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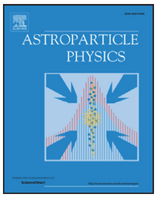

Model for the Cherenkov light emission of TeO_2 cryogenic calorimeters

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ABSTRACT

The most sensitive process able to probe the Majorana nature of neutrinos and discover Lepton Number Violation is the neutrino-less double beta decay. Thanks to the excellent energy resolution, efficiency and intrinsic radio-purity, cryogenic calorimeters are primed for the search for this process. A novel approach able to improve the sensitivity of the current experiments is the rejection of α interactions, that represents the dominant background source. In TeO_2 calorimeters, α particles can be tagged as, in contrast to electrons, they do not emit Cherenkov light. Nevertheless, the very low amount of detected Cherenkov light undermines the complete rejection of α background.

In this paper we compare the results obtained in previous measurements of the TeO_2 light yield with a detailed Monte Carlo simulation able to reproduce the number of Cherenkov photons produced in β/γ interactions within the calorimeter and their propagation in the experimental set-up. We demonstrate that the light yield detectable from a $5 \times 5 \times 5$ cm^3 TeO_2 bolometer can be increased by up to 60% by increasing the surface roughness of the crystal and improving the light detector design.

Moreover, we study the possibility to disentangle α, β and γ interactions, which represent the ultimate background source. Unfortunately γ rejection is not feasible but α rejection can be achieved exploiting high sensitivity light detectors.

1. Introduction

Neutrino-less double beta decay (0νDBD) is an extremely rare process (if it occurs at all) in which a nucleus undergoes two simultaneous beta decays without emitting any neutrinos. Since the absence of emitted neutrinos would violate the lepton number conservation, the 0νDBD cannot be accommodated in the Standard Model. Therefore, the observation of this process would have several implications for particle physics, astrophysics and cosmology. The most common theoretical frameworks account for 0νDBD assuming that neutrinos are Majorana particles. This means that, in contrast to all the other known fermions, they must coincide with their own antiparticles. The measurement of the half-life of 0νDBD ($T^{0\nu}_{1/2}$) would allow to infer the effective Majorana neutrino mass ($m_{\beta\beta}$), provided the dependence: $T^{0\nu}_{1/2} \propto 1/m^2_{\beta\beta}$. $m_{\beta\beta}$ is the coherent sum of the three neutrino mass eigenstates according to the PMNS neutrino mixing matrix and including two Majorana phases, thus it depends on the mass hierarchy of neutrino (see Refs [1–3] and the references therein for a complete discussion on the relationship between 0νDBD and neutrino masses).

CUORE (*Cryogenic Underground Observatory for Rare Events*) [4] is an array of 988 TeO_2 cryogenic calorimeters, historically also called bolometers, of $5 \times 5 \times 5$ cm^3 each. Starting operation in 2017 it will become one of the most sensitive experiments searching for 0νDBD of ^{130}Te. The signal produced by this reaction consists of two electrons with a total kinetic energy of about 2.527 MeV (the Q-value of the transition) [5]. Unfortunately the α background rate, at the level of 0.01 counts/keV/kg/y [6], will limit the sensitivity to $T^{0\nu}_{1/2}$ and, consequently to the effective Majorana mass. The sensitivity to $m_{\beta\beta}$ will be at the level of 0.13–0.05 eV in 5 years live time, i.e. the upper limit of the inverted hierarchy region of the neutrino masses [4]. Next generation 0νDBD experiments, such as CUPID (*Cuore Upgrade with Particle IDentification*) [7,8], aim to reach a sensitivity to $m_{\beta\beta}$ of $\sim$ 0.01 eV, i.e. the lower limit of the inverted hierarchy region. To reach this ambitious goal the source mass must be increased and the background in the region of interest dramatically reduced [9]. The CUPID collaboration aims to increase the number of 0νDBD emitters, i.e. the source mass, using crystals grown from enriched material. The background suppression can be achieved by discriminating β/γ against α events by means of the different light yield produced in the interactions within a scintillating bolometer [10]. The main

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candidates for this technique are ZnSe [11,12], $ZnMoO_4$ [13–15] or Li_2MoO_4 [16] scintillating crystals.

The same technique cannot be used for TeO_2 as this crystal does not scintillate [17,18] and also no difference exists between the shape of the pulses produced by α and β/γ interactions [19].

However, the many advantages offered by this material in terms of bolometric performance and lower enrichment cost with respect to other candidate nuclei provided a strong motivation to pursue another, challenging, option: the active background rejection technique can be applied to the TeO_2 bolometer exploiting, instead of the scintillation light, the Cherenkov radiation. Indeed, as proposed in Ref. [20] detecting the Cherenkov radiation produced in the TeO_2 crystal only by electrons (see Section 2.2), it is possible to disentangle the β/γ interactions from the α interactions.

In order to measure the Cherenkov light yield (LY) of TeO_2 bolometers several tests coupling germanium light detectors [21] were performed in a dilution refrigerator working at 10 mK and located deep underground in the Hall C of Laboratori Nazionali del Gran Sasso. The first indication of the feasibility of this technique to reject the α background can be found in Ref. [22]. In this work a small TeO_2 crystal ($3.0 \times 2.4 \times 2.8$ cm^3) doped with natural Sm and covered with 3M VM2002 reflective foils was faced to a germanium light detector. The amount of Cherenkov light detected at 0νDBD energy of ^{130}Te for β/γ interactions was about 173 eV; no light was detected for α particle interactions. A more systematic study of the Cherenkov LY emitted by a CUORE-size TeO_2 crystal was done in Ref. [23] where several reflectors and detector configurations were tested in order to optimize the photon collection. The result of this study was that the maximum amount of Cherenkov light detected from a CUORE TeO_2 crystal is about 100 eV at the Q-value of ^{130}Te 0νDBD, irrespective of the reflector (aluminum, PTFE tape, 3M VM2002). This, combined with the poor baseline resolution of the light detectors (80 eV RMS) prevented the complete α particles rejection. As discussed in Ref. [23] the reduced light collection efficiency and its invariance over the several reflectors tested suggests that most of the emitted light is reabsorbed by the TeO_2 crystal because of its optical properties.

