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CUORE: The first bolometric experiment at the ton scale for the search for neutrino-less double beta decay

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ABSTRACT

The Cryogenic Underground Observatory for Rare Events (CUORE) is the most massive bolometric experiment searching for neutrino-less double beta ($0\nu\beta\beta$) decay. The detector consists of an array of 988 TeO_2 crystals (742 kg) arranged in a compact cylindrical structure of 19 towers. This paper will describe the CUORE experiment, including the cryostat, and present the detector performance during the first year of running. Additional detail will describe the effort made in improving the energy resolution in the ^{130}Te $0\nu\beta\beta$ decay region of interest (ROI) and the suppression of backgrounds. A description of work to lower the energy threshold in order to give CUORE the sensitivity to search for other rare events, such as dark matter, will also be provided.

1. Introduction

Since their discovery, our understanding of the properties of neutrinos has changed dramatically. In 2000 it was discovered that neutrinos undergo flavor state oscillations proving that neutrinos have nonzero mass [1–3]. The absolute mass scale of the neutrinos has remained elusive with only partial constraints on a pair of mass-squared differences. It is also unknown whether the neutrino is a Dirac or Majorana fermion. To date no known Majorana fermions exist and the push to determine the nature of the neutrino mass is one of the most active areas of neutrino research. If the neutrino were a Majorana fermion it could point to new physics beyond the standard model and have implications for baryogensis.

Double beta decay provides an interesting avenue of research to study the properties of the neutrino. The standard decay mechanism is two-neutrino double beta decay ($2\nu\beta\beta$) in which two neutrons convert to two protons and release two anti-electron neutrinos and two electrons, and has been observed in several isotopes [4–6]. If the neutrino is a Majorana fermion, it is possible that neutrinoless double beta decay ($0\nu\beta\beta$) may be possible.

The Cryogenic Underground Observatory for Rare Events (CUORE) is an experiment that is designed to search for $0\nu\beta\beta$ decay through the process $^{130}\mathrm{Te} \rightarrow {}^{130}\mathrm{Xe} + 2e^-$ [7]. If observed this lepton number violating process would conclusively demonstrate that the neutrino is a Majorana fermion and would represent new physics beyond the standard model. The CUORE experiment is the culmination of a long history of cryogenic bolometric searches for $0\nu\beta\beta$ in ^{130}Te [8–13]. CUORE represents the first cryogenic bolometric experiment to reach the tonne-scale with a detector mass of 742 kg. Other isotopes are also under investigation through a variety of experiments [14–16].

2. The CUORE detector

The CUORE detector is comprised of an array of 988 ^{nat}Te crystals [17] which are operated as cryogenic bolometers. Each crystal is $5 \times 5 \times 5\,\mathrm{cm}^3$ with the total mass of the detector equal to 742 kg (206 kg ^{130}Te). The crystals are arranged into 19 towers with each tower containing 13 floors, and each 4 containing 4 crystals arranged in a 2×2 square pattern (Fig. 1). Each CUORE crystal is weakly coupled to the cryostat bath via PTFE holders. At operating temperature the heat capacity of TeO_2 crystals is $C \sim 100\,\mu\mathrm{K}/1\,\mathrm{MeV}$. In order to detect this minute change in temperature, each crystal is instrumented with a neutron-transmutation doped (NTD) Ge thermistor [18] which has a resistance that is exponentially dependent upon temperature. The CUORE bolometers also have Si-heaters attached with which pulses of fixed amplitude can be created in the crystals for stabilization purposes (Fig. 2).

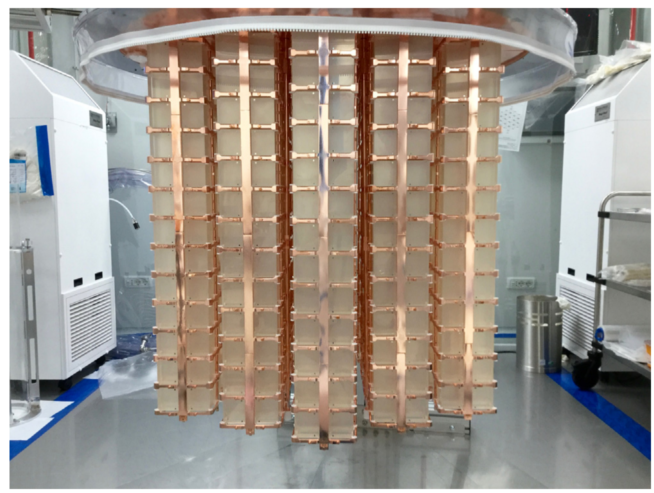

Fig. 1. Photograph of the fully installed CUORE detector inside a radon-free special clean room constructed in order to install each tower.

