PROCEEDINGS OF SCIENCE

# First results from the CUORE background model

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The Cryogenic Underground Observatory for Rare Events (CUORE) is an experiment searching for neutrinoless double beta decay ($0\nu\beta\beta$) in $^{130}$Te, employing low temperature detectors. CUORE is stably taking data at the Gran Sasso underground laboratories since 2017. Being the $0\nu\beta\beta$ an extremely rare decay, mitigating the experimental background is a key requirement to increase the sensitivity. Therefore, a precise modeling of the entire energy spectrum is essential to understand the data, characterize the setup and identify residual background contributions. This is even more important considering that CUPID, the next-generation $0\nu\beta\beta$ bolometric experiment after CUORE, will be operated in the same cryogenic infrastructure.

A comprehensive model of the CUORE data has been developed capitalizing on a substantial analyzed exposure of 1038 kg·yr. It makes use of several energy spectra of different event multiplicities and an extensive set of fits has been performed to obtain a satisfactory reconstruction of the data and estimation of systematic uncertainties. The outcome allows to localize non-uniform sources, study time varying contaminations and determine with high precision all the background activities. On top of this, the result will permit accurate and reliable projections of the CUPID background in the region of interest.

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## 1. Introduction

Neutrinos have always played a pivotal role in solving the puzzle of fundamental particles. As an example, the discovery of neutrino oscillations represented a clear sign of Beyond Standard Model physics and pushed forward researches with ever-increasing efforts. Nonetheless, several properties of neutrinos, including their mass and the nature of their wave-function, remain shrouded in mystery. To the best of our current knowledge, the sole process that could shed light on these unknowns is neutrinoless double beta decay ($0\nu\beta\beta$) [1]. It is a forbidden, lepton-number-violating nuclear transition, whose observation would assess the Dirac or Majorana nature of neutrinos. It would also give important information about their absolute mass together with offering an insight on possible leptogenesis mechanism to explain matter-antimatter asymmetry in the Universe.

The Cryogenic Underground Observatory for Rare Events (CUORE) [2] is the biggest low-temperature calorimetric experiment designed to search for $0\nu\beta\beta$ in $^{130}$Te. The CUORE detector is composed of 988 $TeO_2$ crystals operated as cryogenic calorimeters at around 15 mK inside a world leading cryostat in terms of power and size. CUORE is located deeply underground (approximately 3600 meters water equivalent) at the Gran Sasso national laboratory in Italy. The experiment is presently taking data and has accumulated an exposure greater than 2 ton·yr.

Being the $0\nu\beta\beta$ an extremely rare event, the development of a precise and comprehensive model of the experimental background is of primary importance. It is crucial to understand the sources of such background and devise strategies to suppress and mitigate it for CUPID [3], the proposed upgrade of CUORE. In this case, it is even more important since CUPID will operate in the very same cryogenic facility of CUORE.

## 2. The CUORE background model

The CUORE background model aims at a complete background decomposition obtained by fitting the experimental data with several Monte Carlo simulations. These represent different contaminants distributed all around the CUORE detector and cryogenic facility. We consider a set of data organized in 15 datasets and corresponding to an analyzed exposure of 1038 kg·yr, the same utilized for the $0\nu\beta\beta$ study of 2022 [2], where the study was limited to a narrow energy interval around the decay Q-value. In this case we consider a way broader energy range, therefore a subset of data selection cuts has been specifically optimized. The events under consideration are classified based on their multiplicity (See Fig. 1): multiplicity 1 ($\mathcal{M}1$) events correspond to energy depositions occurring in a single crystal while multiplicity 2 ($\mathcal{M}2$) events are simultaneous depositions in 2 close crystals.

