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First data from CUORE-0

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Abstract

CUORE-0 is an experiment built to test and demonstrate the performance of the upcoming CUORE experiment. Composed of 52 TeO_2 bolometers of 750 g each, it is expected to reach a sensitivity to the $0\nu\beta\beta$ half-life of ^{130}Te around $3 \cdot 10^{24}$ y in one year of live time. We present the first data, corresponding to an exposure of 7.1 kg y. An analysis of the background indicates that the CUORE sensitivity goal is within reach, validating our techniques to reduce the α radioactivity of the detector.

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Keywords:

1. Introduction

Double beta decay experiments con provide a powerful probe into the non-conservation of lepton number. In this decay process, a parent nucleus converts two neutrons simultaneously into two protons. In the lepton number conserving version of this decay ($2\nu\beta\beta$), the nucleus emits two β particles and two electron anti-neutrinos. This process has been observed in a handful of nuclei. However, in neutrinoless double beta decay ($0\nu\beta\beta$), the nucleus produces only the two βs, thus violating lepton number by two. Though this process has never been observed, its discovery would reveal neutrinos to be unlike any other elementary fermion in the standard model, would establish neutrinos to be their own anti-particles and could even shed light on the origins of the matter-antimatter asymmetry of the Universe (for a recent review see for example [1] and references therein).

The CUORE experiment [2, 3] will search for $0\nu\beta\beta$ decay in ^{130}Te. CUORE itself is an array of 988 $^{nat}TeO_2$ cryogenic bolometers that act as both the source and detector of the decay. The bolometers each weigh 750 g and are arranged into 19 towers of 52 crystals each. The total active mass is 741 kg, 206 kg of which is ^{130}Te (34.2% natural abundance [4] in tellurium). The bolometers are operated at a temperature of about 10 mK which allows it to achieve an energy resolution of about 5 keV FWHM at the Q-value of the decay, 2528 keV [5]. CUORE is currently under construction at Laboratory Nazionali del Gran Sasso (LNGS) in Italy, and is anticipated to start data taking in 2015.

The technology of CUORE was proven by its predecessor, Cuoricino, a 40 kg tower of 62 bolometers that, with 19.75 kg y of ^{130}Te exposure, set a lower limit to the decay half-life of $2.8 \cdot 10^{24}$ y at 90% C.L. [6]. The analysis of that data, combined with Monte Carlo simulations, predicted that the sensitivity of CUORE would be limited by the background from α particles, which are generated by the natural radioactivity of the detector structure. To improve the background for CUORE, we implemented a set of strict protocols to limit the radioactive contamination of the detector materials during production and assembly.

The first tower produced on the CUORE assembly line and operated separately from the other 19 towers is called CUORE-0 [7], and has been taking data since March 2013. It is both an experiment which is expected to surpass the Cuoricino sensitivity in one year of live time, and also a technical prototype for CUORE. The data from CUORE-0 is being used to develop and test the detector monitoring tools, the data-acquisition system and the data analysis software for the larger CUORE. In this paper we present the first 7.1 kg y of TeO_2 exposure (2.0 kg y of ^{130}Te) from CUORE-0 and a successful validation of the background reduction techniques developed for CUORE.

2. Detector

CUORE-0 is a CUORE style tower of 52 TeO_2 crystals, for a total TeO_2 mass of 39 kg, 11 kg of which is ^{130}Te. The crystals are arranged in 13 floors of 4 crystals each. Each crystal is operated as an independent bolometer, using a Neutron Transmutation Doped (NTD) germanium thermistor [8] as a temperature sensor. The crystals are thermally linked to a copper frame through small teflon (PTFE) supports (Fig. 1). Additionally, one silicon Joule heater is attached to each crystal for offline correction of drifts in the gain caused by temperature variations [9].

