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Neutrinoless Double Beta Decay with CUORE-0: Physics Results and Detector Performance

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Abstract The CUORE-0 experiment searches for neutrinoless double beta decay in ^{130}Te. It consists of an array of 52 tellurium dioxide crystals, operated as bolometers at a temperature of 10 mK, with a total mass of about 39 kg of TeO_2. CUORE-0 has been built to test the performance of the upcoming CUORE experiment and represents the largest ^{130}Te bolometric setup currently in operation. This experiment has been running in the Gran Sasso National Laboratory, Italy, since March 2013. We report the results of a search for neutrinoless double beta decay in 9.8 kg years ^{130}Te exposure, which allowed us to set the most stringent limit to date on this half-life. The performance of the detector in terms of background rate and energy resolution are also reported.

Keywords Bolometers · Low radioactivity · Neutrinoless double beta decay · Underground detectors

1 Introduction

Neutrinoless double beta decay ($0\nu\beta\beta$) is a hypothesised nuclear process, in which two neutrons simultaneously decay into two protons and two electrons, without any neutrino emission [1]. The observation of this process would indicate the Majorana nature of neutrinos, would constrain the neutrino mass scale and hierarchy, and would uniquely demonstrate the violation of the lepton number conservation. Given its importance, in recent years a lot of experimental efforts are instituted in this research field.

For the CUORE Collaboration.

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CUORE (Cryogenic Underground Observatory for Rare Events) will search for $0\nu\beta\beta$ decay in the isotope ^{130}Te using an array of 988 TeO_2 crystals, arranged in 19 towers, operated as calorimeters at cryogenic temperatures. In this type of detector, the energy deposited by particle interactions in the crystals is measured as temperature variations in the crystals by means of highly sensitive thermometers. CUORE is currently in the commissioning phase at LNGS and it will start its operation in early 2016. With a projected background index of 0.01 counts/keV/kg/year in the region of interest and an energy resolution of 5 keV, CUORE will reach a sensitivity to the half-life of $0\nu\beta\beta$ of ^{130}Te of 9.5×10^{25} year (90 % C.L.) after 5 years of live time [2]. In order to validate the procedures for the CUORE detector fabrication, CUORE-0, the first CUORE-like tower built, was operated in LNGS as an independent detector between March 2013 [3] and March 2015. The performance of the CUORE-0 detector and the results of the search for the $0\nu\beta\beta$ decay using an exposure of 9.8 kg years ^{130}Te are reported here.

2 The CUORE-0 Detector

The CUORE-0 detector consists of 52 $^{nat}TeO_2$ crystals, arranged in a tower structure of 13 floors. A picture of the tower is shown in Fig. 1 while details on the CUORE-0 detector can be found here [4].

Each floor hosts four $5 \times 5 \times 5$ cm^3 crystals, 750 g each. The crystals are enclosed in a copper structure, and they are held in position by means of polytetrafluoroethylene

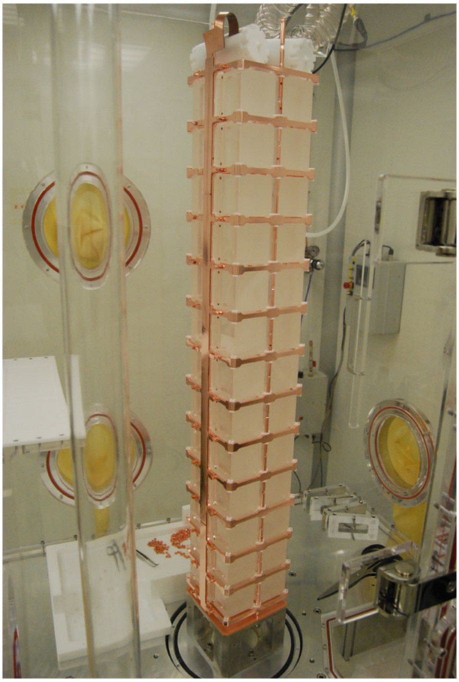

Fig. 1 The CUORE-0 detector: the 52 TeO_2 crystals are arranged in 13 floors of 4 crystals each. The crystals are housed in a copper structure. (Color figure online)

(PTFE) supports. The crystal temperature changes are measured using an neutron-transmutation-doped (NTD) sensor that is coupled on each individual crystal by means of glue spots. Each crystal absorber is instrumented with a Joule heater (an Si semiconductor chip with a typical resistance of 300 kΩ). By pulsing these with a fixed voltage, a known amount of energy is injected into bolometers in order to monitor the gain. The array is cooled down to a temperature of ∼10–12 mK, using the same dilution refrigerator located in the Hall A of the Gran Sasso National Laboratory that already hosted the Cuoricino experiment [5,6]

