Particle Discrimination in TeO\textsubscript{2} Bolometers using Light Detectors read out by Transition Edge Sensors

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An active discrimination of the dominant \(\alpha\)-background is the prerequisite for future DBD experiments based on TeO\textsubscript{2} bolometers. We investigate such \(\alpha\)-particle rejection in cryogenic TeO\textsubscript{2} bolometers by the detection of Cherenkov light. For a setup consisting of a large TeO\textsubscript{2} crystal (285 g) and a separate cryogenic light detector, both read out by transition edge sensors at around 10 mK, we obtain an event-by-event identification of \(e/\gamma\)- and \(\alpha\)-events. In the energy interval ranging from 2400 keV to 2800 keV and covering the Q-value of \(^{130}\text{Te}\) a discrimination power of 3.7 could be demonstrated.

I. INTRODUCTION

The postulation of the neutrino in 1930 by W. Pauli was followed by many decades of intensive experimental investigations, though still today important properties of this particle are unknown. Oscillation experiments have confirmed that the three families of neutrinos mix and that at least two of them have a finite mass. However, information on the absolute mass scale, the ordering of these masses, charge conjugation properties and lepton number conservation is still missing.

In the case that neutrinos are Majorana particles \cite{1}, which implies the presence of physics beyond the Standard Model of particle physics, an extremely rare process should be observable, namely the so-called Neutrinoless Double Beta Decay (\(0\nu\text{DBD}\)) \cite{2}, in a \(0\nu\text{DBD}\) the mother nucleus decays by the simultaneous emission of two beta-particles only. As no neutrinos are emitted, the full energy of the decay, the Q-value, is shared between the two electrons. The evidence of \(0\nu\text{DBD}\) would prove that neutrinos are their own anti-particles and that lepton number conservation is still missing. Also, constraints would be set on the mass scale of the neutrinos.

Numerous experiments are searching for this process with the distinctive signature of a monochromatic line at the Q-value of the decay - the combined energy of the two simultaneously emitted electrons.

Low temperature bolometers are ideal detectors for such surveys: crystals can be grown with a variety of interesting DBD-emitters, and multi-kg detectors \cite{3, 5} can be operated with excellent energy resolution (1-2%/per thousand zero) at the Q-value \cite{4}.

Up to now, low temperature bolometers searching for \(0\nu\text{DBD}\) were mainly using TeO\textsubscript{2} crystals \cite{4, 5}, which show very good mechanical and thermal properties \cite{6}, have a very large natural isotopic abundance of the candidate isotope \(^{130}\text{Te}\) (34.2% \cite{7}) and, most importantly, are produced at industrial scale.

At present, radioactive surface contamination is the key-issue \cite{8, 9} that may limit the sensitivity of tonne scale experiments like CUORE \cite{10}: \(\alpha\)-particles can loose a fraction of their initial energy while passing through the bulk material before interacting in the bolometer. Such, so-called degraded \(\alpha\)-particles show a flat energy spectrum ranging from the Q-value of the decay (several MeV) down to threshold energy, thereby possibly creating background within the region of interest for \(0\nu\text{DBD}\) \cite{11}.

For next-generation bolometric DBD experiments beyond CUORE \cite{12}, the only way to further reduce this \(\alpha\)-background is to actively identify the interacting particles. In case of non-scintillating crystals like TeO\textsubscript{2} this discrimination could be obtained measuring the Cherenkov light emitted by electrons as suggested in \cite{13}. Alpha-particles of few MeV have energies below the threshold for the creation of Cherenkov light. Since the expected light signal of electrons is \(\mathcal{O}(100\text{eV})\) \cite{13}, light detectors with excellent performance should be employed.

The first published measurement on the detection of Cherenkov light in this context was carried out on a 116 g TeO\textsubscript{2} crystal demonstrating that \(\alpha\)-particles can be discriminated \cite{14}. Very recently an event-by-event discrimination was obtained with a very small TeO\textsubscript{2} bolometer based on a 23 g crystal \cite{15}. Measurements on a large crystal (750 g) demonstrate that difficulties may substantially increase with crystal size and light detectors with a threshold as low as some 10 eV are required \cite{16}.

