CUORE-0 background analysis and evaluation of $^{130}$Te $2\nu\beta\beta$ decay half-life

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CUORE is a bolometric experiment that will search for the Neutrinoless Double Beta decay of $^{130}$Te. CUORE-0 is a single CUORE-like tower that was run between 2013 and 2015 to test the performance of the CUORE experiment. In this proceeding we present the results of the model developed to disentangle and quantify the background sources that combine to form the CUORE-0 energy spectrum. We use detailed Geant4-based simulations and a Bayesian fitting algorithm to reconstruct the experimental data and evaluate the activities of the background sources. A direct outcome of this analysis is the measurement of the $^{130}$Te $2\nu\beta\beta$ decay half-life, of which we provide a preliminary evaluation.

1 Introduction

The detection of neutrino oscillations proved that neutrinos are massive particles. However, some questions are still open about their absolute mass scale and their nature, i.e. if neutrinos are Dirac or Majorana particles. The observation of the Neutrinoless Double Beta ($0\nu\beta\beta$) decay would allow to answer both questions. The Double Beta ($\beta\beta$) decay is a rare nuclear process in which an (A, Z) nucleus decays into its (A, Z+2) isobar with the simultaneous emission of two electrons. In the Standard Model, $\beta\beta$ decay is an allowed transition if two (anti-)neutrinos are emitted to preserve lepton number. This decay is called Two-Neutrino Double Beta ($2\nu\beta\beta$) decay and is the slowest process ever directly observed. The same transition through a channel in which no neutrinos are emitted ($0\nu\beta\beta$ decay) violates lepton number conservation and is possible only if neutrinos are massive Majorana particles. The $\beta\beta$ decay is detected measuring the kinetic energy of the two emitted electrons. The signature of the $0\nu\beta\beta$ decay is a peak at the Q-value of the transition, while the $2\nu\beta\beta$ decay produces a continuum spectrum in the detector, because neutrinos take away some part of the energy.

The Cryogenic Underground Observatory for Rare Events (CUORE) experiment is the latest and most massive bolometric detector designed to search for the $0\nu\beta\beta$ decay of $^{130}$Te (34% isotopic abundance, Q-value at 2528 keV). The CUORE detector is composed by 988 TeO$_2$ bolometers, arranged in a structure of 19 towers, for a total mass of 741 kg (206 kg of $^{130}$Te). CUORE is now in its final commissioning phase at Laboratori Nazionali del Gran Sasso (LNGS, Italy) and will start data taking by the end of 2016.

CUORE-0 is the first tower from the CUORE detector assembly line and it was operated at LNGS between 2013 and 2015. In addition to being a competitive $0\nu\beta\beta$ experiment, CUORE-0 was a proof of concept of CUORE in all stages from the assembly line to the DAQ and analysis framework. Last but not least, the reconstruction of the background sources responsible for CUORE-0 counting rate enabled us to verify that the necessary background requirements for CUORE are fulfilled.

2 CUORE-0 detector, experimental data and Monte Carlo simulations

The CUORE-0 detector is a tower of 52 TeO$_2$ crystals (39 kg of total mass, 10.8 kg of $^{130}$Te) operated as independent bolometers at $\sim$10 mK. At these temperatures, single particle interactions produce measurable thermal pulses proportional to the deposited energy. The modularity of the detector allows to classify the events according to their multiplicity, i.e. how many bolometers are triggered within a coincidence window of $\pm$5 ms. In particular, for the analysis of background, we build different energy spectra using the physics data collected with 33.4 kg·y of TeO$_2$ exposure:
• $M_1$ spectrum includes the events that trigger only one bolometer ($M_1$ events);
• $M_2$ spectrum is built with the events that trigger two bolometers ($M_2$ events), using the energies deposited in each crystal;
• $\Sigma_2$ is built with $M_2$ events, using the total energy $E(\Sigma_2)$ deposited in both crystals.

The CUORE-0 tower is located in a cryostat and is surrounded by several layers of shielding to suppress the background due to environmental radioactivity (Fig. 1). Based on the results of previous bolometric experiments, the main background sources are expected to be contaminations of the experimental setup. A small contribution from environmental muons and neutrons is also expected. We simulate the background sources using a Geant4-based Monte Carlo (MC) code that generates and propagates primary and secondary particles through the CUORE-0 geometry. We use the output of MC simulations to build the energy spectra produced in the detector by the different background sources. When possible, we apply some simplifications, merging the simulations of components made with the same material and, thus, characterized by identical contaminations. Similarly, we group the volumes whose contaminations produce degenerate spectra that are indistinguishable, given the statistical uncertainty of CUORE-0 data. The volumes that we use as different positions for background sources are: the TeO$_2$ Crystals, the Holder (i.e. the frame that supports the crystals and the surrounding cylindrical box) and four layers of Shields.

3 Identification of background sources

Identify the relevant sources to be used in the background model is crucial. Indeed, omitting a source can lead to a poor fit or to a wrong model. We exploited some a priori information from material assays, previous bolometric experiments and cosmogenic activation calculations. However, most of the information has been obtained from the analysis of CUORE-0 data. As shown in Fig. 2, the $M_1$ and $\Sigma_2$ spectra exhibit many peaks that allow to identify the corresponding radioisotopes. Below the 2615 keV $\gamma$ line of $^{208}$Tl, the spectra include many $\gamma$ lines, while above 2615 keV most of the events are produced by $\alpha$ decays. These are the $\gamma$ and $\alpha$ regions respectively.

