Performance of the low threshold Optimum Trigger on CUORE data

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Abstract. The Optimum Trigger (OT) is based on a threshold algorithm applied on waveforms filtered by exploiting the matched filter technique. The OT trigger thresholds improve by $60\,\text{−}\,90\%$ with respect to the thresholds obtained with the standard trigger, ranging between $\sim 20\text{ and }100\text{ keV}$. Low trigger thresholds open the way to Dark Matter searches and to improvements in the neutrinoless double beta decay analysis. Nevertheless, running the OT on CUORE data is demanding from the computational resources point of view. For this reason, the algorithm has been revised and adapted to cope with CUORE data. The work done to implement OT in CUORE and its performances will be discussed.

1. Introduction
The Cryogenic Underground Observatory for Rare Events (CUORE) is the first ton-scale experiment based on the bolometric technique to search for neutrino-less double beta decay of $^{130}Te$. The detector is made out of 988 tellurium dioxide crystals for a total mass of 742 kg with an experimental design that guarantees an ultra-low background. Thanks to these characteristics, CUORE is also suitable for low energy rare event searches, such as those that would be produced by Dark Matter interactions with the bolometers. Nevertheless, these kind of signals would be comparable to the fluctuation produced by the noise. An Optimum Trigger (OT) algorithm has been implemented to disentangle low energy signals from fake signals produced by noise.

2. Optimum Trigger implementation
The OT is based on the matched filter technique [1]: the transfer function $1$, maximising the signal to noise ratio, is built from the discrete Fourier transform of the ideal signal, $s(\omega_k)$, and the noise power spectrum, $N(\omega_k)$, and is applied on the raw waveforms:

$$H(\omega_k) = \frac{s^*(\omega_k)}{N(\omega_k)} e^{-j\omega_k t_M}$$  \hspace{1cm} (1)

• a signal is flagged by the OT if the filtered amplitude exceeds a by channel configurable cut, typically $3\sigma_n$ or $4\sigma_n$, where $\sigma_n$ is the filtered noise resolution;
• filtered waveforms are less noisy and consequently lower trigger cuts are achievable with respect to the standard derivative trigger (DT);
OT has been already used in CUORE-0 [2], the predecessor experiment of CUORE. However, the algorithm was not directly portable to CUORE, given the higher computational resources that would be required (19 times more channels and 8 times higher sampling frequency with respect to CUORE-0 values). To ensure that the algorithm can cope with the available computing resources, the following steps have been added [3] with respect to the algorithm described in [1]:

- the signal bandwidth extends up to \( \sim 10 \) Hz, whereas the waveforms are sampled at 1 kHz: for the trigger purposes, the OT is applied on the data stream downsampled at 125 Hz;
- aliasing is avoided by downsampling after a Digital recursive time-domain Chebyshev filter is applied (good compromise between processing speed and filter quality);

### 3. Comparison of OT and Derivative Triggers

This implementation can also be used in future experimental setup, since the downsampling factor and Chebyshev filter parameters are configurable and can be tuned to the specific acquisition parameters. The OT can be configured to run either during online data-taking or offline on data already on tape (re-trigger). A typical offline trigger time of 2 hours is required for a 24 hours long run. A configurable dead-time after a trigger is set to avoid overkilling trigger rates due to unexpected events (i.e. earthquakes). Re-trigger of multiple runs in parallel is also implemented and extensively used in CUORE.

For each bolometer, a trigger threshold is defined as the energy value at which 90% of the trigger detection efficiency is reached. The efficiency is evaluated on signals injected into the crystals at different amplitudes (a resistor is glued on each bolometer, allowing to simulate signals by controlled power injection). A significant improvement of the trigger thresholds for OT is observed with respect to the standard derivative trigger, fig. 1.

**Figure 1.** Comparison of OT (red) and DT (blue) trigger thresholds. Purple line corresponds to the old DT 150 keV threshold, to be compared to the new OT threshold of 40 keV represented by the green line.

The improved thresholds allow to set a 40 keV lower energy cut overall bolometers to select the events included in the neutrino-less double beta decay analysis, instead of the 150 keV used with DT triggered data. This will help rejecting the background in the signal region of interest.

### 4. Toward building a low-energy spectrum

Near the trigger thresholds non-physical events, such as tower vibrations, electric noise, energy deposition in the NTDs, mimic real signals and can pass the trigger cut. To build a low-energy
spectrum from real signals, we need to reject most of the non-physical events: the pulse-shape parameter, $OT\chi^2$, defined as the reduced $\chi^2$ from the fit of the triggered event to a cubic spline of the ideal pulse for each bolometer, is a good discrimination parameter between real and fake events: real signal events lay around $OT\chi^2 \sim 1$ in the distribution in fig. 3, whereas noise events are distributed at the low energy bounds and up to very high values of the shape parameter, and are delimited by the well defined red contour. An algorithm is used to exclude the area in the distribution populated with noise events, finding the best lower energy threshold and cut on the shape parameter, $(E_{\text{thr}}, OT\chi^{2\text{CUT}})$, in order to build the low energy spectrum.

![Figure 3. Pulse shape parameter as a function of energy for a sample channel. Horizontal red line is the shape parameter cut $(OT\chi^{2\text{CUT}})$ whereas vertical red line is the analysis energy threshold $E_{\text{thr}}$.](image)

Analysis energy thresholds, $E_{\text{thr}}$, shown in fig. 4, are compatible among all data-taking periods, and are such that we can start exploring the low energy region of the CUORE data. Improvements could be achieved with future studies focused on finding discriminating variables or techniques that can be exploited to better distinguish true with respect to fake signals at the low energy bounds, where the $OT\chi^2$ loses discrimination power.

$Te$ X-rays can be exploited as a benchmark to check if the OT and the energy calibration work correctly at low energies. $Te$ X-rays can follow a $\gamma$-ray interaction in a crystal and be detected by an adjacent crystal: these events are selected by requiring two coincident events and applying the analysis energy threshold, $E_{\text{thr}}$, and the shape parameter cut, $OT\chi^2$, on the low energy event. Eight K-shell lines ($K_{\alpha 1,2,3}$ and $K_{\beta 1,2,3,4,5}$ see [4]) contribute to the low energy spectrum of CUORE which, due to energy resolution, give rise to a primary and a secondary peak. Fig. 2 shows that OT is able to flag these events and that the calibration procedure correctly reconstructs their energies.

References

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