In this work we report the results from a measurement of the Cherenkov light emitted by a large 285 g TeO\textsubscript{2} bolometer. The light absorber is read out by a Transition Edge Sensor (TES) of the same type as used in the CRESST dark matter search \cite{17}, proving for the first time that an effective event-by-event discrimination can be achieved also on large mass crystals.

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The TeO$_2$ crystal used in this work is a cylinder (40 mm diameter and height, 285 g in weight). The cylindrical surface of the crystal is mechanically roughened to increase the collection of Cherenkov light \cite{13}. The two flat surfaces are polished, close to optical grade. The crystal is operated as a bolometer at about 10 mK and read out by a W-TES. TESs are highly sensitive thermometers which allow to detect tiny temperature excursions \(\Delta T\) \(\mathcal{O}(\mu\text{K})\) due to particle interactions in the crystal, thereby causing a change in the resistance of the TES \(\Delta R\). In our case, the TES consists of a thin tungsten film (200 nm) stabilized in its transition between the normal conducting and the superconducting phase by a dedicated heater. Since a direct evaporation onto the TeO$_2$ crystals did not succeed and would have required an investigation of suitable process parameters, a composite detector design was used instead \cite{19}: a small (20x10x2) mm$^3$ cadmium tungstate carrier crystal (CdWO$_4$), equipped with the W-TES, was attached onto one of the flat surfaces of the TeO$_2$ by vacuum grease (DowCorning UHV). The reason for choosing a CdWO$_4$ crystal as carrier of the W-TES is discussed in section III.

The polished side of the TeO$_2$ crystal is facing a cryogenic light detector of CRESST-II type \cite{17}, which consists of a thin sapphire disc (thickness of 460 \(\mu\text{m}\)) with a diameter of 40 mm, equal to the diameter of the crystal. Since pure sapphire is optically transparent a 1 \(\mu\text{m}\) thick layer of silicon is epitaxially grown onto the sapphire disc. Light detectors of this type we refer to as SOS (Silicon on Sapphire). Also the light absorber is read out by a W-TES, optimized for light detection. The crystal and the light detector are enclosed in a reflective housing (VM2002 Radiant Mirror Film).

To study the discrimination capability of e/\(\gamma\)-events from \(\alpha\)-particles a degraded \(\alpha\)-source of $^{238}$U is facing the flat surface of the TeO$_2$ crystal which also carries the TES. The source is aligned in a way to avoid any line of sight to the TES and to the surrounding.

The measurement was carried out in the test facility of the Max-Planck-Institute for Physics Munich. The facility is located at Laboratori Nazionali del Gran Sasso (LNGS), a deep underground site in central Italy. This set-up consists of a dilution refrigerator which is surrounded by about 20 cm of low background lead to shield the environmental e/\(\gamma\)-radioactivity. A platform attached by a spring to the mixing chamber of the dilution unit mechanically decouples the detector from the cryogenic facility in order to reduce microphonic noise. The readout of the TES is realized via a commercial dc-SQUID electronics (Applied Physics Systems). The hardware triggered signals are sampled in a 409 ms window with a sampling rate of 10 kHz. Both detectors are always read out simultaneously, independent of which channel triggered.

More detailed descriptions of the DAQ, the control of detector stability as well as the pulse height evaluation and energy calibration procedures are given in \cite{20,21}.

### III. DETECTOR PERFORMANCE

In this section we report on pulse-shape parameters and energy resolution of the TeO$_2$ bolometer and its light detector.