To minimize background intrinsic to the crystals, we developed a radiopurity control protocol in collaboration with the crystal grower, the Shanghai Institute of Ceramics [10]. After production, the crystals were transported to LNGS at sea level to minimize the cosmogenic activation. We performed dedicated cryogenic tests to measure the bulk and surface contamination rates and determined them to be less than $6.7 \cdot 10^{-7}$ Bq/kg and $8.9 \cdot 10^{-9}$ Bq/cm^2 at 90% C.L. in ^{238}U, respectively, and less than $8.4 \cdot 10^{-7}$ Bq/kg and $2.0 \cdot 10^{-9}$ Bq/cm^2 in ^{232}Th, respectively [11]. To mitigate the surface contamination of the copper structure, we tested three surface treatment techniques [12], and chose a series of tumbling, electropolishing, chemical etching, and magnetron plasma etching for the surface treatment. The upper limit of the surface contamination of the cleaned copper was measured in R&D bolometers to be $1.3 \cdot 10^{-7}$ Bq/cm^2 at 90% C.L. in both ^{238}U and ^{232}Th [12].

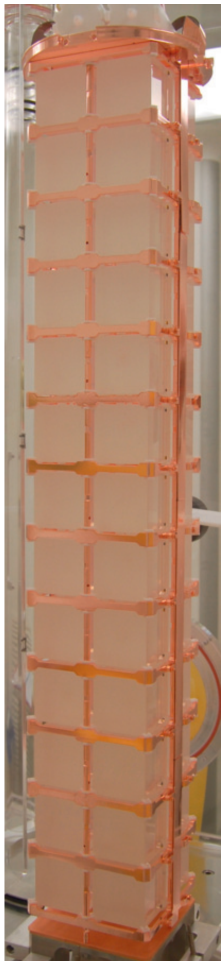

Fig. 1. The CUORE-0 detector.

The detector was assembled underground, in a dedicated clean room built in the CUORE hut. All the steps were performed in glove boxes under nitrogen atmosphere to minimize the radon contamination from contact with air. Only certified tools and materials were used to attach thermistors and heaters to the crystals, assemble the crystals in the copper frame, and electrically connect the sensors to the readout cables [13]. After construction, one thermistor and one heater had non working electrical connections. After the first cool down, we found that we had lost one more heater. In the two channels without heaters the drifts in thermal gain cannot be corrected in the offline data analysis processing, while the channel without a working thermistor is lost completely.

CUORE-0 is operated in the same cryostat that previously hosted Cuoricino, in the Hall A of LNGS [14]. CUORE-0 maintains an operating temperature of about 13-15 mK. At this temperature the typical signal amplitude is $10 - 20\,\mu$K/MeV, with typical rise and decay times of 50 and 250 ms, respectively. The analog read-out of the thermistor is performed using the same electronics as was used for Cuoricino [15]. The signals are first amplified, filtered by 6-pole active Bessel filter [16] and then fed into an 18-bit National Instrument PXI analog-to-digital converter (ADC). The filter cutoff and the ADC sampling frequency are set to 12 Hz and 125 Hz, respectively. The data are then processed with Apollo, the data acquisition software developed for CUORE. The trigger is software generated on each bolometer. When it fires, one second of data preceding the trigger and the 4 seconds following are saved to disk. Additionally, the waveforms from the bolometers on the same floor and on the floors above and below the triggering bolometer are acquired, irrespective of their own trigger.

This feature, not used in the analysis presented here, has been implemented to perform an accurate analysis of multi-site events.

A CUORE-0 "dataset" consists of 3-4 weeks of low background data taking preceded and followed by 2-3 days of calibration runs. To calibrate the detector, we insert two thoriated tungsten wires between the outer vacuum chamber of the cryostat and the external lead shield. During the offline analysis, we calibrate each channel separately over the energy range 511 to 2615 keV using the γ lines from the daughter nuclei of ^{232}Th.

3. Data analysis

The raw data from the bolometers are processed offline with Diana, the analysis software suite developed for CUORE. The data reconstruction steps are the same as in the Cuoricino analysis [6], but we have improved the automation and robustness of many of the algorithms in anticipation of scaling to CUORE.

The offline data production begins by evaluating the signal amplitude of each waveform using the matched filter described in [17, 18]. Each channel has its own signal template, which is built from an average of 2615 keV γ events in the calibration runs, and its noise spectral density, which is built from randomly triggered events collected during the low background runs. The analysis software also uses the filtered waveforms to evaluate shape parameters on the rising and falling edges of each event, which are later used for event rejection.

