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Results of CUORE-0 and prospects for the CUORE experiment

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Abstract

The CUORE (Cryogenic Underground Observatory for Rare Events) experiment is an array of 741 kg of TeO_2 bolometers to search for neutrinoless double beta decay ($\beta\beta0\nu$) of ^{130}Te. The detector is being constructed at the Laboratori Nazionali del Gran Sasso (Italy) where it will start operation in 2015. To test and demonstrate the possibility of realising such a large scale bolometric detector, a prototype (CUORE-0) has been realised. The CUORE-0 detector is a single tower of 52 CUORE-like bolometers. CUORE-0 data taking started in Spring 2013. The status of CUORE and the first CUORE-0 data are here reported.

Keywords: Double Beta Decay, Bolometers, Neutrino Mass

1. Introduction

One of the open questions of elementary particle physics is whether neutrinos are Majorana or Dirac fermions. Neutrinoless double beta decay ($\beta\beta0\nu$) is a hypothetical lepton number violating process that, if it occurs, can prove the Majorana nature of neutrinos. In such a process, two neutrons inside a nucleus simultaneously decay into two protons and two electrons. No electron-antineutrinos are emitted. One of the most established technique to observe $\beta\beta0\nu$ decay consists in the detection of the kinetic energy of the 2 emitted electrons. This gives a monochromatic signal at the Q-value of the transition in the energy spectrum of the decay products.

CUORE is a bolometric experiment that will search for the $\beta\beta0\nu$ decay in ^{130}Te. The Q-value for this transition is 2527 keV [1]. In a bolometer, the energy released by particles interacting in the absorber induces an increase in temperature. This temperature variation can be read through a suitable thermal sensor coupled to the absorber. In CUORE each bolometer is a cubic 5×5×5 cm^3 TeO_2 crystal with a mass of about 750 g. The temperature variations are measured as resistance variations by neutron transmutation doped (NTD) Ge thermistor. The crystals are mechanically and thermally coupled to a copper structure, acting as heat sink, using small PTFE holders.

The CUORE detector is composed of 988 TeO_2 bolometers with a total mass of 741 kg. As the natural abundance of ^{130}Te is ~34%, the total amount of $\beta\beta0\nu$ active mass is 206 kg. The detectors will be arranged in 19 towers, each with 13 layers of 4 crystals. The towers will be operated in a low-radioactivity custom dilution refrigerator, which is under commissioning at the underground Gran Sasso National Laboratories (LNGS), in Italy.

A prototype of CUORE, Cuoricino, took data at LNGS between 2003-2008. Besides demonstrating the feasibility of a large mass bolometric detector, Cuoricino set the most stringent half-life limit for the neutrinoless double-beta decay of ^{130}Te, $> 2.8 \cdot 10^{24}$ y (90% C.L.) [2], with a corresponding upper bound on the neutrino Majorana mass in the range of 0.30-0.71 eV. Cuoricino was also a valuable tool for the understanding of the key challenges to be solved for the construction of CUORE. An intermediate step has preceded the start of CUORE: CUORE-0, the first CUORE-like tower, is being operated in the former Cuoricino cryostat and has been acquiring data since Spring 2013 [3].

2. CUORE

To improve on the Cuoricino results, it is necessary to increase the experimental mass, improve the energy resolution and reduce the background contribution in the energy region of interest (ROI). CUORE will have a detector mass ~20 times larger than that of Cuoricino, and has design goals of a FWHM resolution of 5 keV and a background rate of 0.01 counts/(keV·kg·y) in the ROI. The CUORE detector is a large bolometer array of 988 TeO_2 crystal modules arranged in 19 towers (Figure 1).

The crystals were manufactured by the Shanghai Institute of Ceramics, Chinese Academy of Sciences, following strict radiopurity protocols to limit bulk and surface contaminations introduced during the crystal production [4]. The crystals were then transported

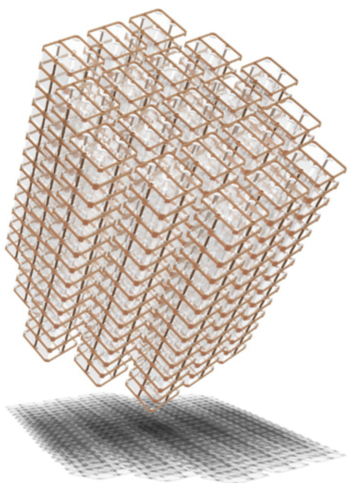

Figure 1: The CUORE detector array scheme.

to LNGS at sea level to minimize cosmogenic activation. Dedicated cryogenic tests on few crystals from different production batches demonstrated ^{238}U bulk and surface contamination levels of <$6.7\cdot10^{-7}$ Bq/kg and <$8.9\cdot10^{-9}$Bq/cm^2 (90% C.L.), respectively, and ^{232}Th bulk and surface contamination levels of <$8.4 \cdot 10^{-7}$ Bq/kg and <$2.0\cdot10^{-9}$ Bq/cm^2 (90% C.L.), respectively [5].

To mitigate the background coming from the copper structure, a specially developed surface treatment protocol was applied to all copper parts directly facing the detectors. This procedure, which we refer to as TECM (Tumbling, Electropolishing, Chemical etching, and Magnetron plasma etching) was demonstrated to efficiently reduce the contamination of both ^{238}U and ^{232}Th on the copper surface to <$1.3 \cdot 10^{-7}$Bq/cm^2 [6].

