

NIMA POST-PROCESS BANNER TO BE REMOVED AFTER FINAL ACCEPTANCE

CUORE: the first bolometric experiment at the ton scale for rare decay searches

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Abstract

Preprint submitted to Elsevier

July 17, 2020

The Cryogenic Underground Observatory for Rare Events (CUORE) is the first bolometric experiment searching for neutrinoless double beta decay that has been able to reach the 1-ton scale. The detector consists of an array of 988 TeO₂ 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 August 2016 and data taking started in spring 2017. In this contribution the achievement of the commissioning phase and the performance of the detector and the cryostat during the first physics run will be presented.

1 The CUORE experiment

2 CUORE [1, 2] is a ton scale bolometric detector built with
3 the primary goal to search for neutrinoless double beta decay
4 ($0\nu\beta\beta$). In principle this process has a clear signature, given
5 by a monochromatic peak in the energy spectrum of the two
6 electrons in the final state. In a real world experiment, we
7 must take care of energy resolution and background, as well
8 as select an isotope candidate for $0\nu\beta\beta$ decay with high natural
9 isotopic abundance or enriched, ensure high detector efficiency
10 and mass, guarantee good detector stability over a long period
11 of time. All these parameters drive the experimental sensitivity.

12 CUORE exploits the bolometric technique [3, 4]: crystals
13 of TeO_2 are in thermal equilibrium, through a weak thermal
14 coupling, with a bath at cryogenic temperature. A particle re-
15 leasing its energy into the crystal produces a rise in tempera-
16 ture of the crystal itself, which is read out through a resistive
17 thermometer (Neutron Transmutation Doped (NTD) thermis-
18 tors) as a voltage variation. The bolometric technique ensures
19 high detection efficiency and energy resolution. The chosen
20 isotope ^{130}Te is a good candidate for $0\nu\beta\beta$ given its high natural
21 isotopic abundance of 34.2%, higher than any other avail-
22 able isotope. Moreover it has a high Q-value for the process,
23 $Q_{\beta\beta} = (2527.515 \pm 0.013)\text{keV}$, above almost all the environ-
24 mental γ background. Also, thanks to the scalability of the
25 bolometric technique, detectors of large mass can be built.

26 Concerning the background, it has to be underlined that
27 CUORE is searching for a very rare event, with an half life
28 which is at least 15 order of magnitudes longer than the age of
29 the Universe. Therefore, it is extremely important to reduce as
30 much as possible the background sources. For this reason, the
31 experiment is located at the LNGS underground laboratories,
32 at an average depth of about 3600 m.w.e., reducing natural ra-
33 dioactivity from outside the detector. Strict protocols have been
34 developed and applied for crystals production and detector as-
35 sembling, and new techniques have been tested and employed
36 to clean the copper parts near crystals. These precautions al-
37 low to reduce natural radioactivity from the detector itself. Fur-
38 thermore, suspensions and dumping systems, as well as noise
39 cancelling tools, have been adopted to reduce the induced noise
40 due to mechanical vibrations.

41 The cryogenic system [5] is a challenge by itself, able to cool
42 down a large mass to cryogenic temperatures in few weeks and
43 in a low radioactive environment. The system is a cryogen-free
44 cryostat, allowing to achieve a high duty-cycle. A combination
45 of a fast-cooling system with 5 pulse tubes (PTs) is employed
46 to bring down the temperature at 4 K. In the last stage of the
47 cool-down a dilution unit (DU) allows to bring the temperature
48 down to 10 mK, which is the temperature of operations. The
49 use of pure copper and roman lead shielding allows to reduce
50 background from the cryostat itself.

51 Detector commissioning and optimization

52 The cryostat underwent a commissioning phase that lasted
53 about two years and ended in March 2016: more than one run
54 has been performed during this period, each time to check a dif-
55 ferent part of the system. In summary this important phase al-
56 lowed to demonstrate that a base temperature as low as 6.3 mK
57 can be reached and kept stable for a long period of time. The
58 electronics, DAQ and calibration system have been successfully
59 tested. An array of 8 crystals was also installed, which allowed
60 to get a first raw estimation of the detector resolution, which
61 turned out to be 10 keV without any detector optimization. The
62 outcome of the cryostat commissioning was that the experimen-
63 tal setup was ready for the installation of the actual detectors.