The peaks in the $\alpha$ region are produced by $^{190}$Pt and by radioisotopes belonging to $^{232}$Th and $^{238}$U decay chains. Due to the short range of $\alpha$ particles and recoiling nuclei, these contaminants must be located in the Crystals or in the Holder. The analysis and the reconstruction of the $\alpha$ region is thus very useful to constrain the $^{232}$Th and $^{238}$U activities in these components, simplifying the reconstruction of the more complicated $\gamma$ region. Thanks to the modularity of the detector, we can apply the coincidence analysis to identify the position of contaminations. For example, if an $\alpha$ decay occurs on a crystal surface, the recoil nucleus and the $\alpha$ can simultaneously interact in two adjacent crystals, producing an $M_2$ event with $\Sigma_2$ energy at the decay Q-value. By analyzing the relative intensity of the peaks in the $\alpha$ region, we observe breaks of secular equilibrium for both $^{232}$Th and $^{238}$U contaminations, particularly evident in the case of 5.3 and 5.4 MeV peaks of $^{210}$Po.

In the $\gamma$ region, we observe many peaks from $^{232}$Th and $^{238}$U decay chains and the $^{40}$K line at 1461 keV. These natural radioisotopes can be found in almost all materials, therefore the corresponding peaks can be produced by contaminations in different parts of the experimental apparatus. We also observe the peaks due to $^{60}$Co and other isotopes produced by cosmogenic activation or nuclear fallout (like $^{137}$Cs). In some cases, we can identify the possible positions of contaminants by comparing the relative intensities of the peaks in the experimental and simulated spectra or exploiting the available a priori information. Otherwise, we provide to the fitting algorithm the simulated spectra of contaminations in different positions of the experimental apparatus.

Figure 1: The CUORE-0 tower (left), the geometry—not to scale—of the cryostat (center) and the scheme of the different volumes used to model the background sources in the cryostat Shields (right).
4 Results

The activities of the sources used for the background model are determined by fitting the experimental \( \mathcal{M}_1 \), \( \mathcal{M}_2 \), and \( \Sigma_2 \) spectra with a linear combination of 57 simulated source spectra. The JAGS tool is used to define a Bayesian statistical model of the fit and solve it. JAGS exploits Markov Chain Monte Carlo simulations to sample the joint posterior Probability Distribution Function (PDF) of the model parameters. The posterior PDF is the product of the prior and likelihood distributions. We use the observed counts in the bins of the experimental and simulated spectra to define Poissonian likelihoods. We define Gaussian (or half-Gaussian) priors when the activity of a source (or its upper limit) is known from independent measurements. Otherwise, we use uniform non-informative priors from 0 to upper limits higher than the maximum activities compatible with the CUORE-0 data. Finally, the joint posterior PDF is used to evaluate the activities of the background sources and their correlations.

The reconstruction of the \( \mathcal{M}_1 \) experimental spectrum is shown in Fig. 3. The normalized fit residual have a Gaussian-like distribution with mean and standard deviation compatible with 0 and 1, respectively. We obtain an equally good reconstruction of the \( \mathcal{M}_2 \) and \( \Sigma_2 \) spectra.

The 2\( \nu \beta \beta \) decay of \(^{130}\text{Te}\) produces \( \sim 10\% \) of the events in the \( \mathcal{M}_1 \) \( \gamma \) region from 118 keV to 2.7 MeV (Fig. 4, left). The resulting activity is \((3.43 \pm 0.09) \times 10^5\) Bq/kg. The statistical uncertainty is amplified by the anti-correlation to the \(^{40}\text{K}\) contamination in Crystals bulk, characterized by a continuum spectrum that partially overlaps that of 2\( \nu \beta \beta \).

The half-life value obtained for 2\( \nu \beta \beta \) decay of \(^{130}\text{Te}\) is \( T_{1/2}^{2\nu} = [8.2 \pm 0.2\text{ (stat.)} \pm 0.6\text{ (syst.)}] \times 10^{20}\text{y} \), where the systematic uncertainty was evaluated by running different fits in which the binning, energy threshold, depth of surface contaminations, priors, list of background sources, and input data were varied.

Finally, we show the reconstruction of the background produced by the contaminations in the different components of the experimental setup (Fig. 4, right). In the 0\( \nu \beta \beta \) region of interest (\([2470–2570]\) keV), the largest contribution to background comes from the shields (\(\sim 74\%\)). The Holder is the second contrib-

Figure 3: Comparison between the experimental \( \mathcal{M}_1 \) spectrum and JAGS reconstruction (top panel). In the bottom panel the bin by bin ratios between counts in the experimental spectrum over counts in the reconstructed one are shown; the corresponding uncertainties at 1, 2, 3 \( \sigma \) are shown as colored bands centered at 1.
Compared to previous results obtained from MiDBD \cite{MiDBD} and NEMO \cite{NEMO}, this is the most accurate measurement to date. We find that the background rate in the $^{130}$Te $0\nu\beta\beta$ region of interest is dominated by the Shields. This result gives us confidence that we are on track to achieve the requirements for CUORE.

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Through the CUORE-0 background model we evaluate the half-life of $^{130}$Te $2\nu\beta\beta$ decay. The preliminary result is: $T^{2\nu\beta\beta}_{1/2} = \left[8.2 \pm 0.2(\text{stat.}) \pm 0.6(\text{syst.})\right] \times 10^{20}\text{y}$.

5 Conclusions

Figure 4: Left: CUORE-0 $M_1$ spectrum compared to the evaluated contribution of $2\nu\beta\beta$ and $^{40}$K background sources in Crystals. Right: Background reconstruction showing the contribution of the contaminations in different positions of the experimental apparatus (stacked histogram).

The remaining background is produced by Crystals contaminants and muons.

5 Conclusions

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