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Abstract. The Cryogenic Underground Observatory for Rare Events (CUORE) is the first bolometric experiment searching for neutrinoless double beta ($0\nu\beta\beta$) decay that has been able to reach the 1-ton scale. The detector consists of an array of 988 TeO_2 crystals arranged in a cylindrical compact structure of 19 towers. The construction of the experiment and, in particular, the installation of all towers in the cryostat was completed in 2016 and data taking started in 2017. In this conference we present the $0\nu\beta\beta$ decay results of CUORE from examining a total TeO_2 exposure of 86.3 kg yr, characterized by an effective energy resolution of 7.7 keV FWHM and a background in the region of interest of 0.014 counts/(keV kg yr). Based on these data, CUORE places a lower limit on the $0\nu\beta\beta$ decay half-life of ^{130}Te $T^{0\nu}_{1/2} > 1.5 \times 10^{25}$ yr (90% C.L.). We then discuss the latest updates in the analysis of background and in the evaluation of the half-life of $2\nu\beta\beta$ decay of ^{130}Te.

1. Introduction

The primary goal of the CUORE experiment is the search of the neutrinoless double beta ($0\nu\beta\beta$) decay of ^{130}Te [1]. The observation of this decay would imply that lepton number is not conserved and that neutrinos are massive Majorana particles [2]. The CUORE detector (Figure 1) is composed by 988 TeO_2 cubic crystals (5 cm side) operated as independent bolometers in a cryostat able to cool down about 1-ton detector at a temperature $\sim$10 mK. The crystals contain natural tellurium, which is about 34% ^{130}Te, so they act both as sources and detectors of the $0\nu\beta\beta$ decay. The total source-detector mass is 742 kg, corresponding to $\sim$206 kg of ^{130}Te. Each crystal is equipped with a neutron transmutation doped (NTD) thermistor that reads out the energy depositions due to particle interactions. At cryogenic temperatures the heat capacity of a crystal is so small that a 1 MeV energy deposition causes a temperature variation of $\sim$100 μK, that is converted into a measurable change in voltage by means of the NTD. When a $\beta\beta$ decay

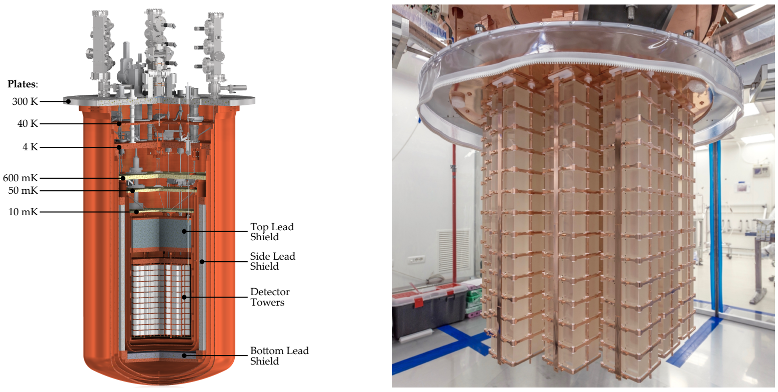

Figure 1. An illustration of the CUORE cryostat (left) and a picture of the CUORE detector (right).

occurs, the energy deposited in the bolometer by the electrons is detected. In the Standard Model, $\beta\beta$ decay is an allowed transition if two (anti-)neutrinos are emitted to conserve lepton number. In this case, the energy carried by neutrinos is not detected and the $2\nu\beta\beta$ decay produces a continuous spectrum. Conversely, the signature of the $0\nu\beta\beta$ decay is a peak at the Q-value of the transition ($Q_{\beta\beta}$=2527.5 keV for ^{130}Te), because all the energy is carried by the electrons.

The main challenge of CUORE is to maximize the experimental sensitivity, because $0\nu\beta\beta$ is an extremely rare decay with $T^{0\nu}_{1/2} > 10^{25}$yr.

With non-zero background the sensitivity scales as: $T^{0\nu}_{1/2} \propto \epsilon\, a \frac{M\, t}{b\, \Delta E}$, where ϵ is the detection efficiency, a the isotopic abundance, M the active mass, t the livetime, and b and ΔE the background rate and the energy resolution at $Q_{\beta\beta}$.