#### A. TeO$_2$ Crystal

Signals of the W-TES caused by interactions in the TeO$_2$ bolometer are very small in comparison to other inorganic scintillating materials read out by a W-TES of the same type as the one used in this work. This behavior can be attributed to the acoustic mismatch between TeO$_2$ and the CdWO$_4$ crystal carrying the W-TES: a particle interaction in an inorganic anisotropic single crystal as e.g. TeO$_2$ creates high frequency phonons \(\mathcal{O}(\text{THz})\) with

#### TABLE I. Calculated phonon group velocities for acoustic transversal and acoustic longitudinal phonon modes in TeO$_2$, CaWO$_4$ and Al$_2$O$_3$. Since values for CdWO$_4$ are absent in literature CaWO$_4$ is listed instead. For each interface only the phonons travelling along the crystal axis normal to the interface are considered. The Debye temperature \(\Theta_D\) is listed for every crystal.

| Material | \(v_{TA}\) | \(v_{LA}\) | \(\Theta_D\) | Ref. |
|----------|------------|------------|-------------|-----|
| TeO$_2$  | 2.2        | 3.2        | 232         | \cite{23}, \cite{24} |
| CaWO$_4$ | 2.45       | 4.76       | 335         | \cite{25}, \cite{26} |
| Al$_2$O$_3$ | 6.1    | 11.2       | 1041        | \cite{22}, \cite{24} |
energies of a few meV. As these energies are much higher than thermal energies at the temperature of the detector operation (about 10 mK) corresponding to 1 µeV, these phonons are called non-thermal phonons.

This initial phonon population is not stable and decays very quickly to a distribution with a mean frequency of few 100GHz [22]. This fast decay is followed by a period of few milliseconds where the distribution of average phonon frequencies remains quasi constant. During this time the phonons spread ballistically over the volume of the crystal.

These phonons may get absorbed directly in the TES, thereby creating the fast so-called non-thermal part of the detected signal. The TES relaxes back to equilibrium temperature via its thermal link to the heat bath (dominant process), but also via re-emission of thermal phonons into the crystal. Phonons that thermalize in the crystal by inelastic scattering (e.g. on the surface or on crystal defects) also lead to an increase in the crystal’s temperature and cause the slow thermal component of the detected signal. Typically, the fast component dominates the signal at very low operating temperatures, where the slow component is suppressed as a consequence of the weak coupling between electrons and phonons in the TES. Thus, being operated in the bolometric mode, the pulse height of the detected signals is determined by the flux of non-thermal phonons and the thermal coupling of the TES to the heat bath.

The left plot of Figure 2 shows a fit of a pulse averaged over a set of $\gamma$ events (208Tl-line) in the TeO$_2$ crystal. Also the signal’s non-thermal component (dotted line) and the thermal component (dashed line) are indicated. For comparison, the right hand side of Figure 2 shows the result of such a fit to the events from 122 keV $\gamma$-events ($^{57}$Co calibration) in a CdWO$_4$ crystal (40 mm in diameter and height). For both measurements the same W-TES evaporated onto a small CdWO$_4$ carrier crystal was used. In case of the TeO$_2$ crystal the carrier was attached by conventional vacuum grease. In the case of CdWO$_4$, the carrier crystal was glued onto the big absorber using a low viscous epoxy resin (EpoTek 301-2).

For the pulses illustrated in Figure 2 the energy deposited in TeO$_2$ (left plot) is about 20 times higher than in the CdWO$_4$ crystal (right plot). However, the detected pulse amplitude is of same order. Especially, the contribution of the non-thermal component in the TeO$_2$ crystal is significantly reduced. Non-thermal phonons seem to thermalize before being detected in the TES resulting in an overall small pulse amplitude with a long decay time.

The explanation for the experimental observation is manifold: phonons that have to be transmitted between two carefully bonded dissimilar crystalline media (crystal -> interface -> carrier crystal -> metal film) will experience a boundary resistance.

The reflection, refraction and mode conversion of phonons on crystalline interfaces is described by the acoustic impedance mismatch model [27]. In contrast, an amorphous interface as epoxy resin or grease allows low energy phonons more easily to pass the interface due to its rich energy spectrum, thus working as a low pass filter [28].

