Neutrinoless double beta decay results from CUORE-0 and status for CUORE experiment

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The Cryogenic Underground Observatory for Rare Events (CUORE) is a 1-ton scale bolometric experiment whose detector consists of an array of 988 TeO_2 crystals arranged in a cylindrical compact structure of 19 towers. CUORE-0 is the CUORE demonstrator: it has been built to test the performance of the upcoming CUORE experiment and represents the largest ^{130}Te bolometric setup ever operated. CUORE-0 has been running at Laboratori Nazionali del Gran Sasso (Italy) from March 2013 to March 2015. The final CUORE-0 analysis on neutrinoless double beta decay and the corresponding detector performance are presented. The status of the CUORE experiment, now in its final construction and commissioning phase, are discussed. The results from assembly of the detector and the commissioning of the cryostat are reported.

1 Introduction

Neutrinoless double-beta decay ($\beta\beta0\nu$) is a nuclear decay that violates lepton number conservation. In this transition a nucleus (A, Z), with even A and Z, decays into (A, Z+2) nucleus with the emission of two electrons and no neutrino, resulting in a peak in the sum energy spectrum of the emitted electrons. This process, first hypothesized in [1], has never been observed so far. Its discovery would demonstrate the lepton number violation, the Majorana nature of neutrinos, and would constrain the absolute neutrino mass scale. Given its importance, an intense experimental effort is ongoing to search for this decay in several nuclei [2].

The Cryogenic Underground Observatory for Rare Events (CUORE) [3], presently in the final stages of construction at the Gran Sasso National Laboratory (LNGS), will be one of the most sensitive upcoming $\beta\beta0\nu$ experiments. It is an array of 988 TeO_2 bolometers with the goal of searching for the $\beta\beta0\nu$ of ^{130}Te. The detectors are arranged in a compact structure of 19 towers, each one containing 52 TeO_2 crystals, disposed on 13 floors. CUORE aims to reach a sensitivity on the half-life of $\beta\beta0\nu$ of ^{130}Te $T_{1/2} = 9.5 \cdot 10^{25}$ yr in 5 years (at 90 % C.L.).

The first tower built in the CUORE assembling line was operated as a stand alone experiment, named CUORE-0 from 2013 to 2015 to prove all the CUORE features and upgrades and to set a world best limit on the half life of $\beta\beta0\nu$ decay of ^{130}Te.

2 CUORE

CUORE is a bolometric experiment searching for $\beta\beta0\nu$ of ^{130}Te. In the bolometric approach, the energy deposited by particle interacting in an absorber is measured as an increase of temperature in the absorber itself. In CUORE each bolometer will use a cubic 5×5×5 cm^3 TeO_2 crystal with a mass of about 750 g as crystal absorber. In this way the detector contains the source of the decay, achieving high efficiency (∼88%) and good energy resolution. The temperature variations of the crystal are detected by a thermistor as resistance variations. The thermistor is a neutron transmutation doped (NTD) Ge semiconductor, that exhibits an exponential response

