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Perspectives of lowering CUORE thresholds with Optimum Trigger

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Abstract. CUORE is a cryogenic experiment that focuses on the search of neutrinoless double beta decay in ^{130}Te and it is located at the Gran Sasso National Laboratories. Its detector consists of 988 TeO$_2$ crystals operating at a base temperature of $\sim$10 mK. It is the first ton-scale bolometric experiment ever realized for this purpose. Thanks to its large target mass and ultra-low background, the CUORE detector is also suitable for the search of other rare phenomena. In particular the low energy part of the spectra is interesting for the detection of WIMP-nuclei scattering reactions. One of the most important requirements to perform these studies is represented by the achievement of a stable energy threshold lower than 10 keV. Here, the CUORE capability to accomplish this purpose using a low energy software trigger will be presented and described.

1. Introduction

The double beta decay is a rare second order weak transition that can occur for a number of heavy even-even nuclei. In many cases, the single beta decay is suppressed or energetically forbidden. Two decay modes are considered for this rare process: the two-neutrino double beta decay ($2\nu\beta\beta$) and the neutrinoless double beta decay ($0\nu\beta\beta$). In the first case, two neutrinos accompany the emitted electrons and it has been observed in several nuclei. Depending on the studied isotope, the measured values for the half lives of this decay range between 10^{19} - 10^{21} years[1]. The neutrinoless double beta decay has never been observed yet. Only two electrons are emitted in this case, therefore it is a lepton number violating process, forbidden by the Standard Model. There are different reasons why the study of this process is interesting. First of all, the observation of such process would be a direct sign of new physics beyond the Standard Model. The most interesting aspect regards the possibility to probe the neutrino Dirac or Majorana nature: in fact, the $0\nu\beta\beta$ decay can only occur if the neutrino is a Majorana particle [2]. The observation of this decay would also give informations on the neutrino absolute mass scale and hierarchy. For all these reasons, several experiments are currently investigating the $0\nu\beta\beta$ decay

of different candidate nuclei. Depending on the considered isotope, the current limits on the $0\nu\beta\beta$ decay half life establish that it cannot be less than 10^{25} - 10^{26} years[1]. The performance of such experiments is described by their sensitivity to the half life of the decay, which can be approximated as[3]:

$$S^{0\nu} = T_{1/2}^{0\nu} \propto \epsilon \cdot \eta \cdot \sqrt{\frac{M \cdot t}{b \cdot \Delta E}} \qquad (1)$$

As shown by eq. 1, the sensitivity depends on several relevant parameters: the detection efficiency ϵ, the isotopic abundance η of the $0\nu\beta\beta$ emitter, the exposure in terms of the mass M and the live time t, the values of energy resolution ΔE and the background b in the region of interest. The region of interest (ROI) is an energy range that includes the transition energy (the Q_{value}) of the decay. A high sensitivity experiment aims at simultaneously optimizing the majority of these parameters.