The CUORE-0 array is the first tower that has been realised using all the procedures that have been developed for the construction of the upcoming CUORE experiment. A tremendous effort was put in all the stages of the detector construction, starting from the selection of extremely pure raw materials, up to the cleaning techniques of the detector components [7] in order to mitigate any surface contaminations which can produce background in the region of interest due to degraded αs [5]. In addition, to reduce any possible surface re-contamination due to the exposure of the clean components to Rn-contaminated air [8], special packaging techniques were developed for the storage of the clean detector components in a controlled atmosphere. Moreover, all the steps for the construction of the detector array were performed in custom-made glove boxes [9], continuously flushed with nitrogen gas, with the aim of reducing the exposure of the clean detector components to radon.

3 Detector Operations

The CUORE-0 detector was assembled in spring 2012 and data taking started in March 2013. The detector acquired data for $0\nu\beta\beta$ search until March 2015, with a total exposure of 35.2 kg × year of TeO_2, corresponding to 9.8 kg year of ^{130}Te.

The data collected for the $0\nu\beta\beta$ decay search is organised in *datasets*. A *dataset* starts usually with a 2–3 days of calibration measurement, performed by inserting two thoriated tungsten sources, with an activity of ∼90 Bq each, in the proximity of the detector. The *dataset* then continues for about 3 weeks with the physics data taking, during which the calibration sources are removed. Every 48 h, we are forced to interrupt the data taking for 2–3 h in order to refill the liquid He main bath of the cryostat. After 3 weeks since the initial calibration, the sources are inserted again to check the stability of the detector. The typical event rate per crystal during the physics data taking is of ∼1 and ∼60 mHz in the calibration. The overall duty cycle of the detector was 78.6 %, with a relative fraction of physics data talking of ∼64 %.

The voltage across each NTD is continuously acquired at a rate of 125 Hz. Events are identified with a software trigger, with a threshold of between 30 and 120 keV. Typical particle-induced pulses have rise and decay times of 0.05 and 0.2 s, respectively, and amplitudes of ∼0.3 μV/keV before amplification. Once triggered, we analyze a 5-s-long window consisting of 1 s before and 4 s after the trigger. The pre-trigger voltage determines the NTD temperature before the event; the pulse amplitude, determined from the remaining waveform, establishes the energy of the event.

3.1 TeO_2 Bolometer Performance

One of the main goals of CUORE-0 was to demonstrate the improvement in the uniformity of the detector performance compared to Cuoricino. As a first result, CUORE-0 demonstrated that the techniques implemented for the bonding connections of the NTDs and silicon heater chips were successful. Despite several thermal cycles through which the detector passed, only one out of the 102 connections was lost during the initial cooldown of the detector to base temperature.

We also evaluated the distribution of the NTDs resistances at base temperature: the RMS of the distribution (2 %) is remarkably reduced with respect to the cuoricino one (9 %), showing the valuable improvement in the reproducibility of the detector construction technique.

Another fundamental parameter of the experiments aiming to $0\nu\beta\beta$ decay search is the energy resolution since it has a strong influence on the detector's power to discriminate a signal peak from the background in the region of interest. We evaluated the energy resolution of the detector using the 2615 keV line from ^{208}Tl during calibration runs. The harmonic mean of the FWHM values obtained by fitting the CUORE-0 peaks, weighted by physics exposure, is 4.9 keV (with a corresponding RMS of 2.9 keV). Comparing it to the Cuoricino value (5.8 keV, RMS of 2.1 keV), we can state that this result demonstrates that the CUORE goal of 5 keV FWHM in the region of interest has been achieved. The comparison between the detector energy resolution in CUORE-0 and Cuoricino is shown in Fig. 2. The results of CUORE-0 in terms of background reduction are also extremely important: the value measured in the CUORE-0 region of interest (0.058 ± 0.004 counts/keV/kg/year), compared to the Cuoricino one (0.153 ± 0.006 counts/keV/kg/year), demonstrates that the techniques adopted for the preparation of the detector components have been effective for the mitigation of the background counts in the ROI. When extrapolated to CUORE (taking also into account the improved cryo-