In the years prior to CUORE start-up, the collaboration endeavoured to reduce background and improve the energy resolution. The background in CUORE comes from natural radioactivity and to suppress it complementary strategies are put in place: (1) the CUORE detector is located at Laboratori Nazionali del Gran Sasso (Italy), where ∼1400 m of rock provide an effective shielding from cosmic rays; (2) the detector is surrounded by several layers of shielding to minimize the background due to environmental radioactivity inside the cavern; (3) all the materials used to build the detector and the cryostat were selected and cleaned to meet strict requirements about radio-purity; (4) analysis techniques based on pulse shape and time coincidence are used for event selection and background discrimination.

The CUORE-0 experiment [3], a single CUORE-like tower operated between 2013 and 2015, allowed to test the performance of the bolometers, proving that is possible to achieve a resolution of 5 keV FWHM [4, 5] and a background rate of 10^{-2} counts/(keV kg yr) [6]. According to these design parameters, CUORE is expected to reach a sensitivity of $9{\times}10^{25}$yr after 5 years livetime [7].

2. Results

In 2017 CUORE collected the first physics data, corresponding to a TeO_2 exposure of 86.3 kg yr. The CUORE cryostat is working very well and 92% of detector channels produced good quality data that were used for this first analysis. The physics data sets are bracketed by calibration measurements in which ^{232}Th sources are temporarily deployed inside the detector region. The energy calibration curve is built using six γ-lines of the ^{232}Th decay chain (from 239 keV to 2615 keV). Then, we build the physics spectrum applying selection criteria aimed at improving the experimental sensitivity. We also exclude events that simultaneously trigger more than one crystal, because most of the $0\nu\beta\beta$ events (∼88%) are fully contained in a single crystal and, in this way, we reduce the background due to events depositing energy in multiple crystals. The overall detector efficiency is ∼80%.

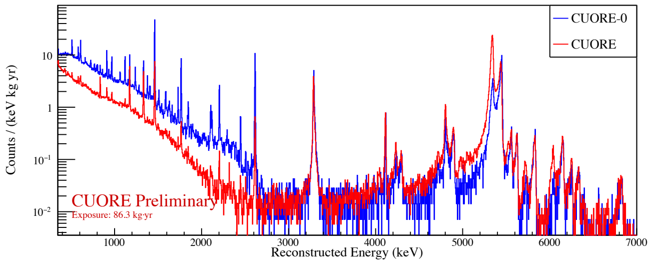

Figure 2. The CUORE physics spectrum compared with the CUORE-0 one, showing the significant reduction of background rate in the energy region below the ^{208}Tl line at 2615 keV. Figure coloured online.

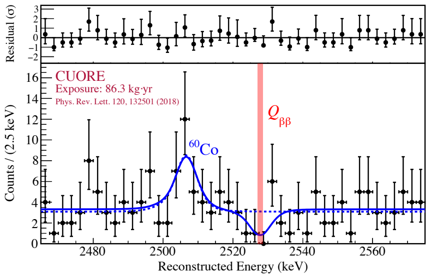

Figure 3. Fit in the region of interest with 3 components: a constant background, a peak near 2506 keV attributed to ^{60}Co and a posited peak at $Q_{\beta\beta}$.

In Figure 2 we show the first physics spectrum measured by CUORE. These data are characterized by an effective energy resolution of (7.7±0.5) keV FHWM at $Q_{\beta\beta}$ and by a background rate of (0.014±0.002) counts/(keV kg yr) in the region of interest.

There is no evidence for $0\nu\beta\beta$ decay of ^{130}Te and we perform an Unbinned Extended Maximum Likelihood fit in the [2465–2575] keV range (Figure 3) to extract a new limit on its half-life: $T^{0\nu}_{1/2} > 1.3 \times 10^{25}$ yr, 90% confidence level (C.L.).

This result is then combined with the ones from CUORE-0 and Cuoricino experiments, obtaining the best limit to date for the $0\nu\beta\beta$ decay of ^{130}Te: $T^{0\nu}_{1/2} > 1.5 \times 10^{25}$ yr (90% C.L.) [8].

In order to analyze quantitatively the main sources of background, evaluate their impact in the $0\nu\beta\beta$ ROI and measure the half-life of $2\nu\beta\beta$ decay of ^{130}Te, we develop a background model for CUORE, according to the methodology used for CUORE-0 and described with detail in [9]. The main background sources are expected to be contamination of TeO_2 crystals and cryostat shields by natural radioisotopes (^{40}K, ^{232}Th, ^{238}U and their progeny). A small contribution from isotopes produced by cosmogenic activation or radioactive fallout and from environmental muons is also expected.