The next step of the data production is to stabilize the gain drifts caused by thermal variations using the Joule heater attached to each crystal. The heater injects fixed amplitude pulses of about 3 MeV pulses every 300 s on each bolometer, which provide a measure of the gain dependence on temperature. After stabilizing all events in the dataset, we fit the calibration peaks to a 3rd order polynomial with zero intercept for each channel, and apply this calibration function to all of the events in the low background data. The final step of the data production, is to evaluate the time coincidences between events on different crystals which are later used in the anti-coincident analysis.

The first step in the analysis procedure is to filter the processed data through a series of quality cuts. First, we remove noisy periods on each channel caused by temperature or electronic instabilities. We use the evaluated pulse shape parameters to remove pile-up and "noise-like" events. Since the majority of $0\nu\beta\beta$ events are expected to be fully contained in a single crystal, we select only single crystal events by applying a 200 ms anti-coincidence window around each event.

We evaluate all cut efficiencies on the 2615 keV ^{208}Tl γ line, except for the anti-coincidence cut, for which we use the 1461 keV γ line from ^{40}K. The overall quality cut efficiency is estimated to be 92.9 ± 1.8%. Since we are considering only single crystal events, we include the containment efficiency which was evaluated using Monte Carlo to be 87.4 ± 1.1% [6]. And finally, we include the trigger efficiency which is measured on heater events to be 99.00 ± 0.01%. The overall detection efficiency in this analysis is 80.4 ± 1.9%. This is comparable to the Cuoricino detection efficiency of 82.8 ± 1.1%.

For now, the $0\nu\beta\beta$ ROI is kept blinded using a procedure of "data salting". We randomly choose events from the 2615 keV line and move them to the ROI and vise-versa. Since there are more events in the 2615 keV peak than the ROI, this process produces a false peak in the ROI. The fraction of events that are moved are in the range $1 - 3\%$, but the exact value is also kept blinded. The true energy of an event is encrypted with a public RSA key and stored. The associated private key is available to only a few collaborators and will be distributed for the unblinding. The advantage of this blinding procedure is that it preserves the energy spectrum in the ROI, and allows one to test the fitting algorithms that will be used after unblinding.

4. Results

Figure 2 (left) shows the acquired calibration spectrum from the thoriated tungsten source and the low background spectrum corresponding to an exposure of 7.1 kg y (2.0 kg y of ^{130}Te). In the low background spectrum, the peaks from ^{208}Tl,^{40}K and ^{60}Co are attributed to contamination in the cryostat, while the peaks

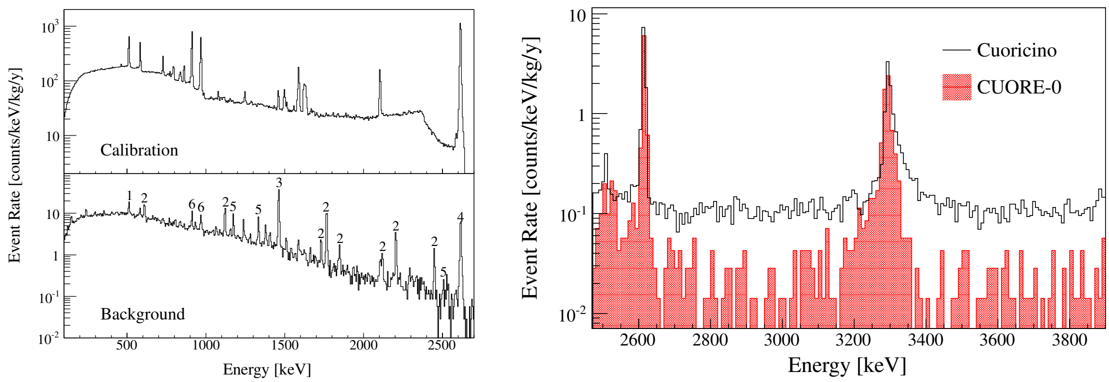

Fig. 2. Left: calibration and background spectra from threshold to 2.7 MeV. The peaks labeled in the background are due to γs from (1) e^+e^- annihilation, (2) ^{214}Bi, (3) ^{40}K, (4) ^{208}Tl, (5) ^{60}Co and (6) ^{228}Ac. Right: α continuum background compared to Cuoricino. The peak at 3.2 MeV is due to ^{190}Pt contamination in the crystals.

