Monte Carlo simulation of the Cherenkov radiation emitted by TeO$_2$ crystal when crossed by cosmic muons


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TeO$_2$ crystals are currently used as bolometric detectors in experiments searching for the neutrinoless double beta decay of $^{130}$Te. The extreme rarity of the studied signal forces the experiments to reach an ultra low background level. The main background source is represented by $\alpha$ particles emitted by radioactive contaminants placed in the materials that compose and surround the detector. Recent measurements show that a particle discrimination in TeO$_2$ bolometers detecting the light emitted by $\beta = \gamma$ particles is possible, opening the possibility to make large improvements in the performance of experiments based on this kind of materials. In order to understand the nature of this light emission a measurement at room temperature with TeO$_2$ crystals was performed. According to these results, the detected light was compatible with the Cherenkov emission, even though the scintillation hypothesis could not be discarded. In this work a Monte Carlo (MC) simulation of the Cherenkov radiation emitted by TeO$_2$ crystal when crossed by cosmic muons was performed. The data from MC and the room temperature measurement are perfectly compatible and prove that the Cherenkov light is the only component of the light yield of TeO$_2$ crystals.

1. Introduction

Tellurium dioxide (TeO$_2$) crystals are used as bolometers for the search of neutrinoless double beta decay [1,2]. They are able to measure energies in the MeV region with a resolution of the order of a few keV. The main source of background is represented by $\alpha$ particles emitted by radioactive contaminants, located on the surfaces of the detector or on passive elements facing them. As predicted in Ref. [3] and demonstrated in Ref. [4], the observation of light emitted by electrons in a TeO$_2$ bolometer can provide a powerful tool to disentangle $\alpha$ from $\beta / \gamma$ particles. The Cherenkov radiation is the most probably origin of this light signal. In order to assess and measure the Cherenkov contribution in the light yield of a TeO$_2$ crystal and distinguish it from a possible scintillation emission a measurement at room temperature was performed [5]: the study of the signal shape and of the directionality of the light yield allow to conclude that Cherenkov light represents at least the 66% of all the light emitted by a TeO$_2$ crystal.

The aim of this work is to demonstrate that the light production in the TeO$_2$ crystal can be ascribed to the Cherenkov radiation only. For this purpose, a Monte Carlo simulation that reproduces the experimental set-up used in Ref. [5] was performed. This simulation is based on the LITRANI software [6], that is able to simulate the propagation of optical photons in any type of optical media and model the response of surface or volume detectors like photomultipliers or APDs. The aim is to follow each photon until it is absorbed or detected.

In the next sections the experimental set-up used in Ref. [5] is reproduced, and the results obtained from the MC are compared with the experimental ones.

2. Experimental set-up

The experimental set-up is shown in Fig. 1. A $5 \times 2.5 \times 2.5$ cm$^3$ crystal placed inside a black box was read-out on the two small opposite faces with two photo-multiplier tubes (PMTs) XP2970.
with an extended sensitivity in the UV region where the production of Cherenkov photons is expected to be large.

The box was free to rotate in the $XY$ plane giving the possibility of changing the angle $\phi$ between the longest crystal axis and the horizontal direction in the range $\pm 40^\circ$.

The Cherenkov photons are emitted in a cone with an opening angle $\theta_c = \arccos(1/\beta)$ with respect to the particle direction. Therefore the Cherenkov light transmission to a PMT is expected to be at a maximum when the crystal is parallel to the Cherenkov photon direction. Since the TeO$_2$ refractive index in the band of the detected light is about 2.27, for an angle $\phi_{m} = 90 - \theta_{c} = 26^\circ$, PMT-Left is expected to see the maximum amount of Cherenkov light which, instead, reaches PMT-Right for $\phi = 26^\circ$. In order to select vertical muons in cosmic rays, the trigger signal to the data acquisition was provided by the coincidence of two 2 cm thick, $4 \times 7$ cm$^2$ scintillator fingers placed above and below the crystal; see Ref. [5] for more details.

In order to reproduce the production and the propagation of the Cherenkov photons in this experimental set-up the optical properties of all optical materials must be known. The main optical material is the TeO$_2$ crystal and his refractive index and absorption length are shown in Figs. 2 and 3.

The two faces of the crystal, read-out with the PMTs, are polished and optically coupled with the PMTs windows in order to maximize the transmission of the photons between these two different media and increase the numbers of photons that hit the photocathode. The optical properties of the optical grease and of the PMTs windows are also taken into account in the MC simulation.

Special attention has to be given to the simulation of the interaction of photons with the lateral surface of the crystal. Indeed the Fresnel equations, which describe the behavior of light when moving between media of differing refractive indices, are suitable only when the surfaces are perfectly smooth. Otherwise the real interaction between photons and unpolished surfaces needs to be parameterized. LITRANI uses the following technique: the normal to the surface at the point hit by the photon is randomly tilted (with respect to the true normal of the surface) by an angle $\theta$, which is generated according to a distribution $\sin(\theta) \, d\theta \, d\phi$, between 0 and $\theta^\circ$. The parameter $\theta^\circ$ is a function of the surface roughness.

For the TeO$_2$ crystal a lateral surface roughness corresponding to $\theta^\circ \sim 10^\circ$ was assumed. This value is reasonable for the crystal measured in Ref. [5] and his effect on the simulation results will be discussed in detail in Section 4.

The last fundamental parameter of the simulation is the photocathode quantum efficiency of the PMT and it is shown in Fig. 4.