64 The assembling of the modules holding the crystals, called
65 towers, and their installation on the cryostat followed a strict
66 protocol developed during the assembling of CUORE-0 [6],
67 the predecessor experiment of CUORE. CUORE-0 has been an
68 important demonstrator to test installation procedures and ma-
69 terial cleaning techniques, but it has also been an experiment
70 producing physics results by itself [7, 8, 9, 10]. The assem-
71 bling of the CUORE towers has been performed within glove
72 boxes in nitrogen atmosphere to avoid radioactive recontamina-
73 tion, and their installation in a protected area inside the clean
74 room flushed with radon free air. All 19 towers have been
75 installed between July-August 2016; the specifics of the de-
76 tector design are: 988 crystals overall, for a total amount of
77 206 kg of ^{130}Te ; their arrangement is such that the crystals form
78 closely packed arrays with high granularity, and the material
79 employed in the tower holding structure is minimized to reduce
80 the radioactive background from the material surrounding the
81 bolometers. The goals are to reach a background as low as
82 10^{-2} counts/(keV·kg·yr) [11], an energy resolution in the re-
83 gion of interest of 5 keV FWHM, values that lead to a projected
84 sensitivity of $T_{1/2}^{0\nu} > 9 \cdot 10^{25}$ yr in 5 years at 90% confidence
85 level [12].

86 The cryostat has been closed during September-October
87 2016 and right after CUORE started with the detector cool-
88 down on December 5th. The cool-down phase lasted 26 days
89 overall, not taking into account two periods devoted to system
90 debugging; the last 4 days the DU was switched on and the
91 temperature reached the stable base temperature of 7 mK. Any-
92 way, the detector was not ready to take data for physics anal-
93 ysis, because it needed optimization, so an important phase of
94 detector optimization started, which was then alternated with
95 data-taking periods.

96 Temperature scans have been performed to optimize the de-
97 tector resolution and the NTDs resistances around the design
98 values: in the first scan a temperature of 15 mK has been identi-
99 fied as the best working temperature for the data taking; the sec-
100 ond scan was performed in between the two data-taking periods
101 during 2017, to check the settings. Results of the resolution of
102 the baseline and of injected pulses showed a trend towards bet-
103 ter resolutions at lower temperatures. The trend was confirmed
104 on physics events on the last scan performed with calibration
105 sources deployed, at the end of the 2017 data taking, thus the
106 new temperature of 11 mK was set as working temperature of

¹Deceased

²Deceased

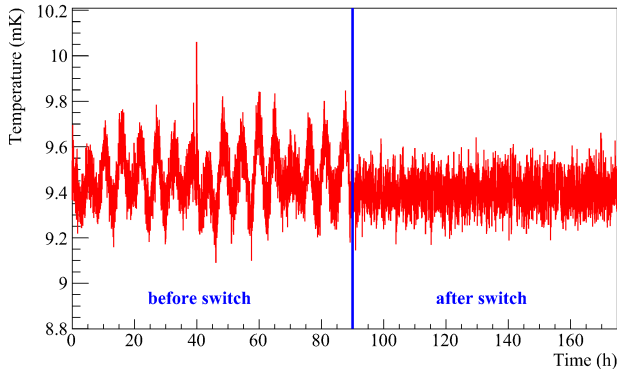


Figure 1: Base temperature at the mixing chamber plate of the CUORE cryostat, before (left) and after (right) the switch-on of the linear drives. The effect of the linear drives is an improvement of the temperature stability.