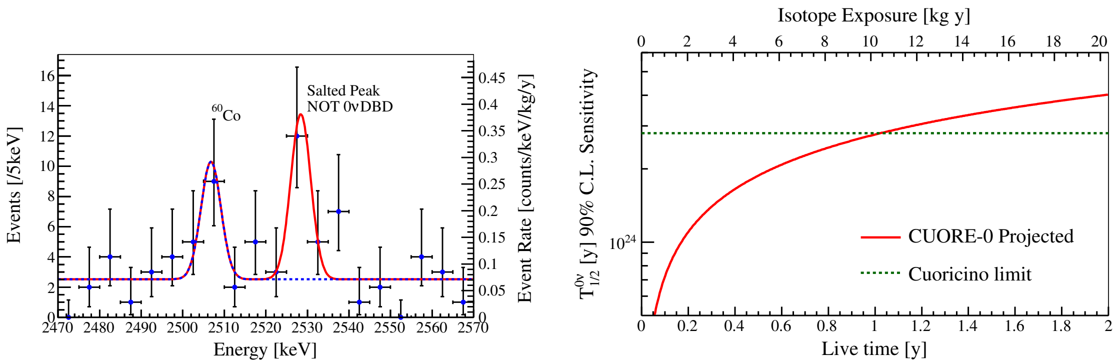

Fig. 3. Left: $0\nu\beta\beta$ energy region of interest. The peak at 2506 keV is due to the sum of the two γs from ^{60}Co. The peak at 2528 keV is the salted $0\nu\beta\beta$ peak (see text). Right: Projected sensitivity to the $0\nu\beta\beta$ half-life.

from ^{214}Bi are attributed to ^{222}Rn in the air around the cryostat during the initial runs. We began purging the space between the detector and the external lead shield with nitrogen gas, and observed that the peaks were reduced by more than a factor of 5. The energy resolution is evaluated on the low background spectrum, and found to be 5.7 keV FWHM at 2615 keV.

Figure 2 (right) shows the background from the $0\nu\beta\beta$ region up into the α region. The peak between 3.1 and 3.4 MeV is due to ^{190}Pt contamination internal to the crystal. The continuum from 2.7 to 3.9 MeV, excluding the ^{190}Pt peak, is attributed to degraded α particles that deposit only a fraction of their energy in the crystal and the rest in inactive materials. This α continuum extends down into the ROI and was a significant background for Cuoricino, 0.110 ± 0.001 counts/(keV kg y). The α background in CUORE-0 is measured to be 0.019 ± 0.002 counts/(keV kg y). This factor of 6 reduction from Cuoricino proves the success of the radiopurity protocols that were implemented for the CUORE production and assembly.

We show the energy spectrum in the $0\nu\beta\beta$ ROI in Fig 3 (left). The false peak produced by the data salting is clearly evident. The fit consists of a flat background with two gaussians, one for the 2506 keV ^{60}Co sum peak and one for the 2528 keV $0\nu\beta\beta$ peak. The peak centers are fixed to the nominal decay energies and the FWHM is fixed to 5.7 keV. The flat background rate in the ROI is measured to be 0.071 ± 0.011 counts/(keV kg y). The excess over the α background stated above is attributed to scattered 2615 keV γs originating from the cryostat. This excess is consistent with the γ rate similarly observed in Cuoricino, which was run in the same cryostat.

5. Conclusions and perspectives

With an isotope mass of 11 kg, a background index of 0.071 ± 0.011 counts/(keV kg y) and an energy resolution of 5.7 keV FWHM, CUORE-0 is the most sensitive experiment searching for the $0\nu\beta\beta$ of ^{130}Te. It is expected to surpass the Cuoricino sensitivity in about 1 year of live time (Fig. 3).