Geometry and materials of the CUORE detector, the surrounding cryostat and all the external shields are implemented in a Geant4-based application [4]. We take into account several contaminants including main decay chains ($^{232}$Th, $^{238}$U and $^{235}$U)[1], ubiquitous long-lived isotopes ($^{40}$K and $^{60}$Co), cosmogenic and neutron activation isotopes, common fallout products, $^{190}$Pt coming from the growing process of the $TeO_2$ crystals, cosmic muons and $^{130}$Te decaying via $2\nu\beta\beta$. We simulate them uniformly distributed in the bulk of the CUORE volumes and on their surface by considering exponential contamination profiles at different effective depths. Subsequently, all the Monte Carlo

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[1] We include possible secular equilibrium breaks e. g. $^{228}$Ra, $^{226}$Ra, $^{210}$Pb, etc.

simulations undergo a post-processing step to make them similar to the real data. This accounts for many data-taking effects, all the analysis efficiencies, detector response features such as a detector finite energy resolution and the event multiplicity.

For the statistical analysis, we model the background as a linear combination of the Monte Carlo templates where the coefficients of the sum are proportional to the contamination activities. We perform a simultaneous Bayesian fit on a broad energy range, spanning from 200 keV up to 7 MeV, on several binned input spectra. These include the $\mathcal{M}1$ energy spectrum and many different $\mathcal{M}2$ spectra obtained by splitting the data based on the total energy of the $\mathcal{M}2$ events as depicted in Figure 2. Such a selection allows to exploit all the information coming from the highly granular structure of CUORE, ensuring a better separation between degenerate background components. The convergence of the fit is managed by a Markov Chain Monte Carlo engine implemented in JAGS [5]. Default non-informative prior probability distributions are adopted; if prior knowledge is available, mainly coming from the pilot experiment CUORE-0 [6] or material radio-purity screenings, we make use of Gaussian and exponential distributions depending on whether the past measurement outcome is a value or a limit. Eventually, we establish a wide binning for events exceeding 2.8 MeV; this is done to avoid biases related to our poor knowledge of the detector response in that energy range.

**Figure 1:** Sample event topologies illustrating the CUORE event multiplicities. On the left, a particle depositing energy in a single crystal ($\mathcal{M}1$ event). On the right, *simultaneous* energy depositions in two close bolometers ($\mathcal{M}2$ event) originating from the same decay.

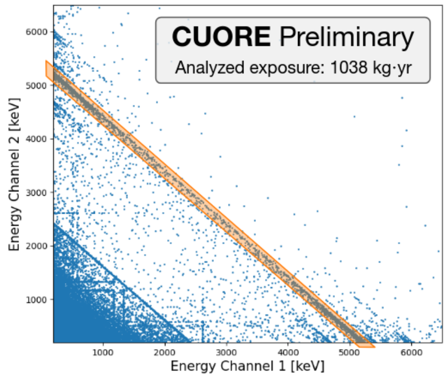

**Figure 2:** Scatter plot of $\mathcal{M}2$ CUORE events. By selecting bands of total energy and projecting them onto one of the two axis, we obtain the spectra used for the fit. As an example, the orange filled bar selects events with total energy around the $^{210}$Po peak.

## 3. First preliminary results

The result of the fit shows a great degree of similarity with the collected data, for all the $\mathcal{M}1$ and $\mathcal{M}2$ spectra. We report in Figure 3 the $\mathcal{M}1$ data reconstruction which represents the largest fraction of statistics. We are able to well explain all the spectra features at energies lower than 2.8 MeV, therefore, a dedicated analysis will be conducted to extract an extremely precise measurement of the $2\nu\beta\beta$ half-life and spectrum shape. At very high energies, we are still limited by a lacking comprehension of the detector response to $\alpha$ particles.