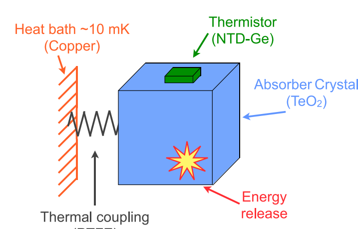

Fig. 2. Schematic of a CUORE bolometer. Here a TeO_2 crystal is connected to a heat batch via PTFE holders. The crystal can absorb energy through particle interactions which cause a small increase in the temperature of the crystal. This increase in temperature is detected via an NTD-Ge thermistor which has a strongly temperature-dependent resistance.

The CUORE bolometers are not only detectors, but also act as the source for double beta decay processes. When a decay occurs in the bulk of the crystal, the emitted electrons deposit their energy into the crystal lattice via phonons and any energy carried by the neutrinos is lost. In the case of $0\nu\beta\beta$ no neutrinos are emitted so the two electrons carry a total energy equal to the Q-value of the decay ($Q_{\beta\beta} = 2527.5\,\mathrm{keV}$). The containment efficiency of this process in CUORE is ~88% [19].

3. The CUORE cryostat

The CUORE detector is housed within the CUORE cryostat. The challenge of cooling nearly a tonne of TeO_2 to $\sim 10\,\mathrm{mK}$ is non-trivial.

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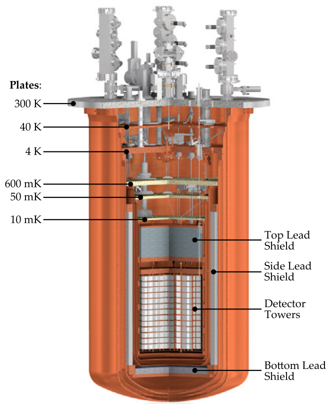

Fig. 3. Schematic of the CUORE cryostat. The 300 K plate is a stainless steel plate to which the outer vacuum can is attached. The innermost region contains the CUORE detector which is surrounded by two lead shields: a 4.5 tonne 6 cm thick shield of ancient Roman lead at ∼4 K around and below the detector, and a 2 tonne 30 cm thick shield at ∼50 mK located above the detector.

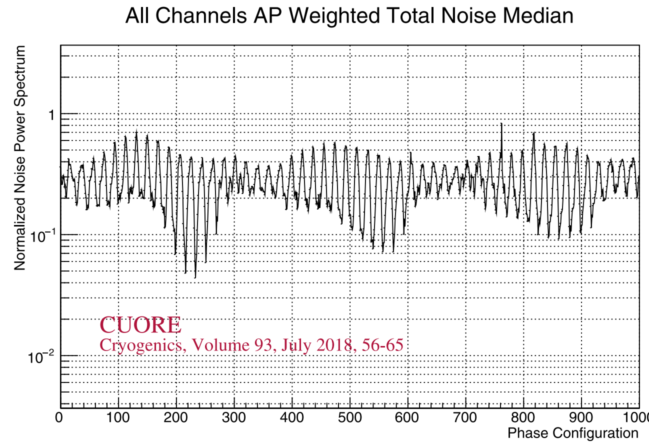

Fig. 4. Whole-detector typical noise as a function of various relative phase configurations of 4 active PTCs in CUORE. The minimum phase configuration is locked to mitigate PTC induced vibrational noise.

