counts/s to avoid overlap of scintillation events due to the rather slow scintillation response of $ZnWO_4$. The energy spectra were accumulated for 40 min, each. Before taking data the experimental setup was allowed to stabilize for 30 min after switching on the high voltage of the PMT. The temperature during the measurements was in the range of 21–26 °C. Variation of the $ZnWO_4$ light output was estimated to be about 3% in this temperature interval. To correct for this effect as well as for possible drift in stability the detection system repeated, periodic checks were made through measuring the γ spectrum of a ^{137}Cs source, using a control $ZnWO_4$ scintillation sample of size $10 \times 10 \times 5$ mm^3. All experimental data were then processed off-line, taking into account the position of the ^{137}Cs peak measured for the $10 \times 10 \times 5$ mm^3 control scintillator.

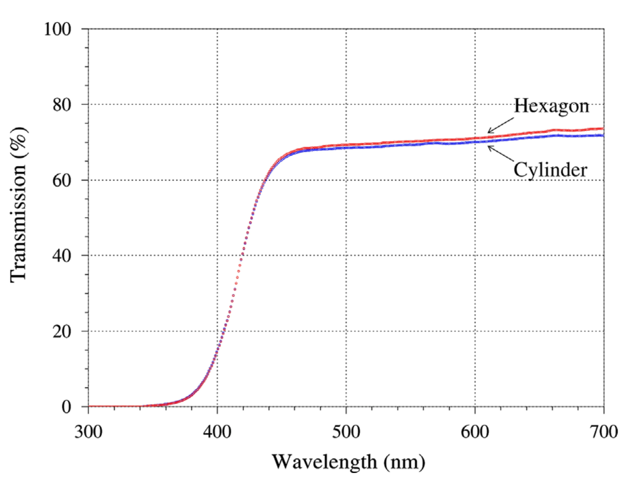

Fig. 1. The optical transmission spectra of cylindrical and hexagonal $ZnWO_4$ crystals measured along the vertical axis.

The measurements were carried out for the following arrangements of experimental setups (see Fig. 2):

(*A*) $ZnWO_4$ crystal wrapped in 3 layers of PTFE tape and optically coupled to the PMT;
(*B*) $ZnWO_4$ crystal surrounded by a cylindrical 3 M reflector ⌀ 26×25 mm, not in contact with the crystal, and optically coupled to the PMT;
(*C*) $ZnWO_4$ crystal surrounded by a cylindrical 3 M reflector ⌀ 26×25 mm and placed on small acrylic supports (three cubes with dimensions $2 \times 2 \times 2$ mm^3) between the crystals and the PMT.

The optical contact in geometries *A* and *B* was provided by Dow Corning Q2-3067 optical gel. It should be noted that geometry *C* represents, to some extent, the conditions of light collection in a cryogenic scintillating detector. There the scintillation crystal must be separated from the other parts of the detector to minimize loss of phonons [22] and not to introduce excess heat capacity.

The measurements were carried out for four conditions of crystals' surfaces:

1) all surfaces of the $ZnWO_4$ crystal scintillator polished;
2) the side surfaces of the crystals diffuse, the top and bottom surfaces polished;
3) the side surfaces and the top face of the crystals diffuse, the face viewed by the PMT polished;
4) all surfaces of the crystals diffuse.

Lapping of the crystal surfaces was done using sandpaper P1000 (KWH Mirka Ltd) with grain size 18 ± 1 μm. The roughness of the diffuse surfaces, evaluated by using an optical microscope, is about 5–40 micrometres (see Fig. 3). The roughness of the polished surfaces is about 0.2 micrometres.

The measurement for surface conditions 1–3 was repeated three times and for condition 4 was carried out once.

The energy spectra of ^{137}Cs and ^{207}Bi γ quanta presented in Fig. 4 (upper part) were collected for the hexagonal $ZnWO_4$ crystal scintillator with all diffuse surfaces in optical contact with the PMT surrounded by the 3 M reflector.

Data on the energy resolution measured with 662 keV γ quanta of ^{137}Cs for different conditions of experiments are displayed in Fig. 5. It is immediately seen that a cylindrical scintillator has worst energy resolution when compared with a scintillator of hexagonal shape. The difference in energy resolution is very noticeable for polished surfaces in geometry *C* and reduces when crystal surfaces are diffused.

Data on the relative pulse amplitude measured with 662 keV γ quanta of ^{137}Cs for different conditions of experiments are presented in Fig. 6. The experimental data are normalized with respect to the values of light collection efficiency calculated using ZEMAX (see Section 3.2) for the configuration – geometry *B* – chosen as a reference.