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

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ABSTRACT

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 TeO_2 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.

Contents

1. The cuore experiment

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

CUORE exploits the bolometric technique [3,4]: crystals of TeO_2 are in thermal equilibrium, through a weak thermal coupling, with a bath at cryogenic temperature. A particle releasing its energy into the crystal produces a rise in temperature of the crystal itself, which is read out through a resistive thermometer (Neutron Transmutation Doped (NTD) thermistors) as a voltage variation. The bolometric technique ensures high detection efficiency and energy resolution. The chosen isotope ^{130}Te is a good candidate for $0\nu\beta\beta$ given its high natural isotopic abundance of 34.2%, higher then any other available isotope. Moreover it has a high Q-value for the process, $Q_{\beta\beta} = (2527.515 \pm 0.013)\,\mathrm{keV}$, above almost all the environmental γ background. Also, thanks to the scalability of the bolometric technique, detectors of large mass can be built.

Concerning the background, it has to be underlined that CUORE is searching for a very rare event, with an half life which is at least 15 order of magnitudes longer than the age of the Universe. Therefore, it is extremely important to reduce as much as possible the background sources. For this reason, the experiment is located at the LNGS underground laboratories, at an average depth of about 3600 m.w.e., reducing natural radioactivity from outside the detector. Strict protocols have been developed and applied for crystals production and detector assembling, and new techniques have been tested and employed to clean the copper parts near crystals. These precautions allow to reduce natural radioactivity from the detector itself. Furthermore, suspensions and dumping systems, as well as noise canceling tools, have been adopted to reduce the induced noise due to mechanical vibrations.

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

2. Detector commissioning and optimization

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

The assembling of the modules holding the crystals, called towers, and their installation on the cryostat followed a strict protocol developed during the assembling of CUORE-0 [6], the predecessor experiment of CUORE. CUORE-0 has been an important demonstrator to test installation procedures and material cleaning techniques, but it has also been an experiment producing physics results by itself [7–10]. The assembling of the CUORE towers has been performed within glove boxes in nitrogen atmosphere to avoid radioactive recontamination, and their installation in a protected area inside the clean room flushed with radon free air. All 19 towers have been installed between July–August 2016; the specifics

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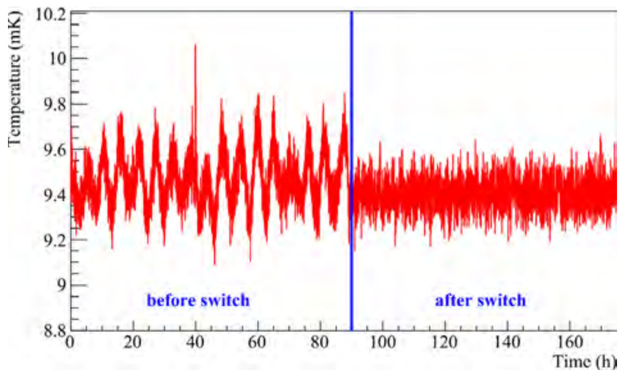

Fig. 1. Base temperature at the mixing chamber plate of the CUORE cryostat, before (left) and after (right) the switch-on of the linear drives. The effect of the linear drives is an improvement of the temperature stability.

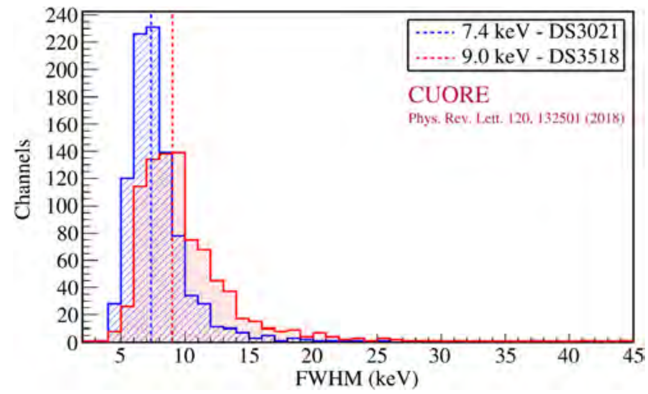

Fig. 2. Distribution of the crystals resolution at the 2615 keV ^{208}Tl γ-line in calibration data. In red is the resolution from the first dataset, and in blue the one from the second dataset, after the detector optimization phase that took place in between the two data taking periods.

of the detector design are: 988 crystals overall, for a total amount of 206 kg of ^{130}Te; their arrangement is such that the crystals form closely packed arrays with high granularity, and the material employed in the tower holding structure is minimized to reduce the radioactive background from the material surrounding the bolometers. The goals are to reach a background as low as 10^{-2} counts/(keV kg yr) [11], an energy resolution in the region of interest of 5 keV FWHM, values that lead to a projected sensitivity of $T^{0\nu}_{1/2} > 9 \cdot 10^{25}$ yr in 5 years at 90% confidence level [12].

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

Temperature scans have been performed to optimize the detector resolution and the NTDs resistances around the design values: in the first scan a temperature of 15 mK has been identified as the best working temperature for the data taking; the second scan was performed in between the two data-taking periods during 2017, to check the settings. Results of the resolution of the baseline and of injected pulses showed a trend towards better resolutions at lower temperatures. The trend was confirmed on physics events on the last scan performed with calibration sources deployed, at the end of the 2017 data taking, thus the new temperature of 11 mK was set as working temperature of 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.

3. 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 kg 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 $\Gamma_{0\nu} = \left(-1^{+0.4}_{-0.3}(stat.) \pm 0.1(syst.)\right) \times 10^{-25}\,\mathrm{yr}^{-1}$; with zero signal, the background index best-fit is $BI = (0.014 \pm 0.002)$ counts/(keV kg 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 $T^{0\nu}_{1/2} > 1.5 \times 10^{25}$ 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 $m_{\beta\beta} < (110 - 520)$ meV at 90% C.L.

4. 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

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the filtered data are less noisy, thus lower thresholds are achievable. The technique has already been applied in CUORE-0 data and allowed to perform the study in [16]. Typical values of the trigger thresholds obtained in CUORE-0 range from 4 up to 12 keV. Moreover, for low energy triggered signals a shape discriminator can be used to better distinguish between signal and noise, such as electronic noise, tower vibrations and particle interactions in the thermistors. This is a work in progress in CUORE: currently the detector is taking data exploiting this trigger and studies will be done to check the algorithm performances.

5. Conclusions

In conclusion, CUORE is the first ton scale bolometric experiment in operation, employing the largest cryostat and most powerful cryogenic techniques available nowadays. The construction of the experiment was completed by the end of 2016, and in the following year important detector optimization phases, alternated with data taking periods, have been performed. During the detector optimization phases, new methods and tools have been developed to reduce the induced noise and set the best detector working conditions. CUORE delivered the first data for physics analysis in 2017, for a total TeO_2 exposure of $86.3\ \mathrm{kg\ yr}$, analyzed to search for the $0\nu\beta\beta$ [14]. After acquiring the first two datasets for physics, a new optimization phase and schedule interventions started. The experiment resumed data taking on May 2018, and the collaboration is exploring the possibility to lower the trigger thresholds to perform DM searches.

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