A first idea on the quality of the phonon transmission between solid-solid interfaces can be gained by comparing the Debye temperatures $T_D$ of the bonded materials (see Table 1). The larger the discrepancy between the $T_D$ values of the two bond materials the lower the transmission probability. A qualitative estimation on the phonon transmission can be achieved by comparing the sound velocity of the various materials: the ratio of the speed of...
sound in material 1 to the speed of sound in material 2 \(v_{m1}/v_{m2}\) gives a very rough estimation for the phonon transmission probability. A quantitative way of calculating the transmission and related parameters while including the anisotropy of a real crystal is illustrated in \[29\]. However, such calculations cannot be performed because the elastic constants and the lattice orientation are unknown for the materials of this work.

The thin grease/epoxy layer used to attach the carrier onto the large crystal does not affect the phonon propagation. This is proven by composite detectors made from CaWO\(_4\) and CdWO\(_4\) where no degradation of the phonon signal, in particular the non-thermal component is observed. Estimating the transmission probability for the material combination TeO\(_2\) and CaWO\(_4\) by using the simple ratio results in a transmission of about 30\%. A similar value is expected for the material combination TeO\(_2\) and CdWO\(_4\).

Prior to the measurement reported in this publication the same TeO\(_2\) crystal was operated using a carrier crystal made out of sapphire (Al\(_2\)O\(_3\)). The pulse amplitude of 2615 keV \(\gamma\)-s in this configuration was about six times smaller than in the measurement reported (see Figure \[2\]). The simple calculation for the phonon transmission results in about 3\% for the configuration TeO\(_2\) and Al\(_2\)O\(_3\) and is roughly consistent with the observed degradation in pulse amplitude in comparison to the combination TeO\(_2\) and CaWO\(_4\).

However, the acoustic mismatch between carrier and crystal is not sufficient to serve as the unique explanation for the observed degradation in the non-thermal signal component. In TeO\(_2\) other processes which reduce the life time of the non-thermal phonon population due to inelastic processes in the crystal or on the crystals’ surface may play a role. The crystal used for the work presented here was mechanically roughened on the lateral surface. Surface imperfections induced by a mechanical treatment showed a degradation of the detected signal amplitude, in other experimental works, using Si or sapphire substrates. Further studies are necessary to gain a better understanding of the observed small signal amplitudes in TeO\(_2\) crystals read out by W-TES.

The energy resolution achieved at the 2.6 MeV \(^{208}\text{TL}\) line is: \(\sigma=10.2\) keV. In comparison, the energy resolution of a CUORE crystal (750 g) read out by a NTD-Ge with optimized thermal design and working conditions is 2.2 keV \(\sigma\) [4]. An energy resolution of 1-2\%\(\gamma\) at the Q-value energy is a prerequisite for a future DBD experiment. Thus, thermistors to read out the signals of large bolometers are superior to transition edge sensors in the energy region interesting for DBD (MeV-scale), given their large dynamic range of operation.

## IV. RESULTS

The background data of the TeO\(_2\) bolometer acquired in 0.67 days of live time in the light yield-energy plane are shown in Figure \[5\]. The light yield in this context is defined as the direct energy detected in the light detector in eV per one MeV of deposited energy in the TeO\(_2\) crystal. Two distributions can be observed. The highly populated band is due to e/\(\gamma\)-interactions, the less populated band at zero light yield is due to \(\alpha\)-particle interactions from the degraded \(^{238}\text{U}\) \(\alpha\)-source.

The test facility does not exhibit a low-background environment and several \(\gamma\)-lines are visible in the scatter plot (Figure \[5\]). The dominant part of the e/\(\gamma\)-background comes from non-radiopure materials used for manufacturing the cryostat and the LHe-dewar located inside the Pb shield. Furthermore, the Pb-shield around the LHe-dewar does not completely enclose the experiment. The highest observable \(\gamma\)-line from thallium appears at 2615 keV. We find the energy of the detected Cherenkov light at this \(^{208}\text{TL}\)-line to be 128.9 eV (\(\sigma=32\) eV).