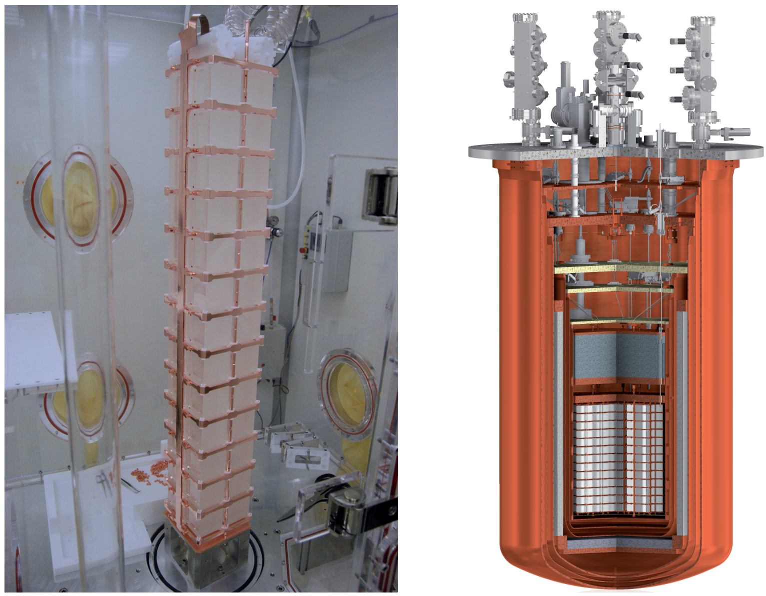

Figure 1 – Left: the CUORE-0 detector during the assembling: the 52 TeO_2 crystals are arranged in 13 floors of 4 crystals each. Right: sketch of the CUORE cryostat with the CUORE detector surrounded by the vessels of increasing temperature.

to T variations of the resistance at low temperatures. The crystals are held and thermally coupled to a heat sink, that is a copper structure cooled down to about 10 mK, by means of eight Polytetrafluoroethylene (PTFE) supports. Typical sensitivity of the thermistor is ∼100 μV/MeV of deposited energy. The CUORE detector will be composed by 988 natural TeO_2 bolometers for 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 of 13 layers each. The towers will be placed in a roughly cylindrical compact configuration in a new low radioactivity custom dilution refrigerator, to be commissioned and installed in Laboratori Nazionali del Gran Sasso (LNGS), in Italy.

A demonstrator experiment, CUORICINO [4], was operated in the same laboratory from 2003 to 2008. The CUORICINO detector was composed by 62 TeO_2 bolometers, for a total mass of 40.7 kg. The acquired statistics was 19.75 kg(^{130}Te)· y, and no $\beta\beta0\nu$ signal was found. The background level in the $\beta\beta0\nu$ energy region was 0.169 ± 0.006 counts/keV/kg/y and the corresponding lower limit on the $\beta\beta0\nu$ half-life of ^{130}Te is $2.8 \cdot 10^{24}$ y (90% C.L.). This limit translates into an upper limit on the neutrino effective Majorana mass ranging from 300 to 710 meV, depending on the nuclear matrix elements considered in the computation.

2.1 Experimental challenges

The aim of future neutrinoless experiments, as CUORE, is to begin to probe the inverted hierarchy region of neutrino masses. To achieve the necessary sensitivity the key experimental parameters are: i) large sample of candidate nuclei under control, ii) long live time, iii) good detector energy resolution, and iv) very low radioactive background. The first two challenges are matched by the described CUORE design. Crucial requirements are the capability of completing 988 TeO_2 bolometers in clean and reproducible conditions and the capability of delivering a uniform base temperature in a low vibration and low background environment. The status of detector realisation and assembling and of the cryostat commissioning are reported in section 4. Requirements iii) and iv) were part of the intense CUORE R&D program. In CUORICINO the average energy resolution at 2615 keV (^{208}Tl line) was 6.3 ± 2.5 keV [5]. After CUORICINO, the detector performances of the R&D bolometers for CUORE have been improved thanks to a new layout of the detectors that uses new copper frames and new PTFE crystal supports, and the target energy resolution in the CUORE is 5 keV. Moreover a strong material selection and cleaning campaign was performed for the detectors and for the cryostat components to reduce the background events in the region of interest (ROI). The $\beta\beta0\nu$ Q-value for this nucleus is 2527.515 ± 0.013 keV [6]. A challenge related to the detector performances is the uniformity of their behaviour. In CUORICINO, we observed a large spread in the pulse shape among the detectors. This leads to a complication in the data analysis that could be more challenging in case of an experiment, like CUORE, with about 1000 single detectors. To improve the detector response uniformity special care has been devoted in the realisation of a new detector assembly system. The background level is expected to be as good as 0.01 counts/keV/kg/y due to: improvements in the radio-purity of the copper and crystal surfaces as well as in the assembly environment; thicker shields using low-activity ancient Roman lead; and the fact that the 19-tower array affords superior self-shielding and better anti-coincidence coverage (discussion of the different contribution can be found in [11]).

