Cherenkov light identification in TeO$_2$ crystals with Si low-temperature detectors

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Abstract.
Low temperature thermal detectors with particle identification capabilities are among the best detectors for next generation experiments for the search of neutrinoless double beta decay. Thermal detectors allow to reach excellent energy resolution and to optimize the detection efficiency, while the possibility to identify the interacting particle allows to greatly reduce the background. Tellurium dioxide is one of the favourite compounds since it has long demonstrated the first two features and could reach the third through Cherenkov emission tagging [1]. A new generation of cryogenic light detectors are however required to detect the few Cherenkov photons emitted by electrons of few MeV energy. Preliminary measurements with new Si light detectors demonstrated a clear event-by-event discrimination between alpha and beta/gamma interactions at the $^{130}$Te neutrinoless double beta decay Q-value (2528 keV).

1. Introduction
Large mass thermal detectors are powerful tools for the search of neutrinoless double beta decay. Next generation experiments plan to exploit their excellent properties to push the sensitivity inside the inverted hierarchy region of neutrino masses. Tellurium dioxide is one of the favourite compounds for the next generation bolometric experiments because of the excellent quality and purity of the crystals, high isotopic abundance and excellent bolometric performance. Recently, the idea of exploiting Cherenkov emission to tag the electrons produced in the double beta decay was proposed [1]. At the typical energy of the decay products, electrons are above threshold for Cherenkov emission, while alphas are not. This allows to identify and reject the main source of background: alpha surface contamination [2].

2. Upgrade of TeO$_2$ bolometers for a ton scale experiment
CUORE [4] is a 741 kg array of 988 TeO$_2$ bolometers currently in an advanced construction phase in the underground laboratories of Gran Sasso. With a background of 0.01 counts/keV/kg/yr, in five years of data taking and with an energy resolution of 5 keV FWHM, CUORE will have a 90% C.L. half life sensitivity to the 0$\nu$DBD of $^{130}$Te of $9.5\times10^{25}$ yr. To further reduce
this challenging background level, we are looking forward on several R&Ds to design a future ton-scale bolometric experiment with a background close to zero at the ton×year exposure scale. CUPID (CUORE Upgrade with Particle Identification) [3] aims at satisfying this request thanks to particle identification. Different lines of research and development are considered in order to identify the most promising approach. Among them, the detection of the Cherenkov light emitted from beta/gamma events is one of the most promising, once an event-by-event discrimination is proven for TeO$_2$ crystals of hundreds of grams.

3. Si low-temperature detectors
In order to detect the photons emitted by large mass crystals operated as calorimeters at few mK, other calorimeters are usually the most effective tool. Running experiments or advanced R&Ds use calorimetric light detectors of various materials and temperature reading techniques. Silicon is a promising one because the available technological expertise of the semiconductor industry is wide and it is comparatively inexpensive. Moreover, the specific heat of silicon is a factor $\sim 4.5$ and its density a factor 2.3 smaller than germanium. This feature allows, in principle, to detect smaller releases of energy since the temperature increase is inversely proportional to the heat capacity. However, this may not be enough to have an event-by-event discrimination and therefore the powerful possibility to amplify the thermal signal has been exploited.

The Neganov-Luke effect is a mechanism that leads to thermal signal amplification in semiconductor calorimeters when a static electric field is applied. The electron-hole pairs produced by the primary particle interactions are drifted by the field and the kinetic energy thus acquired is converted into heat through lattice scattering, producing an additional temperature increase. The total energy resulting in a thermal signal is:

$$E_{\text{tot}} = E + E_{\text{field}} - E_{\text{production}} = E \left( 1 + \frac{qV}{\epsilon} - \frac{\delta}{\epsilon} \right).$$

where $E$ is the energy deposited by the particle interaction, $E_{\text{field}}$ is the energy converted into heat to enhance the thermal signal, $E_{\text{production}}$ is the fraction of energy used to produce electron-hole pairs, $\delta$ is the band gap (1.17 eV for silicon), $q$ is the charge of the electron, $V$ is the potential and $\epsilon$ is the mean energy needed to produce a pair. It is clear that a high enough field could allow an amplification as high as a factor 100 in the signal-to-noise ratio, once the noise level is proven to be not affected by the application of the static electric field [5].

4. Preliminary measurement with a 1 cm$^3$ TeO$_2$ crystal
Excellent results in the $\alpha$ discrimination were obtained with a 1x1x1 cm$^3$ TeO$_2$ crystal as main absorber (heat channel) and a 20x20x0.625 mm$^3$ silicon light detector equipped with properly designed electrodes as secondary read-out channel [6] (light channel). In order to improve the light collection efficiency, the crystal is surrounded by VM2000 (3M) reflecting foil. Both detectors are equipped with a small NTD germanium thermistor for thermal read-out. The waveforms are continuously acquired and saved and the event reconstruction is performed completely off-line. The Optimal Filter technique to evaluate the pulse amplitudes with the best signal-to-noise ratio was applied.

In order to evaluate the discrimination capability two radioactive sources were used: a drop of $^{232}$Th as $\alpha$ source facing the base of the TeO$_2$ crystal and a $^{232}$Th source placed outside the cryostat vessels as $\gamma$ source. Both sources are expected to produce events in the 2-3 MeV energy region. Finally, the detectors are mounted inside an Oxford Instruments TL200$^3$He/$^4$He dilution refrigerator and operated at a temperature of about 15mK.

The Neganov-Luke electrodes on the light detector were biased at 300 V, obtaining an improvement of the signal-to-noise ratio of a factor $\sim$100.
Combining the information from the heat and light channels it was possible to identify different classes of events (Figure 1):

- $\alpha$ events are below threshold for the Cherenkov emission. The width of the band is dominated by the waveform baseline resolution.
- $\gamma$ events with an amount of Cherenkov light detected roughly linear with the electrons energy in the considered range of energies. The resulting yield of detected photons is $11.2 \pm 0.3\text{(stat.)} \pm 0.7\text{(syst.)}$ photons/MeV. The band width is a combination of baseline resolution and statistical fluctuation of the number of detected photons.
- Bi-Po events due to a $^{212}\text{Bi}$ beta decay followed by the $^{212}\text{Po}$ alpha decay. Due to the short half-life (299 ns) of this decay, most of these events are registered as a single energy deposition. The result is a band of mixed events with an amplitude in the TeO$_2$ crystal proportional to the sum of the $\alpha$ and $\beta$ energies and a signal in the Si light detector proportional only to the energy of the $^{212}\text{Po}$ $\beta$.

Thanks to the good performance of the light detector it was also possible to note that the average light signal corresponding to the full-energy, single escape and double escape peaks in the heat channel spectrum is slightly smaller than the extrapolation from the continuum at the same energy. This is compatible with the fact that the most probable topologies of events in the peaks are characterised, on average, by a larger number of primary electrons with respect to the Compton dominated continuum of the same energy.

5. Conclusions and perspectives
Thanks to the excellent performance of these devices, the interactions of few photons with our light detectors were recorded. This allowed an event-by-event discrimination with high significance between alpha and beta/gamma interactions at the $^{130}\text{Te}$ neutrinoless double beta decay Q-value, resulting in an alpha background reduction by a factor $10^3$ with a signal efficiency $>99\%$, evaluated with a toy Monte Carlo accounting for both the Poisson statistics of the photon number and the smearing of alpha and beta/gamma bands due to the detector noise. This result demonstrates that this technique is able to satisfy the requirements on background reduction of the proposed CUPID experiment, once the scalability on larger devices will be proven.

References
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