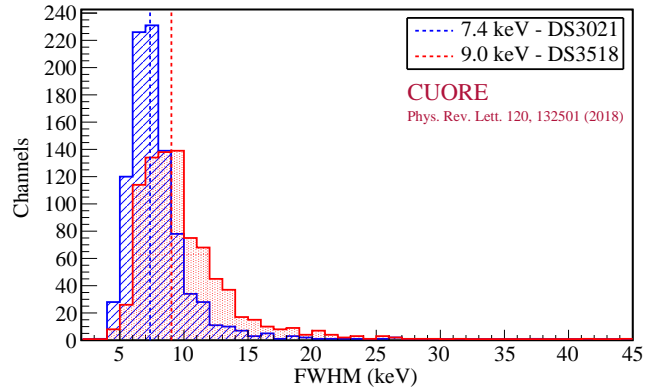


Figure 2: Distribution of the crystals resolution at the 2615 keV ^{208}Tl γ -line in calibration data. In red is the resolution from the first dataset, and in blue the one from the second dataset, after the detector optimization phase that took place in between the two data taking periods.

the detector .

Tools have been developed to minimize the vibrational noise induced by the PTs: an improvement of the temperature stability has been obtained by using linear drives to control the PTs rotating valves (see Fig. 1); a scan of the PTs phases has been introduced, allowing to find the configuration inducing the minimum vibrational noise into the detector. The distribution of the induced noise in each channel and for each phase reveals a clear pattern where phase configurations with reduced noise are clearly visible. The median across all channels of the PTs induced noise shows a clear modulation as a function of the phase configuration, where a minimum of noise can be identified and used during data taking [13].

Once the temperature is fixed, and consequently the NTDs resistances are set, the correct bias current to be supplied to the thermistors has to be identified. For each bolometer the characteristic voltage versus current curve, Load Curve (LD), is measured; moreover, the amplitude of a reference pulse, the noise RMS and corresponding SNR are measured at each point of the LD curve. The bias current is chosen such that the SNR is maximized, and at the same time at values lower than the inversion point, to avoid distorted signal shapes and get the correct response from each bolometer.

The first phase of detector optimization was completed by the end of April 2017, when CUORE started taking the first data for physics analysis. The typical data-taking period consists of three weeks of data, bracketed by two calibration periods, one at the beginning and another at the end to check the initial calibration. We had two of these periods, called datasets, in 2017. In between a second phase of detector optimization took place, which consisted in different activities; for instance, it was introduced the PTs phase scan to refine the reduction of the noise. The effect of this second optimization phase is an improvement of the detector resolution, from 9 keV to 7.4 keV (see Fig. 2). This shows the importance of the detector optimization phases for CUORE.

First physics results

The data acquired during 2017 have been analyzed to search for neutrinoless double beta decay [14]. The total exposure of TeO_2 is $86.3 \text{ kg} \cdot \text{yr}$. A fit around the Q-value of the process, the region of interest (ROI), has been performed. The fit has three components: a flat background from alphas, a peak accounting for two gammas from ^{60}Co and a peak at the Q-value for the $0\nu\beta\beta$; the peak is modeled with the detector response function studied using gamma lines from calibration data. The signal rate best-fit is $\Gamma_{0\nu} = (-1_{-0.3}^{+0.4}(\text{stat.}) \pm 0.1(\text{syst.})) \times 10^{-25} \text{ yr}^{-1}$; with zero signal, the background index best-fit is $BI = (0.014 \pm 0.002) \text{ counts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$. The result shows that there is no evidence for $0\nu\beta\beta$, thus the results from CUORE, CUORE-0 [10] and Cuoricino [15] experiments are combined together and an upper limit on the decay rate of $T_{1/2}^{0\nu} > 1.5 \times 10^{25} \text{ yr}$ at 90% C.L. is obtained. Interpreting the combined half-life limit as a limit on the effective Majorana neutrino mass, within the framework of models where the $0\nu\beta\beta$ is mediated by an exchange of a light Majorana neutrino, yields $m_{\beta\beta} < (110 - 520) \text{ meV}$ at 90% C.L.