To identify the background sources, we extract a lot of information directly from CUORE data. We build different spectra by splitting the events depending on time coincidences and interaction position, and we analyze the α and γ lines, which represent specific signatures of different contamination. In particular, we build the $\mathcal{M}_1$ spectra with the events that triggered one bolometer, and the $\mathcal{M}_2$ and Σ_2 spectra with the events that simultaneously triggered two bolometers ($\mathcal{M}_2$ comprises the two energies deposited in the crystals, while Σ_2 includes the total energy). The $\mathcal{M}_1$ events are further split into *Inner* and *Outer* layers, because the crystals in the *detector core* are more shielded from external radiation with respect to those closer to the cryostat shields. In this way, by exploiting the modularity of the CUORE detector, it is possible to better identify the position of the contaminants and distinguish among background sources that mainly produce $\mathcal{M}_1$ events –like $2\nu\beta\beta$ decay– with respect to other sources that produce a significant fraction of $\mathcal{M}_2$ events.

We simulate the background sources using a Geant4-based Monte Carlo (MC) code that generates and propagates primary and secondary particles through the CUORE geometry. The MC outputs are then processed to include the detector features like resolution, energy thresholds and time coincidences, and to build the energy spectra produced in the detector by the different background sources. By comparing the features of MC and experimental data, we identify a list of background sources whose contributions, once summed, can fit the experimental spectra.

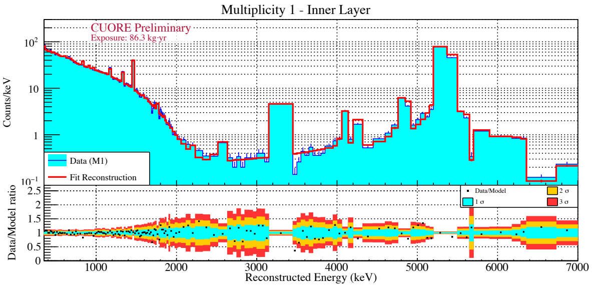

Figure 4. Top: The measured $\mathcal{M}_1$-*Inner Layer* spectrum and its reconstruction. Bottom: The ratio of the data to the reconstructed model with 1σ, 2σ and 3σ error bars. Figure coloured online.

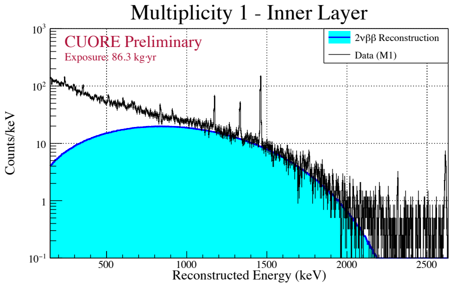

Figure 5. Fit reconstruction of the ^{130}Te $2\nu\beta\beta$ decay component in the $\mathcal{M}_1$-*Inner Layer* spectrum.

We reconstruct the CUORE background by fitting a linear combination of 60 source spectra to the experimental data. We perform a simultaneous Bayesian fit of the $\mathcal{M}_1$-*Inner Layer*, $\mathcal{M}_1$-*Outer Layer*, $\mathcal{M}_2$ and Σ_2 spectra. A variable binning of the spectra is adopted to avoid systematic uncertainties due to complicated line shapes. The fit is performed using the JAGS software package [10, 11], that samples the *joint posterior* probability distribution function of the fit parameters with a Markov Chain Monte Carlo (MCMC). The Bayesian approach allows to include the *a priori* information from previous experiments, radioassay measurements of materials and cosmogenic activation calculations.

As shown in Figure 4, we were able to reconstruct the major features of the experimental spectra. The $2\nu\beta\beta$ decay of ^{130}Te is one of the main components of the $\mathcal{M}_1$ spectra (Figure 5) and, thanks to the model implemented, we were able to disentangle it from the contribution of the other background sources and to evaluate its half-life. The preliminary result, that is going to be published in a paper currently in preparation is: $T^{2\nu}_{1/2} = (7.9 \pm 0.1_{\rm stat} \pm 0.2_{\rm syst}) \times 10^{20}$ yr. This result is consistent with previous measurements of this half-life [9, 12, 13] and represents the most precise and accurate measurement of $2\nu\beta\beta$ decay of ^{130}Te to date.

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