3 The CUORE-0 experiment

CUORE-0 is a single CUORE-like tower, the first one built using the low-background assembly techniques developed for CUORE [7]. It is made of 52 TeO_2 bolometers, for a total mass of 39 kg. The TeO_2 crystals are held in an ultra-pure copper frame by PTFE supports and arranged in 13 floors, with 4 crystals per floor (see Fig. 1). Each TeO_2 detector is instrumented with a Neutron Transmutation Doped (NTD) Ge thermistor glued on its surface, to measure the temperature change of the absorber and convert it into an electric signal. Each crystal is instrumented also with a silicon resistor ("heater") to generate reference pulses. The tower was operated in Hall A of LNGS, in the same dilution refrigerator that previously hosted the CUORICINO experiment, and it took data between March 2013 and March 2015. Technical details are reported in [8], while the CUORE-0 physics results can be found in [9].

3.1 Detector performance

CUORE-0 acquired data for the $\beta\beta0\nu$search accumulating a total exposure of 9.8 kg·y of ^{130}Te. Data are collected in month-long blocks called datasets. At the beginning and end of each dataset we calibrate the detector by placing a ^{232}Th source next to the outer vessel of the cryogenic system. We use the calibration line with the highest intensity and next to the ROI, 2615 keV from ^{208}Tl, in order to study the detector response function to a mono energetic energy deposit for each bolometer and dataset. We estimate the shape parameters of the 2615 keV line with a simultaneous, unbinned extended maximum likelihood (UEML) fit to calibration data. The physics exposure-weighted effective mean of the FWHM values for each bolometer and dataset is 4.9 keV, with a corresponding RMS of 2.9 keV. We evaluate the background level in the alpha-dominated region (2700-3900) keV to be 0.016±0.001 counts/keV/kg/y), 6 times smaller with respect to the Cuoricino background in the same region (see Fig. 2 right) .

3.2 $\beta\beta0\nu$ decay result

We search for $\beta\beta0\nu$ decay of ^{130}Te in the final CUORE-0 energy spectrum performing a simultaneous UEML fit in the energy region 2470-2570 keV (Fig. 2). The fit function is composed by three parameters: a posited signal peak at the Q-value of the transition, a peak at

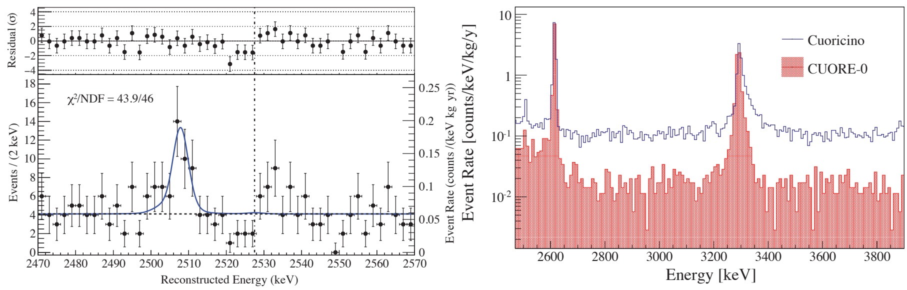

Figure 2 – Left bottom: The best-fit model from the UEML fit (solid blue line) overlaid on the spectrum of $\beta\beta0\nu$ decay candidates in CUORE-0 (data points); the data are shown with Gaussian error bars. Dotted black line shows the continuum background component of the best-fit model. Left top: normalized residuals of the best-fit model and the binned data. The vertical dot-dashed black line indicates the position of $Q_{\beta\beta}$. Right: Comparison of CUORE-0 and CUORICINO spectra in the flat alpha region (2700-3900 keV).