The purpose of this paper is to demonstrate this hypothesis and to quantify its effects exploiting a detailed Monte Carlo simulation of the Cherenkov photon production and propagation in the crystal and in an experimental set-up similar to the one described in Ref. [23]. Thanks to the simulation, it is also possible to identify the parameters able to improve the light collection efficiency of the set-up. Finally, the simulation demonstrates that the Cherenkov radiation tagging technique does not allow for the discrimination between β and γ interactions, that will constitute the ultimate background source for the bolometric experiments based on TeO_2 crystals. Concerning the α background rejection, the simulation results confirm that it can be achieved exploiting a high sensitivity light detector.

2. Cherenkov photon production in a TeO_2 crystal

The number of Cherenkov photons produced per unit path length and per unit wavelength of a particle with charge ze is [24]:

$$\frac{dN^2}{dxd\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2(n(\lambda))^2}\right) \tag{1}$$

where α is the fine-structure constant, β is the ratio between the velocity of the particle and the speed of light, λ the wavelength of the Cherenkov photons, and $n(\lambda)$ the refractive index of the material. Eq. (1) is valid as long as it is positive, namely as long as the charged particle moves faster than light in the respective medium ($\beta n > 1$). As shown in Eq. (1) the evaluation of the number of Cherenkov photons produced by a particle interaction within a TeO_2 crystal requires the knowledge of its optical properties and the particle range. Therefore in the following sections the optical properties of TeO_2 crystals will be presented together with its stopping power for electrons, in order to perform an estimation of the Cherenkov photons emitted in the β/γ interactions.

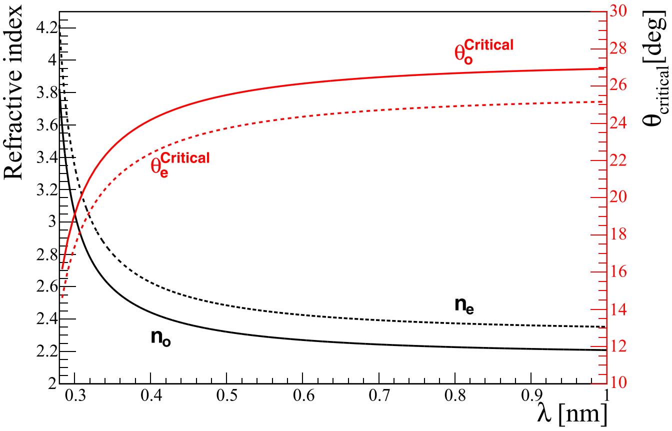

Fig. 1. Ordinary (n_o, continuous black line) and extraordinary (n_e, dotted black line) refractive indices of TeO_2 crystal as function of wavelength at room temperature [25]. $\theta^{Critical}$ is the critical angle for total internal reflection for an optical photon that hits the internal surface of a TeO_2 crystal surrounded by vacuum using the ordinary ($\theta_o^{Critical}$, continuous red line) and extraordinary ($\theta_e^{Critical}$, dotted red line) refractive indices. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Coefficients of the Sellmeier equations for the TeO_2 crystal at room temperature [25].

	A	λ_1 [µm]	B	λ_2 [µm]
n_o	2.584	0.1342	1.157	0.2638
n_e	2.823	0.1342	1.542	0.2631

2.1. Optical properties of TeO_2 crystals

TeO_2 is a birefringent material. The ordinary and extraordinary refractive indices (n_o and n_e, respectively) are shown in Fig. 1. Both the refractive indices are described by the Sellmeier equation [26]:

$$n(\lambda)^2 - 1 = \frac{A\lambda^2}{\lambda^2 - \lambda_1^2} + \frac{B\lambda^2}{\lambda^2 - \lambda_2^2} \tag{2}$$

The Sellmeier parameters for the TeO_2 crystal are shown in Table 1.

As TeO_2 crystals are currently produced for acousto-optic devices, special attention is given in literature only to optical properties connected to this application. The study of optical characteristics as transmission and reflection near and above the fundamental absorption edge, at low temperatures, were carried out down to only 80 K [27] and experimental results [25,27] do not allow for a definitive interpretation of the electronic band structure for TeO_2 crystals. It is also missing from the literature a detailed study of the agreement between calculated electronic structure [28] and optical transmission measurements. We performed optical transmission measurements on pure TeO_2 slices using a Perkin Elmer Lambda 900 spectrophotometer and a Leybold RDK10-320 ($T_{min} = 12$ K) cryostat. The results around the fundamental absorption edge are shown in Fig. 2; for wavelengths longer than 340 nm the absorption length approaches a value of about 80 cm, irrespective of the temperature. The absorbance spectra show a temperature dependence typical of an indirect band structure, and the shift in the $\lambda_{cut-off}$ due to the temperature variation reaches an asymptotic value for $T < 50$ K. This suggests that for temperatures below