2. The CUORE experiment

CUORE (Cryogenic Underground Experiment for Rare Events) is an experiment searching for $0\nu\beta\beta$ decay in ^{130}Te[4]. The choice of this isotope is due to its high natural isotopic abundance $\eta = 34.167\%$, and the $Q_{value} = 2527.515$ keV, that falls in a low background region of the gamma spectrum, namely between the ^{208}Tl peak, which is the cutoff of the natural beta gamma radioactivity, and its Compton edge. The CUORE detector consists of an array of 988 cryogenic TeO$_2$ crystals for a total mass of 742 kg, with 206 kg of ^{130}Te. This candidate isotope for the $0\nu\beta\beta$ emission is embedded in the detector itself: this provides a high detection efficiency, close to 80%. The crystals are operated as bolometers: this technique exploits the thermal variation experienced by the absorber crystal when a particle passes through it and deposits energy[4]. The amplitude of the thermal raise is proportional to the energy deposition and depends on the temperature by means of the heat capacity of the absorber. Since the thermal variation would be unmeasurable at room temperature, the CUORE bolometers are operated at a working temperature of ~10 mK. Such cryogenic temperature is reached and mainteined by means of a custom built multi-stage cryostat[5]. In order to work at low background conditions, CUORE is installed at the Gran Sasso National Laboratories in Italy at a 3600 m.w.e. depth, to suppress the background from cosmic rays. Accurate procedures to avoid contaminations were applied during the CUORE construction, assembly and cleaning of the materials. The bolometers protection from external radioactivity is provided by lead shields installed into the CUORE cryostat; part of this lead has extremely low radioactivity since it belongs to Ancient Roman age[6].
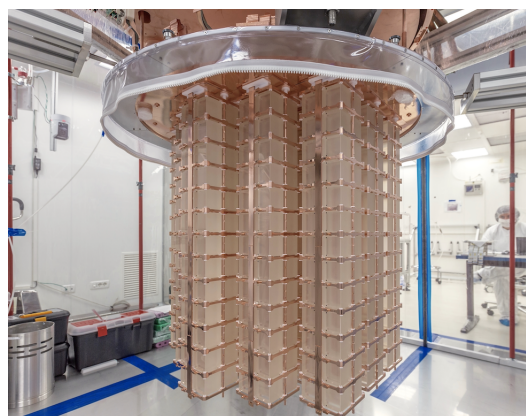

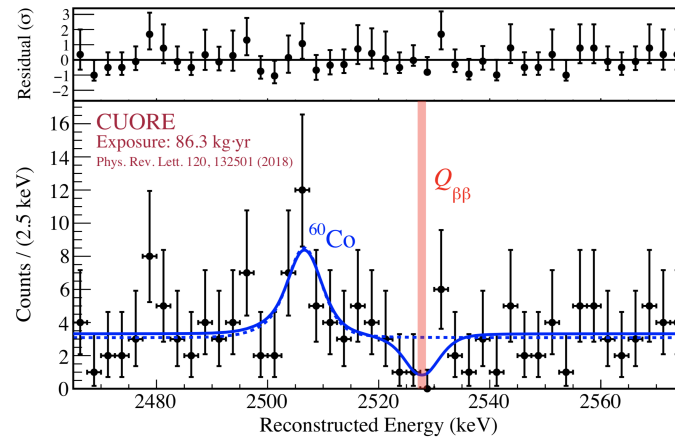**Figure 1.** The 988 CUORE crystals, before the cryostat was closed.

Figure 2. The ROI (2465 - 2575 keV) best fit. The $Q_{\beta\beta}$ value is enlightened by the red band, which width refers to the systematics uncertainty on the reconstructed energy[7].

2.1. CUORE first results

The CUORE physics data collection started in spring 2017. The first obtained results refer to 7 weeks of data taking collected during 2017, for a total TeO_2 exposure of 86.3 kg·yr[7]. The fit in the CUORE ROI is shown in figure 2. From this fit, we extracted a decay rate of $\Gamma_{0\nu} = (-1.0^{+0.4}_{-0.3} \pm 0.1(syst.)) \times 10^{-25}$ y^{-1}. The decay rate is proportional to the inverse of the half life, and is also related to the Majorana neutrino mass $m_{\beta\beta}$ through the equation $\Gamma^{0\nu} \propto G^{0\nu}(Q,Z)|M^{0\nu}|^2| < m_{\beta\beta} > |^2$; therefore, we were able to set a limit on ^{130}Te $0\nu\beta\beta$ half life of $T^{0\nu}_{1/2} > 1.5 \times 10^{25}$ y (90% C.L.), and a corresponding limit on the effective Majorana neutrino mass of $m_{\beta\beta} < 110 - 520$ meV. Besides the search of the $0\nu\beta\beta$ peak, it is possible to analyze other phenomena contributing to the CUORE measured spectrum. This can be performed thanks to an accurate Monte Carlo reconstruction of the CUORE background. This includes detailed informations achieved by exploiting the granularity of the detector, in particular the knowledge of the number of crystals involved in the interactions (event multiplicity), and by separating the detector into an inner and an outer layer. A major contribution to the CUORE
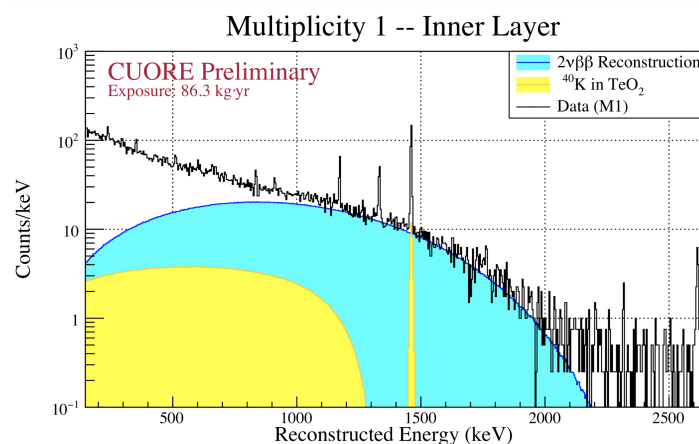