All these components are arranged coherently with the experimental setup shown in Fig. 1. The trigger system is not included in the simulation as it has no influence on the measured data.

Finally a muon beam with an energy of 4 GeV crossing the TeO$_2$ was simulated: for each angle between $-40$ and $+40^\circ$ with steps of $10^\circ$ 50 muons are propagated. These muons interact with the TeO$_2$ crystal emitting Cherenkov photons.
3. Monte Carlo results

The average number of photons seen by the PMT-Right \( N_R(\phi) \) and PMT-Left \( N_L(\phi) \) as function of the incident angle are shown in Fig. 5.

The number of photons expected at angles far from \( \phi_m \) (\(-26^\circ\) for \( N_R(\phi) \) and 26° for \( N_L(\phi) \)) should be almost zero. On the contrary, in Fig. 5 one can see that a considerable number of photons was detected even at disadvantageous angles for the light transmission to a PMT.

Although the Cherenkov photons are emitted in a cone with an opening angle \( \theta_c \) with respect to the particle direction, the photons scatter on the lateral surface of the crystal. This interaction makes losing their initial directionality producing a flat component in the light yield, independent from the angle between the muon and the crystal.

4. Monte Carlo and experimental data

The experimental results in Ref. [5] were presented in terms of the light exiting from the faces of the crystal equalized at \( \phi = 0 \) and corrected for the muon path length \( 1/\cos \phi \):

\[
L(\phi) = \frac{\overline{L}(\phi)}{\overline{L}(0)} = \frac{1}{k}(A + B(\phi)),
\]

\[
R(\phi) = \frac{\overline{R}(\phi)}{\overline{R}(0)} = \frac{1}{k}(A + B(-\phi)),
\]

where

- \( A \) is the flat component of the light yield independent from the angle between the muon and the crystal produced by scintillation light or by Cherenkov light diffused by the internal reflections on the crystal faces losing its initial directionality;
- \( B(\phi) \) is the component produced by the Cherenkov effect with directionality and for which the probability of exiting from a face of the crystal is a function of the angle \( \phi \);

and \( k \) is the normalization factor equal to \( A + B(0) \). (see Ref. [5] for more details).

The quantities \( L(\phi) \) and \( R(\phi) \) are equal to the number of photons seen by the PMTs \( N_R(\phi) \) and \( N_L(\phi) \) normalized for the number of photons seen at \( \phi = 0 \), corrected for the muon path length \( 1/\cos \phi \). The comparison between data and simulation (Fig. 6) shows that all the light emitted by the TeO\(_2\) crystal can be ascribed to Cherenkov radiation: the trend of \( R(\phi) \) near the maximum position (\( \phi_m = -26^\circ \)) is compatible with the measured one, confirming that the directional component \( B(\phi) \) produced by the Cherenkov photons is very well reproduced by the simulation; also, at angles far from \( \phi_m \), where the contribution of \( B(\phi) \) should be almost zero and the flat component is dominant, the simulation reproduces the data; the same considerations are valid for \( L(\phi) \).

In this simulation all the optical photons produced into the crystal come from the Cherenkov effect, any scintillation process was not taken into account. This implies that the flat component
measured in Ref. [5] is totally due to the Cherenkov photons scattered by the internal reflections on the crystal faces.

The experimental values of \( L(\phi) \) and \( R(\phi) \) match the simulated ones if the lateral surface roughness is characterized by \( \theta_n \sim 10^{1} \). Increasing this parameter the total amount of Cherenkov photons escaping from crystal faces increases, and the number of photons absorbed inside the crystal decreases. The result is that the trend for \( L(\phi) \) and \( R(\phi) \) are no longer reproduced by the simulation as in Fig. 6. Nevertheless the conclusions about the nature of the light yield of the TeO\(_2\) crystal are still valid. This is proven by the study of the charge asymmetry \( \Delta(\phi) \): the ratio between the isotropic and the directional light component. In Ref. [5] the charge asymmetry is defined as:

\[
\Delta(\phi) = \frac{L(\phi) - R(\phi)}{L(\phi) + R(\phi)} = \frac{B(\phi) - B(-\phi)}{2A + B(\phi) + B(-\phi)}, \tag{3}
\]

Using the number of photons seen by the PMTs \( N_R(\phi) \) and \( N_L(\phi) \), we have that

\[
\Delta(\phi) = \frac{N_L(\phi) - N_R(\phi)}{N_L(\phi) + N_R(\phi)}. \tag{4}
\]

As expected this quantity is well reproduced by the simulation (Fig. 7), and turns out to be not affected by the value of \( \theta_n \) as shown in Fig. 8 where three different values of \( \theta_n \) are tested: 5\(^\circ\), 10\(^\circ\) and 15\(^\circ\). The three curves are compatible with each other and prove that variations of \( \pm 50\% \) of the lateral surface roughness do not affect the ratio between the isotropic and directional components of the Cherenkov light yield.

The agreement between simulations and data in the charge asymmetry implies that any contribution due to the scintillation light would increase the isotropic component, mismatching simulations and data. This suggests that the contribution of an hypothetical scintillation process in the light yield of the TeO\(_2\) crystals is to discard.

5. Conclusion

The Monte Carlo simulation performed in this work well reproduces the experimental data, confirming the hypothesis that the light emission from TeO\(_2\) crystals is entirely due to the Cherenkov effect. The flat component is compatible with the expected number of Cherenkov photons scattered by the lateral surfaces of the crystal. Therefore the contribution of scintillation light, if it exists, is negligible.

References