The background in CUORE-0 is now dominated by γs from the cryostat. The measured α background index of 0.019 ± 0.002 counts/(keV kg y) validates the background reduction techniques developed for CUORE. Projecting the observed background to CUORE, where the cryostat contaminations are expected to be negligible, the target background index of 0.01 counts/(keV kg y) in the ROI seems highly achievable. With this background CUORE is expected to achieve a sensitivity to the $0\nu\beta\beta$ half-life of ^{130}Te of $1 \cdot 10^{26}$ y [19].

References

[1] S. Bilenky, C. Giunti, Neutrinoless double-beta decay. A brief review, Mod. Phys. Lett. A27 (2012) 1230015. arXiv:1203.5250v2.
[2] C. Arnaboldi, et al., CUORE: A Cryogenic Underground Observatory for Rare Events, Nucl. Instrum. Meth. A. 518 (2004) 775. arXiv:hep-ex/0212053v1.
[3] D. Artusa, et al., Searching for neutrinoless double-beta decay of ^{130}Te with CUORE, submitted to Adv.High Energy Phys.arXiv:1402.6072.
[4] M. A. Fehr, M. Rehkamper, A. N. Halliday, Application of MC-ICPMS to the precise determination of tellurium isotope compositions in chondrites, iron meteorites and sulfides, Int. J. Mass spectrom. 232 (2004) 83–94.
[5] M. Redshaw, B. J. Mount, E. G. Myers, F. T. Avignone, Masses of Te-130 and Xe-130 and Double-beta-Decay Q Value of Te-130, Phys. Rev. Lett. 102 (2009) 212502. doi:10.1103/PhysRevLett.102.212502.
[6] E. Andreotti, et al., ^{130}Te Neutrinoless Double-Beta Decay with CUORICINO, Astropart. Phys. 34 (2011) 822. arXiv:1012.3266, doi:10.1016/j.astropartphys.2011.02.002.
[7] C. Aguirre, et al., Initial performance of the CUORE-0 experiment, submitted to Eur. Phys. J. CarXiv:1402.0922.
[8] K. M. Itoh, et al., Neutron transmutation doping of isotopically engineered Ge, Appl. Phys. Lett. 64 (1994) 2121.
[9] A. Alessandrello, et al., Methods for response stabilization in bolometers for rare decays, Nucl. Instrum. Meth. A 412 (1998) 454.
[10] C. Arnaboldi, et al., Production of high purity TeO_2 single crystals for the study of neutrinoless double beta decay, J. Cryst. Growth 312 (20) (2010) 2999. doi:DOI: 10.1016/j.jcrysgro.2010.06.034.
[11] F. Alessandria, et al., CUORE crystal validation runs: results on radioactive contamination and extrapolation to CUORE background, Astropart. Phys. 35 (2012) 839–849. arXiv:1108.4757.
[12] F. Alessandria, et al., Validation of techniques to mitigate copper surface contamination in CUORE, Astropart. Phys. 45 (2013) 13–22. arXiv:1210.1107.
[13] C. Brofferio, et al., Electrical characterization of the low background Cu-PEN links of the CUORE experiment, Nucl. Instrum. Meth. A 718 (2013) 211–212. doi:10.1016/j.nima.2012.08.047.
[14] C. Arnaboldi, et al., Results from a search for the 0 neutrino beta beta-decay of Te-130, Phys. Rev. C 78 (2008) 035502. arXiv:0802.3439.
[15] C. Arnaboldi, et al., The front-end readout for CUORICINO, an array of macro-bolometers and MIBETA, an array of mu-bolometers, Nucl. Instrum. Meth. A 520 (2004) 578. doi:10.1016/j.nima.2003.11.319.
[16] C. Arnaboldi, et al., A programmable multichannel antialiasing filter for the CUORE experiment, Nucl. Instrum. Meth. A 617 (2010) 327–328. doi:10.1016/j.nima.2009.09.023.
[17] V. Radeka, N. Karlovac, Least-square-error amplitude measurement of pulse signals in presence of noise, Nucl. Instrum. Methods 52 (1967) 86.
[18] E. Gatti, P. F. Manfredi, Processing the signals from solid state detectors in elementary particle physics, Riv. Nuovo Cimento 9 (1986) 1.
[19] F. Alessandria, et al., Sensitivity of CUORE to Neutrinoless Double-Beta Decay, submitted to Astropart. Phys.arXiv:1109.0494.