Figure 3. The CUORE measured spectrum from 0 to the $Q_{\beta\beta}$: the contribution of $2\nu\beta\beta$ decay of ^{130}Te is drawn in cyan[8].

continuous energy region from 0 to the Q_{value} is given by the $2\nu\beta\beta$ decay of ^{130}Te (fig.3). The background model reconstruction allows to disentangle this contribution, from which it was possible to measure the half life of ^{130}Te $2\nu\beta\beta$ decay: $T_{1/2}^{2\nu} = (7.9 \pm 0.1(stat.) \pm 0.2(syst.)) \times 10^{20}$ y[8].

3. Lowering the CUORE energy thresholds

The CUORE detector large mass and low background level make it suitable for the study of other rare events[9]. The WIMP direct detection could be searched for through the measurement of the nuclear recoil due to WIMP - Te/O nuclei scattering, as well as through the observation of their rate annual modulation signal. The solar axions search can also be performed by exploiting the inverse Primakoff effect in the Coulomb field of the TeO_2 crystals. In addition, the coherent scattering of supernova neutrinos with Te/O nuclei could be detected by CUORE. Since all these interactions are expected to produce signals at energies below few tens of keV, a fundamental requirement for studying them is to achieve a sufficiently low detection energy threshold. In CUORE, this can be accomplished by an improved trigger algorithm, named Optimum Trigger.

3.1. The Optimum Trigger

The low energy region of the CUORE spectrum is strongly affected by noise contributions, e.g. from electronic disturbances and mechanical vibrations. The CUORE standard derivative trigger fires when the baseline slope remains above threshold for a certain amount of time[10]. Since it does not carry any information about the signal pulse shape, it is not very efficient in distinguishing between physical and non-physical pulses at low amplitudes. Indeed, the energy threshold cannot go below tens of keV. In order to lower the energy threshold, the non-physical background must be identified and rejected. This is accomplished by the Optimum Trigger (OT)[9]: the trigger algorithm is applied on a continuous data stream, previously filtered with an optimum filter, with a transfer function given by