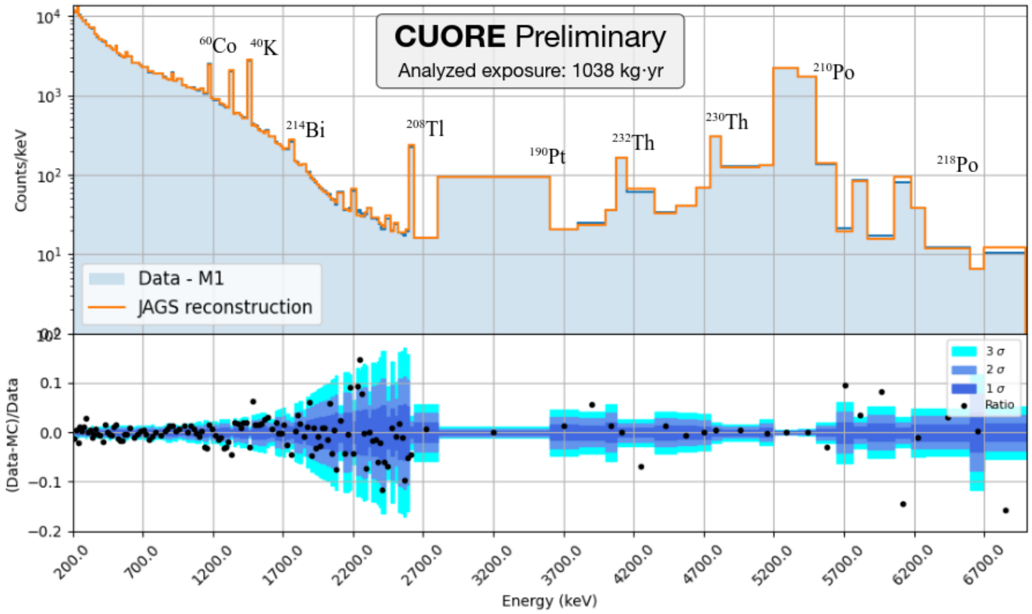

**Figure 3:** CUORE background model data reconstruction of $\mathcal{M}1$ events together with the residuals normalized to the data and the correspondent standard deviation bands. The most prominent $\alpha$ and $\gamma$ lines are also depicted.

When building the background model we inevitably need to make assumptions. The contaminations are assumed to be equal over all the $TeO_2$ crystals and uniform in all the cryostat and copper components and the activities are considered stable along time. In order to provide accurate results, we test these assumptions by repeating the data reconstruction while modifying several models and fit specifications. For instance, we vary the low energy threshold, we fit separately all the 15 datasets, we consider one by one the floors and towers of the CUORE detector structure and we add plausible background components that have large correlation with the $2\nu\beta\beta$ spectrum. We incorporate all the outcomes in a systematic uncertainty that we quote together with the statistical one that is coming from the posterior distributions of the fit. Eventually, we can extract all the background activities (we do not report them for brevity). They are characterized by better constraints on contaminations with respect to previous measurements and reduced correlations between the different components. The fit over the single dataset correctly describes the time development of short lived activation isotopes such as $^{54}$Mn and $^{60}$Co, found in copper parts, and $^{125}$Sb produced in $TeO_2$, opening the possibility to further activation studies. The very same set of fits allows to have access to the contamination history by studying the chain break of $^{210}$Po which is not in equilibrium with the precursor isotope $^{210}$Pb in few volumes of the experiment. The background model fit also identified a clear excess of $^{40}$K located on one single tower of CUORE coming from a higher contamination of the crystals; investigations are ongoing to determine whether an issue during the tower storage before the commissioning is the cause.

## 4. Conclusions

We presented the reconstruction of the first 1 ton·yr data collected by the CUORE experiment. The background model covers a wide energy region through many different energy spectra taking advantage of the different event multiplicities of the detector. This, combined to the significant exposure considered and a thorough assessment of systematic uncertainties, enables a robust and reliable determination of the different background components with unprecedented precision. The outcome of the fit serves as an essential input to develop the projections for the CUPID backgrounds, quantifying the contributions coming from the cryogenic infrastructure where the next-generation experiment will be put. Furthermore, it is now possible to conduct precision measurements of the $2\nu\beta\beta$ half-life of $^{130}$Te and its shape by applying novel studies [7, 8]. This will be done in the near future by optimizing and adapting the data analysis. Lastly, the CUORE background model tools offer the bases for new high level analysis that require a fit of the CUORE data, giving the possibility to perform them with higher selection efficiencies.

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