The band ascribed to e/\(\gamma\)-events is shown in form of a central probability band. Two functions define this band: the mean value of the light yield and the energy-dependent width of the band around the mean value which is set by the finite energy resolution of the detectors. The following notation is used: the energy de-
FIG. 3. Left figure: Fit of an averaged pulse (solid line) from a direct hit in the light detector and from a Cherenkov event (dashed line), both at an absolute energy of about 125 eV (this work). Right figure: Fit of an averaged pulse from a direct hit in a SOS light detector at 5.9 keV ($^{55}$Mn K-$\alpha$-line). The light detector is paired with a CaWO$_4$ crystal. The corresponding scintillation light event (same energy deposition in the light detector) from the CaWO$_4$ crystal is shown as a dashed line. Since the scintillation process is slow in comparison to the production of the prompt Cherenkov light, the scintillation light events can be discriminated by pulse shape from direct hits of the light detector. A discrimination of Cherenkov light events from direct hits of the light detector (left plot) is not feasible.

FIG. 4. Calibration spectrum of the light detector. The $^{55}$Mn K-$\alpha$- and K-$\beta$-line at 5.9 keV and 6.5 keV show a resolution of 109 eV $\sigma$. These lines are used to establish a direct energy calibration of the light detector.

Posited in the crystal is $E$, the corresponding energy emitted in form of Cherenkov light is $L$. In this data-oriented model the mean of the light yield of the $e/\gamma$-event distribution is

$$LY_{e/\gamma}(E) = p_0 E.$$  \hspace{1cm} (1)

The value of $p_0$ is around 50 since the light yield after absolute energy calibration of the light detector is about 50 eV for 1 MeV of deposited energy in the crystal.

The width of the band is given by the energy resolution of the detectors. Due to high statistics, the energy dependence of the resolution can be extracted from a fit of the $e/\gamma$-band. The width of the $e/\gamma$-band can be well described by a Gaussian function with the width $^{[30]}$

$$\sigma_{e/\gamma} = \sqrt{\sigma_l^2 + \left(\frac{dL}{dE} \cdot \sigma_{TeO_2}\right)^2 + S_1 L} \hspace{1cm} (2)$$

where $\sigma_l$ and $\sigma_{TeO_2}$ is the baseline noise of the light detector and the TeO$_2$ bolometer and $S_1$ accounts for the statistical fluctuations in the number of detected photons (Poisson statistics). During the detector operation so-called test pulses are injected to the detector via the TES heater. The resolutions of a test pulse in the light detector and the TeO$_2$ bolometer directly yield the $\sigma_l$ and $\sigma_{TeO_2}$ parameters since test pulses, in comparison to particle pulses, are not affected by photon statistics.$^{[3]}$

The band description is shown in Figure 5: the dotted contour lines are plotted with central $\pm 1.28 \sigma$ boundary lines whereas the solid lines are plotted with central $\pm 3.1 \sigma$ boundary lines, thus 99.8% of all $e/\gamma$-events are expected to be within the two solid contour lines. The $\alpha$-particle distribution appears at a light yield of zero, well separated from the populated $e/\gamma$-band.

A projected view of the light yield in [eV/MeV] allows to visualize the achieved discrimination of $\alpha$-particles from $e/\gamma$-events; in Figure 6 a histogram of all events observed in the energy interval from 2400 keV to 2800 keV is shown. Two Gaussian functions (all parameters free) are used to fit the two distributions (red solid line): $\alpha$-particles appear at $(0.80 \pm 0.89)$ eV/MeV, whereas for the distribution of $e/\gamma$-events the mean value is found to be $(48.55 \pm 0.36)$ eV/MeV.

$^{[3]}$ The values for the detector module of this work are $\sigma_l = 261$ keV, $\sigma_{TeO_2} = 9.8$ keV and $S_1 = 360$ keV.
The fit gives a resolution of $\sigma = (8.74 \pm 0.27) \text{ eV/MeV}$ for the $e/\gamma$-peak and $\sigma = (9.53 \pm 0.75) \text{ eV/MeV}$ for the $\alpha$-peak. Since the $\alpha$-events do not produce light the resolution is expected to be slightly better in respect to the $e/\gamma$-events because of the missing Poisson statistics contribution. However, the $\sigma$'s of both distributions are compatible due to the lack of statistics (see Figure 6).