$$H(\omega_k) = \frac{S(\omega_k)}{N(\omega_k)} e^{-j\omega_k t_M} \tag{2}$$

where $S(\omega_k)$ is the Discrete Fourier Transform of the signal shape, and $N(\omega_k)$ is the detector noise power spectrum. The filtered data are characterized by a higher signal-to-noise ratio and reduced noise fluctuations (fig. 4). The informations on the signal pulse shape carried by the
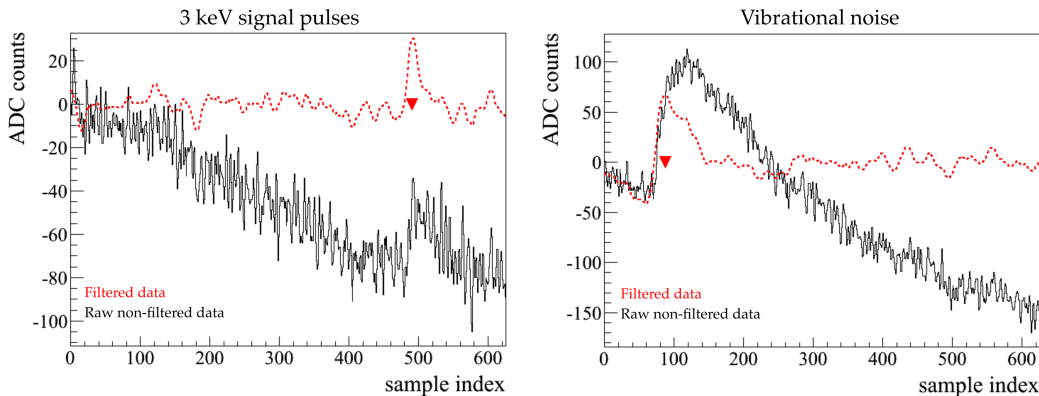

Figure 4. Windows of data samples in the presence of a pulse. Raw data are represented by the black solid line, while filtered data by the red dashed line; the red triangle is the OT position[9].

optimum filter allow to suppress the non-physical pulses, which have a different pulse shape. The trigger energy threshold is defined, for each bolometer, as the energy corresponding to the 90% trigger detection efficiency. In order to evaluate the efficiencies, we perform specific data acquisitions where a defined number of heater pulses at different amplitudes are fired on each bolometer. The efficiency curve is then constructed for each crystal by evaluating the number of pulsers detected at each energy. A preliminary study of the efficiencies of the standard trigger and of the OT has been performed with part of the data collected by CUORE during 2019[11]; from a comparison of the standard and OT thresholds, we obtain that the usage OT significantly lowers the energy thresholds (fig. 5).
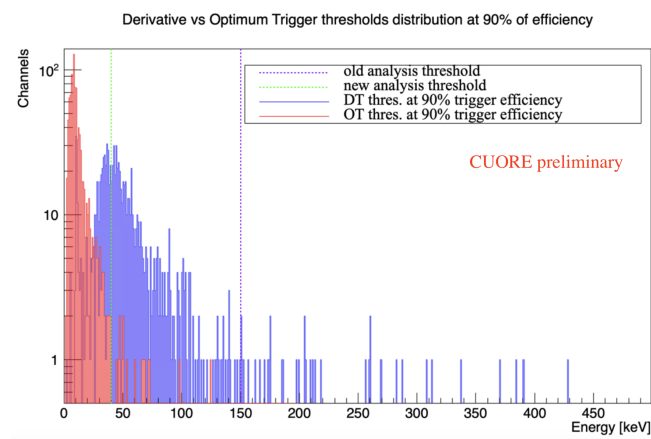

Figure 5. Comparison of the energy thresholds obtained by the standard derivative trigger (blue distribution) and by the Optimum Trigger (red distribution)[11].

4. Conclusions

CUORE is searching for $0\nu\beta\beta$ decay of ^{130}Te. Its first data release refers to the analysis of a TeO$_2$ exposure of 86.3 kg·yr: with only 7 weeks of data taking, the strongest limit on $0\nu\beta\beta$ decay half life and the most precise measurement of $2\nu\beta\beta$ decay half life of ^{130}Te were set. Thanks to its characteristics of large mass and low background, CUORE is also suitable for the search of other rare events, provided that a sufficiently low energy threshold is achieved. The Optimum Trigger has been developed for this purpose, and the first tests on its efficiencies showed that it significantly improves the energy threshold with respect to the standard trigger; further studies on OT optimization for CUORE are currently ongoing, exploiting the higher statistics that CUORE is collecting. Data for an exposure of ∼400 kg·yr are already available for analysis.

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