Special care was also devoted to the CUORE assembly line. To avoid possible recontamination after cleaning [7], all the detector assembly operations were performed in a dedicated class 1000 clean room, equipped with a set of specially designed glove boxes [8]. The tower assembly consists essentially of three steps: sensors gluing on the crystals, crystal assembly into towers and signal connections to the crystals with 25 μm gold wires. Completed towers are stored in nitrogen-flushed containers awaiting installation in the cryostat.

The CUORE detector will be installed in a complex cryogenic apparatus where it will be operated at a temperature of ∼10 mK. We have designed a large cryogen-free cryostat with five pulse tubes and a custom dilution refrigerator to cool the detector. All materials used in the construction of the experimental apparatus have been selected following stringent radiopurity requirements. The detector towers will be suspended from a thick copper disk thermally anchored to the 10 mK stage and mechanically decoupled from the rest of the setup to minimize vibrational noise. An inner Roman lead shield [9] will protect the detectors from the residual radioactive contaminations of the cryogenic system. A detector calibration system has been designed in order to uniformly irradiate the detectors during the energy calibrations. Finally, heavy room-temperature shields made of layers of borated polyethylene, boric acid, and lead bricks surround the apparatus to reduce the external background contribution from neutrons and γ rays.

The CUORE experiment is currently being commissioned at LNGS and the detector installation is scheduled for Summer 2015. All 19 towers have been assembled, instrumented with sensors, and stored in nitrogen-flushed atmosphere.

The dilution unit was tested in the CUORE cryostat, where it reached a base temperature of 6 mK in September 2014. Before the end of 2014 we will perform the first bolometric test of the cryostat: we acquire and analyse signals from a mini-tower of 8 CUORE-like crystals at base temperature. Starting in the beginning of 2015, the mounting of the final components of the cryostat (i.e., the Detector Calibration System and the cold shields) will take place. CUORE operation is expected to commence by the end of 2015.

3. CUORE-0

CUORE-0 is a CUORE-like tower built using the detector components, cleaning protocols and assembly procedures developed for CUORE. It is made of 52 TeO_2 bolometers, for a total detector mass of 39 kg (∼11 kg of ^{130}Te). CUORE-0 is operated in the same experimental setup that hosted Cuoricino, a dilution refrigerator located in Hall A of LNGS.

The cryogenic system is shielded by a 20-cm thick lead shield, to absorb γ-rays, and by 20 cm of borated polyethylene, to thermalise and absorb neutrons. The detector is shielded from radioactive contamination in the cryostat by 1 cm of low-activity lead. The whole system is enclosed in a Faraday cage that suppresses electromagnetic disturbances. The analogue read-out of the thermistors is performed using the same electronics that were designed for Cuoricino [10]. The signals are first amplified, filtered by 6-pole active Bessel filter and then fed into an 18-bit National Instrument PXI analogue-to-digital converter (ADC).

The CUORE-0 detector is operating at a temperature of 13-15 mK. At this temperature, the typical signal am-

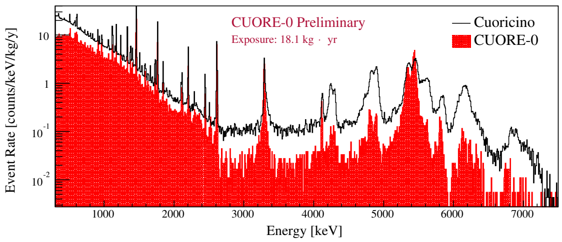

Figure 2: Cuoricino (line) and CUORE-0 (shaded) background spectra comparison. The strong background reduction achieved with the CUORE-0 detector is evident. It amounts to a factor of ~6 in the α region (i.e. energies above 2.7 Mev) and to a factor of ~2 in the γ region (i.e. energies below 2.7 Mev).

plitude is 10 - 20 μK/MeV, with rise and decay times of 50 and 250 ms, respectively. The bolometers are calibrated every month by inserting two thoriated tungsten wires between the outer vacuum chamber of the cryostat and the external lead shield. The total exposure acquired between March 2013 and May 2014, and summed over all the detectors, is 18.1 kg·y.
For comparison, in Figure 2, the CUORE-0 and Cuoricino energy spectra are superimposed. The plot demonstrates the effectiveness of both the new surface cleaning procedures developed for CUORE and the new CUORE-detector design.

The flat α background index is (0.020±0.001) counts/(keV·kg·y) in CUORE-0, which improves on the Cuoricino result of (0.110±0.001) counts/(keV·kg·y). The flat α background index is estimated in the energy regions between 2.7 MeV and 3.1 MeV, and between 3.4 MeV and 3.9 MeV, excluding the α-peak from ^{190}Pt. The CUORE-0 $\beta\beta0\nu$ signal region is blinded. The flat background in the ROI is (0.063 ± 0.006) counts/(keV · kg · y), compared to (0.153 ± 0.006) counts/(keV · kg· y) in Cuoricino, a reduction of a factor of approximately 2.5. The energy resolution in the ROI is defined as the FWHM of the 2615 keV γ-ray peak, and a fit to the summed background spectrum of all fully functional channels gives a value of 5.1 keV. With this resolution and background index, in early 2015 the CUORE-0 sensitivity will overtake that achieved by Cuoricino.

At that point, data in the ROI will be unblinded. CUORE-0 will continue taking data until CUORE begins to do so.

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