Radiopurity requirements need to be strictly enforced in the choice of materials used to construct the cryostat itself [19], and were done following the screening protocols used in CUORE-0 to reduce the α and γ backgrounds [6]. CUORE also incorporates passive shielding inside the cryostat to mitigate backgrounds. This shielding consists of ∼4.5 tonnes of ancient (Roman) Pb [20] cooled to 4 K and ∼2 tonnes of modern lead cooled to 50 mK. The layout is shown in Fig. 3. There is also an external shield comprised of a 20 cm thick outer layer of borated polyethylene and boric acid which surrounds a 25 cm thick layer of lead.

The CUORE cryostat is a custom built cryogen free dilution fridge by Leiden Cryogenics. In order to provide sufficient cooling power it is outfitted with 5 Cryomech pulse tube coolers (PTC) delivering 1.2 W of cooling power at 4.2 K each. The powerful dilution unit provides 2 mW of cooling power at 100 mK and with a full payload 3 μW of excess cooling power at 10 mK. In order to isolate the CUORE detector from external vibrations the detector suspension is independent of the cryostat suspension. A stainless steel Y-beam supports the detector via Kevlar rope and Cu bars. The Y-beam itself is coupled to the main support plate via 3 minus-K springs that dampen oscillations. The whole structure rests on elastomers to provide seismic isolation.

Calibration of the CUORE detector is achieved using the Detector Calibration System (DCS) to deploy calibration strings that contain ^{232}Th γ-sources [21]. Additionally an external DCS exists that allows for quick deployment of a variety of different calibration sources.

4. Detector operation and optimization

The CUORE detector is read out via a sophisticated room temperature electronics system that is low-noise and allows for adjustable control over each bolometer and is described in detail in [22].

In order to optimize the detector energy resolution via the NTD resistance a temperature scan around the cryostat base temperature is performed. Initial scans revealed 15 mK to be an optimal operating temperature. After a period of electronics upgrades a third scan in late September 2017 showed 11 mK to be a more optimal operating temperature. The determination is performed by examining the resolution of the stabilization pulsers and baseline noise at various temperatures. An additional cross-check in the third temperature scan by using calibration lines showed agreement with the pulser method.

Once the ideal operating temperature is selected vibrational noise from the operating PTCs is mitigated. Beyond passive vibration isolation techniques (e.g., soft Cu-braids at the 4 K stage, suspending the PTC motor heads separate from the cryostat) an active noise cancellation technique is employed. This novel active noise cancellation technique involves controlling the relative phases of the PTC compression cycle and scanning over a discretized space of all possible configurations of relative phases to identify configurations of maximal destructive interference in the induced vibrations in the CUORE detector (Fig. 4). Once a phase configuration that minimizes the noise is located it is locked [23].

The final detector optimization step is to determine the optimal bias current to use for the NTDs. This is performed by sweeping the bias current to obtain a (IV) load-curve. From this sweep the variation of the NTD resistance, signal amplitude, and noise RMS can be seen as a function of the voltage across the NTD. An optimal point will yield linear detector response in the presence of small fluctuations, and CUORE selects an optimal point by looking for a compromise that maximizes the signal amplitude while minimizing the noise RMS without entering an unstable operating point.

5. CUORE data and performance

Starting in May 2017 the initial data in CUORE was accumulated with 984 out of 988 of the bolometers functioning. Trigger thresholds were distributed around 20 keV with a small tail extending up to a few hundred keV. Physics data is bounded in time by calibration data and referred to as a dataset. The initial dataset (DS 1) ran from May–Jun 2017 and accumulated a raw exposure of 37.6 kg yr, and had an energy resolution of 9.0 keV FWHM at the 2615 keV γ peak (Fig. 5), and 8.3 keV FWHM at the Q-value.

After DS 1, a pause was taken to perform some optimization on the front-end electronics and to implement the PTC active noise cancellation technique. DS 2 was acquired from Aug–Sept 2017 and accumulated a raw exposure of 48.7 kg yr, with similar trigger thresholds as DS 1. The resolution in this dataset improved markedly to 7.4 keV FWHM at the 2615 keV γ peak (Fig. 5), and 7.4 keV FWHM at the Q-value. A blinded $0\nu\beta\beta$ decay search was performed on these two datasets and released the world-leading limits on the half-life for $0\nu\beta\beta$ decay in ^{130}Te ($T^{0\nu}_{1/2} = 1.5 \times 10^{25}$ y), the details of which are described in [24].