Following [31], the discrimination power (DP) between two symmetric distributions can be given by comparing the difference between the mean values of the two distributions weighted by the square root of the quadratic sum of their widths

$$DP = \frac{\mu_{\beta/\gamma} - \mu_{\alpha}}{\sqrt{\sigma_{\beta/\gamma}^2 + \sigma_{\alpha}^2}} \quad (3)$$

where $\mu_{\beta/\gamma}$ and $\mu_{\alpha}$ are the mean values of the two distributions' and $\sigma_{\beta/\gamma}$ and $\sigma_{\alpha}$ are their corresponding widths. Inserting the values gained from the double-Gaussian fit displayed in Figure 6 yields a value of DP equal to 3.7. Thus, we achieve the highest suppression up to now, in particular carried out on a large TeO$_2$ bolometer (see Table I).

Experiments using light detectors read out by NTD-Ge with the characteristics presented in [14] [16] so far do not arrive at a sensitivity level which allows for a discrimination on an event-by-event base. An improvement by a factor of four ($\sigma \approx 20 \text{ eV (RMS)}$) on the performance of the thermistor would be needed for an effective $\alpha$-particle suppression. A TES-based light detector combined with Neganov-Luke amplification technique [14] showed an $\alpha$-suppression of 99% while accepting 99.8% of all $e/\gamma$-events at the $^{208}\text{Tl}$-line, but on a very small 23 g TeO$_2$ crystal.

In Table I we summarize the properties and the performance of the before mentioned cryogenic light detectors used for the detection of Cherenkov light from TeO$_2$ bolometers.

V. CONCLUSION AND PERSPECTIVE

In order to explore the inverted hierarchy region, next-to-next $0\nu$DBD experiments based on TeO$_2$ bolometers have to adopt a particle discrimination method to reject the $\alpha$-background in the region of interest for $0\nu$DBD. We demonstrated for the first time, using a large TeO$_2$ bolometer (285 g), that the detection of the Cherenkov light by operating a TES-based cryogenic light detector allows to suppress the $\alpha$-background. We achieve a discrimination power for $e/\gamma$-events from $\alpha$-particles in the energy interval from 2400 keV to 2800 keV comprising the Q-value of $^{130}\text{Te}$, of 3.7.

For what concerns the readout of the TeO$_2$ crystal a NTD-Ge thermistor is superior to a TES since such thermistors have shown to be able to reach a resolution of 1-2% at the Q-value.

The light detector used in this work has an RMS of the baseline of about 24 eV $\sigma$. Best performing TES-based light detectors operated in the CRESST-II dark matter search show $\sigma=5 \text{ eV (RMS)}$ [32]. This is an improvement of a factor of about five that would allow to enlarge the light absorber without losing discrimination.
TABLE II. Summary on the performance of different cryogenic light detectors used for the detection of Cherenkov light from TeO$_2$ bolometers.

| Material | Area [cm$^2$] | Thermometer | $\sigma$ [eV RMS] | TeO$_2$ mass [g] @ 2.6 MeV in [eV] | Cherenkov light DP | Ref. |
|----------|---------------|-------------|----------------|-----------------|-----------------|-----|
| Ge       | 19.6          | NTD-Ge      | $\approx 72$  | 750             | $\approx 100$   | 1.5 | [10]|
| Ge       | 34.2          | NTD-Ge      | $\approx 97$  | 117             | $\approx 195$   | 1.4 | [14]|
| Si       | 4.0           | IrAu-TES + NL | $\approx 8$   | 23              | $\approx 78$    | 2.9 | [15]|
| SOS      | 12.6          | W-TES       | $\approx 23$  | 285             | $\approx 129$   | 3.7 | this work |

power. A light absorber with a larger area might be employed in order to detect the Cherenkov light from several large TeO$_2$ crystals (750 g each), in a CUORE-like structure. To equip a next-generation CUORE-type experiment with 1-tonne of isotopic mass using enriched TeO$_2$ crystal with such large light absorbers would allow for a limited number of SQUID channels and would mitigate the challenge of manufacturing W-TES on a mass-production scale.

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