$\sim$2507 keV from ^{60}Co double-gammas, and a smooth continuum background attributed to multi-scatter Compton events from ^{208}Tl and surface decays. The best-fit values are $\Gamma_{0\nu} = 0.01 \pm 0.12(\text{stat}) \pm 0.01(\text{syst}) \times 10^{-24}\text{yr}^{-1}$ for the $\beta\beta0\nu$ decay rate and $0.058 \pm 0.004(\text{stat}) \pm 0.002(\text{syst})$ counts/keV/kg/y) for the background index in the ROI. This result is 3 times lower than the Cuoricino background, 0.169 ± 0.006 counts/keV/kg/y, in the same ROI. Using a Bayesian approach, we set a 90% C.L. lower bound on the decay half-life of 2.7×10^{24}yr [9]. When combined with the 19.75 kg·y exposure of ^{130}Te from the Cuoricino experiment, we find a Bayesian 90% C.L. limit of $T_{0\nu} > 4.0 \times 10^{24}$yr, which is the most stringent limit to date on the ^{130}Te $\beta\beta0\nu$ half-life. Additional details on the analysis techniques can be found in [10].

4 CUORE commissioning

The commissioning of the CUORE experiment has two main deliverables: i) the 988 TeO_2 bolometers properly assembled and wired and ii) the cryostat able to host the detector and cool it to the expected base temperature (<10 mK) in stable conditions.

The assembly of the CUORE detector towers started in late February 2013. Following the experience of CUORE-0, the assembling was performed under nitrogen atmosfere in a dedicated assembling line. The assembly of all the 19 CUORE towers has been completed in July 2014. The towers are presently stored inside the CUORE clean room until they will be installed into the cryostat just before the final cool-down. Each tower is maintained inside its individual cage and flushed with nitrogen.

The commissioning of the CUORE cryostat was concluded in March 2016. The cryostat (see sketch in Fig. 1) is composed by 6 coaxial vessels, kept at 300, 40, 4 K, 600, 50, 10 mK, respectively. 300 and 4 K shields are vacuum tight. The detector will be placed inside the 10 mK vessel. The cryostat is suspended from above to a structure called Main Support Plate (MSP). A Y-Beam, isolated from the MSP through Minus-K special suspensions, supports the detector. In this way, vibration transmission from the cryostat to the crystal is minimized. To suppress external γ background, inside the cryostat, just above the detector, is placed a 30-cm-thick cylindrical shielding, made of lead sheets, kept at about 50 mK. This is the only shielding wall from the top side. Another cold lead shielding, kept at 4 K, is a 6-cm-thick wall that surrounds the 600 mK vessel. The lateral shield is made of ^{210}Pb-free ancient roman lead The aim of the cold shields is to prevent radioactivity contamination from the external vessels (300, 40, and 4 K) and from all the cryostat plates. The 4K temperature stage is obtained by means of 5 two-stage Cryomech PT415 Pulse Tubes (PTs), with nominal cooling power of

1.5 W at 4.2 K and 40 W at 45 K each. Base temperature is reached using a modified DRS-CF3000 continuous-cycle Dilution Refrigerator (DR) made by Leiden Cryogenics. Its nominal cooling power is 5 μW at 12 mK (3 mW at 120 mK), and the minimum reachable temperature is around 5 mK (for more details on the CUORE cryostat see [12]). CUORE wiring consists of 2600 NbTi cables with 0.1-mm diameter, grouped in 100 ribbons, 13 twisted pair each. Wiring ribbons bring the thermistors and heaters signal from the top plate (300 K) to the Mixing Chamber (MC) plate (10 mK) and they can carry heat directly to the bolometers, so their thermalization requires special care. From 300 to 4 K, the ribbons are thermalized by radiation, while below 4 K by conduction, by means of dedicated thermalization clamps connected to the 4 K, 600 and 50 mK stages. A mini-tower with 8 crystals was built, mounted, and connected to the electronics to check bolometer functionality. The commissioning consisted in a sequence of could run of increasing complexity in the cryostat. The last cold run was performed with the full cryostat with all the components installed but the detector. The cryostat provided a stable base temperature of $\sim$ 6.3 mK for about 70 days. The performance of the detectors measured on the on 8 bolometer array (Mini-Tower) were encouraging and a full debugging of the electronics, DAQ, temperature stabilization, and detector calibration systems was performed.

The installation of the detectors in the CUORE cryostat is foreseen in summer 2016. Cool down will start immediately after.

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Standard Model