In addition to searching for $0\nu\beta\beta$ CUORE can be utilized for other rare event searches, such as $2\nu\beta\beta$, or dark matter. In CUORE-0 a $2\nu\beta\beta$ search was performed [6] by constructing a detailed background model. A similar search is possible with CUORE and under preparation, preliminary results of which can be found in [25].

Other rare event searches can be performed if the energy threshold of CUORE can be lowered. In particular sensitivity to dark matter interactions are possible. These interactions would deposit only a few keV of energy into CUORE crystals. Using a noise decorrelating optimum

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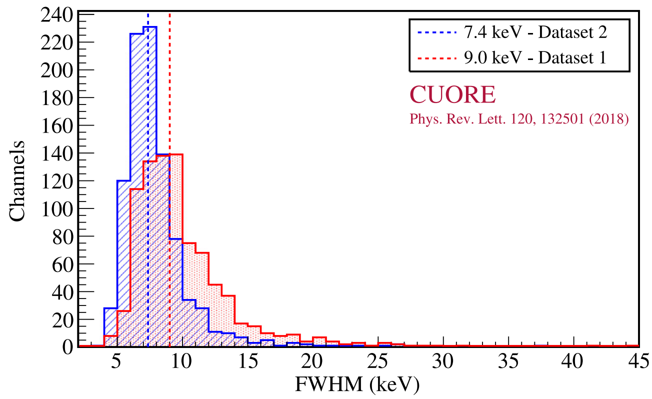

Fig. 5. Resolution of the 2615 γ peak from calibration data split between the initial two datasets. Between DS 1 and DS 2 a period of detector optimization was performed, improving the electrical environment and implementing the active pulse tube noise minimization.

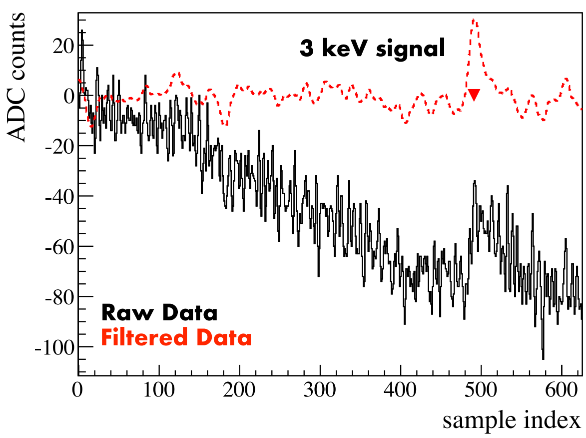

Fig. 6. Example of the ability of an optimum trigger to improve threshold. In black a raw waveform with a descending baseline is shown with a very low amplitude pulse that is not identified. In red the same waveform after being filtered with an optimal filter. Here the signal is clearly seen above the noise.

filter was shown in CUORE-0 to improve energy resolution, and using a so-called 'optimum trigger' in which one triggers on optimally filtered wave forms can also lower the energy threshold (Fig. 6).

6. Conclusions

The CUORE experiment is the culmination of many years of development leading to the operation of the world's first tonne-scale cryogenic bolometer in the search for $0\nu\beta\beta$ decay. The CUORE cryostat has performed well in providing the necessary cooling power required for the use of cold passive shielding and the large mass of the CUORE detector. The initial performance of the CUORE detector has been extremely robust, setting the world's leading limit on the $0\nu\beta\beta$ decay half-life in ^{130}Te with just 2 months of livetime. Detector optimization campaigns focused on improving the electrical environment and a novel technique for mitigating vibrational noise from multiple pulse tube coolers have proven successful in improving the energy resolution of the CUORE detector. Further techniques for improving the energy resolution and lowering the threshold of the CUORE detector are under development as more data is accumulated by the CUORE detector, allowing analyses not just for $0\nu\beta\beta$ but also for other rare decays such as $2\nu\beta\beta$ and rare interaction searches such as dark matter. The CUORE detector is a powerful tool for many different rare event searches.

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