Dark Matter with CUORE

It is interesting to explore the possibility for CUORE to search for Dark Matter (DM) induced signals: from a study that has been performed on CUORE-0 data [16], the projected sensitivity at 90% C.L. on the WIMP-nucleon cross-section for different masses shows that CUORE could have the capability of exploring the DAMA/LIBRA positive signal region. This capability strongly depends on the performances of CUORE in triggering events at very low energies. Simulations of the expected energy spectrum modulation due to WIMPs of different masses show that the expected effects induced by WIMPs extend up to few tens of keV. The trigger thresholds in CUORE on the first two dataset range from 20 keV up to about 100 keV. Currently a trigger algorithm based on the Optimal Filter technique [17] is under test: the data are filtered in the frequency domain with a filter having a transfer function maximizing the SNR, so the

179 filtered data are less noisy, thus lower thresholds are achievable.²³⁰
 180 The technique has already been applied in CUORE-0 data and²³¹
 181 allowed to perform the study in [16]. Typical values of the trig-²³²
 182 ger thresholds obtained in CUORE-0 range from 4 up to 12 keV.²³³
 183 Moreover, for low energy triggered signals a shape discrimina-²³⁴
 184 tor can be used to better distinguish between signal and noise,²³⁵
 185 such as electronic noise, tower vibrations and particle interac-²³⁶
 186 tions in the thermistors. This is a work in progress in CUORE:²³⁷
 187 currently the detector is taking data exploiting this trigger and²³⁸
 188 studies will be done to check the algorithm performances.²³⁹

189 Conclusions

190 In conclusion, CUORE is the first ton scale bolometric²⁴⁰
 191 experiment in operation, employing the largest cryostat and²⁴¹
 192 most powerful cryogenic techniques available nowadays. The²⁴²
 193 construction of the experiment was completed by the end of²⁴³
 194 2016, and in the following year important detector optimiza-²⁴⁴
 195 tion phases, alternated with data taking periods, have been per-²⁴⁵
 196 formed. During the detector optimization phases, new methods²⁴⁶
 197 and tools have been developed to reduce the induced noise and²⁴⁷
 198 set the best detector working conditions. CUORE delivered the²⁴⁸
 199 first data for physics analysis in 2017, for a total TeO₂ expo-²⁴⁹
 200 sure of 86.3 kg · yr, analyzed to search for the $0\nu\beta\beta$ [14]. After²⁵⁰
 201 acquiring the first two datasets for physics, a new optimization²⁵¹
 202 phase and schedule interventions started. The experiment re-²⁵²
 203 sumed data taking on May 2018, and the collaboration is ex-
 204 ploring the possibility to lower the trigger thresholds to perform
 205 DM searches.

206 Acknowledgments

207 The CUORE Collaboration thanks the directors and staff
 208 of the Laboratori Nazionali del Gran Sasso and our techni-
 209 cal staff for their valuable contribution to building and op-
 210 erating the detector. We thank Danielle Speller for contri-
 211 butions to detector calibration, data analysis, and discussion
 212 of the manuscript. We thank Giorgio Frossati for his crucial
 213 support in the commissioning of the dilution unit. This
 214 work was supported by the Istituto Nazionale di Fisica Nucle-
 215 are (INFN); the National Science Foundation under Grant Nos.
 216 NSF-PHY- 0605119, NSF-PHY-0500337, NSF-PHY-0855314,
 217 NSF- PHY-0902171, NSF-PHY-0969852, NSF-PHY-1307204,
 218 and NSF-PHY-1404205; the Alfred P. Sloan Foundation; and
 219 Yale University. This material is also based upon work sup-
 220 ported by the US Department of Energy (DOE) Office of Sci-
 221 ence under Contract Nos. DE-AC02- 05CH11231 and DE-
 222 AC52-07NA27344; and by the DOE Office of Science, Of-
 223 fice of Nuclear Physics under Con- tract Nos. DE-FG02-
 224 08ER41551, DE-FG03-00ER41138, 7 DE-SC0011091, and
 225 DE-SC0012654. This research used resources of the National
 226 Energy Research Scientific Computing Center (NERSC).

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