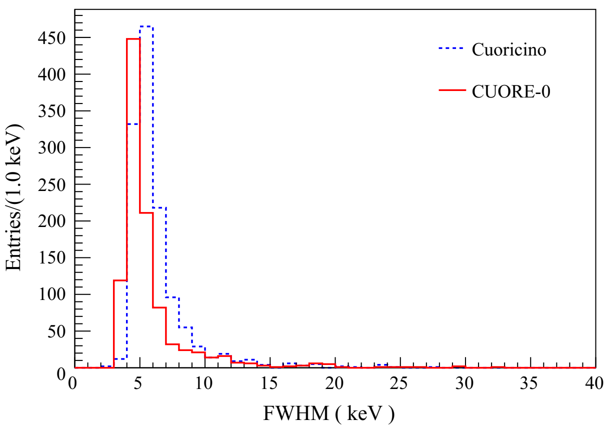

Fig. 2 The distribution of FWHM values for each CUORE-0 (channel, *dataset*) pair (*red solid line*) compared to the similar distribution for Cuoricino (*blue dashed line*). (Color figure online)

stat shield materials and the more efficient anti-coincidence rejection), the CUORE-0 result demonstrates that the goal of 0.01 counts/keV/kg/year is within reach.

4 $0\nu\beta\beta$ Search Result

The CUORE-0 physics spectrum in the region of interest is shown in Fig. 3. It refers to a total TeO_2 exposure of 35.2 kg year, corresponding to 9.8 kg year of ^{130}Te. The peak visible in the spectrum is at ∼2506 keV from the single-crystal coincidence of the two γ lines from the ^{60}Co decay coming likely from cosmic activation of copper frames and internal shielding of the tower before mounting underground. We perform a simultaneous fit of the unbinned data for each (bolometer, dataset) pair using a 3-component function which contains the hypothetical $0\nu\beta\beta$ signal at 2527 keV, the peak from the ^{60}Co γ lines, and a flat background, attributed to multi-scatter Compton events from ^{208}Tl and surface α events [10]. We find no evidence for $0\nu\beta\beta$ decay of ^{130}Te, and the best-fit value for this decay rate is $\Gamma_{0\nu} = 0.01 \pm 0.12$ (stat.) $\pm$ 0.01 (syst.) $\times 10^{-24}$ year^{-1}. Using a Bayesian approach, we set a 90 % C.L. lower bound on the decay half-life of 2.7×10^{24} year. Combining this result with the 19.75 kg year of ^{130}Te data from the Cuoricino experiment, we set a global lower limit of 4.1×10^{24} year at 90 % C.L. (Bayesian): this is, up to date, the most stringent limit on the half-life of $0\nu\beta\beta$ decay of ^{130}Te. The corresponding upper bound on the effective neutrino Majorana mass is in the range 270–650 meV, considering the most recent nuclear matrix element calculations in the context of $0\nu\beta\beta$ decay mediated by light Majorana neutrino exchange [11–15] and assuming $g_A \simeq 1.27$ for the axial coupling constant [16].

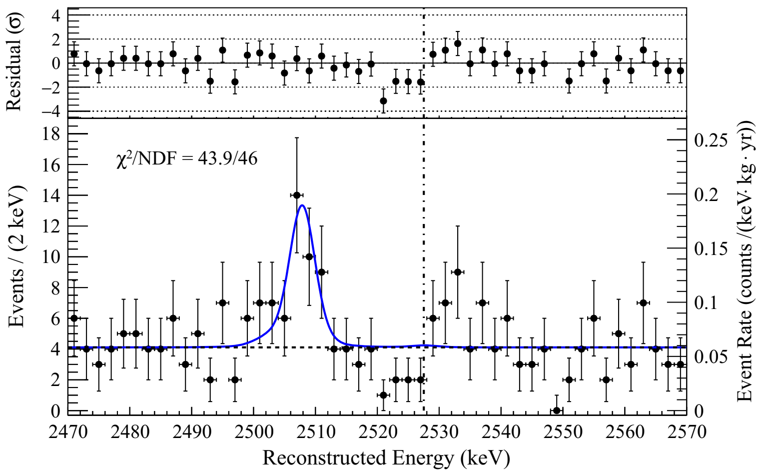

Fig. 3 *Bottom* the best-fit function (*blue solid line*) superimposed on the energy spectrum: the peak at ∼2507 keV is attributed to ^{60}Co; the *black dotted line*shows the continuum background component of the fit. The *vertical black dot-dashed line* indicates the expected position of Q_{value}. *Top*: the normalized residuals of the best-fit model and the binned data points. (Color figure online)

5 Conclusions

CUORE-0 did not find any evidence for neutrinos double beta decay of ^{130}Te. Combined with Cuoricino, it achieved the most stringent limit to date on this process. The CUORE-0 results demonstrate that the CUORE goals in terms of radiopurity and energy resolution are within reach.

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