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First CUORE-0 Performance Results and Status of CUORE Experiment

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Abstract The CUORE (Cryogenic Underground Observatory for Rare Events) experiment will search for neutrinoless double beta decay in ^{130}Te. Observation of the process would unambiguously establish that neutrinos are Majorana particles as well as provide information about the absolute neutrino mass scale and mass hierarchy.The CUORE setup will consist of an array of 988 tellurium dioxide crystals (containing

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206 kg of ^{130}Te in total), operated as bolometers at a temperature of $\sim$10 mK. The experiment is now under construction at the Gran Sasso National Laboratory in Italy. As a first step towards CUORE, a tower (CUORE-0) has been assembled and is taking data. Here a detailed description of the CUORE-0 tower and its performance is reported. The status of the CUORE experiment and its expected sensitivity will then be discussed.

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1 Introduction: TeO_2 Bolometers for Rare-Event Searches

Neutrinoless double-beta decay (0vDBD) is a rare nuclear transition not allowed in the Standard Model framework. Its discovery would indicate the Majorana nature of neutrinos and provide information on the hierarchy of the neutrino masses and scales [1].

The purpose of the CUORE experiment is to search for 0vDBD in ^{130}Te using TeO_2 crystals operated as cryogenic bolometers. The 0vDBD Q-value for this nucleus is 2527.5 keV [2]. The CUORE detector will consist of a tightly packed array of 988 TeO_2 crystals containing 206 kg of ^{130}Te and cooled inside a large cryostat operated at 10 mK. At this low temperature the crystals work as highly sensitive calorimeters, converting the energy deposited by particle interactions into measurable temperature rises.

Each TeO_2 crystal, $5\times5\times5$ cm^3 with a mass of 750 g, serves as both the source of double-beta decaying ^{130}Te and the energy absorber. The crystals are mechanically and thermally coupled to a copper holder, acting as heat sink, using small Teflon (PTFE) pieces. A Neutron Transmutation Doped Ge thermistor (NTD), for the detection of temperature variations, and a heater, are glued on each crystal. The heaters are used to inject pulses of heat into the crystals at regular intervals, to stabilize the bolometer response against small fluctuations in operating temperature over time. TeO_2 bolometers have long been used to search for 0vDBD in ^{130}Te because their properties are well matched to the experimental requirements [3,4]. Taking into account the large-mass of the experiment, this determines a high sensitivity to 0vDBD, which makes CUORE one of the most competitive experiments in the field.

A prototype of CUORE, Cuoricino, took data at Gran Sasso National Laboratories in the years 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: $> 2.8 \times 10^{24}$ year at 90 % C.L., with a corresponding upper bound on the neutrino Majorana mass in the range (0.30–0.71) eV [5]. Cuoricino was also a precious tool for the understanding of the key problematics to be solved for the construction of CUORE. An intermediate step has preceded the start of CUORE: its first tower, named CUORE-0, is being operated in the former Cuoricino cryostat and is now acquiring data. CUORE-0 served as a test of the new CUORE assembly line, as well as a high-statistics check of the improvements implemented to reduce the background sources and to improve the bolometric response of the detectors. It will also be a promising detector, that will surpass the limit on the effective neutrino mass set by Cuoricino.

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2 The CUORE Experimental Challenges

The aim of future neutrinoless double beta decay experiments like CUORE is to probe the inverted hierarchy region of neutrino masses. Reaching such a challenging sensitivity requires very demanding specifications on the design and construction of the CUORE detector. The key experimental parameters for achieving this goal are: extremely low radioactive background, excellent detector energy resolution and long live time of the measurement.

To accomplish background suppression, the first step was identification of the main sources responsible for Cuoricino background in the Region Of Interest (ROI), whose measured value was of (0.169 ± 0.006) counts/keV/kg/y. By means of Monte Carlo simulations [6] two main background sources were identified: surface contaminations of the detector components (responsible of ∼60 % of the ROI background), and ^{232}Th bulk contaminations of the materials surrounding the experimental set up (e.g. cryostat), mainly due to ^{208}Tl decays (responsible of ∼30 % of the ROI background). Surface contaminations of detector parts (mainly the copper structure surfaces facing the absorber and the crystal surfaces themselves) are the most dangerous because they produced degraded alphas, that release only part of their energy in the crystal absorber. These events can contribute to a flat background that goes from the full alpha energy peak to much lower energies, reaching the neutrinoless double beta decay ROI. The main contaminants were identified as coming from the ^{238}U and ^{232}Th natural decay chains.

The knowledge gained from Cuoricino guided the design and construction of CUORE. After a series of thorough studies on the background abatement, a special detector structure was designed to reduce the copper surface area facing the detectors. New surfaces-cleaning techniques were defined to reduce surface contaminations and minimize the induced background in the ROI [7], [8]. Moreover, all radiochemically pure materials are continuously kept under strict controls to prevent possible recontaminations. To cool the CUORE detector a large cryogen-free cryostat with five pulse tubes and one specially designed high-power dilution refrigerator has been designed. The detector assembly has a total mass of about 1.5 tonne and uses a vibration decoupling suspension system. Because of the stringent radioactivity requirements, about 10 tonnes of lead shielding will need to be cooled below 4 K, and only a limited number of construction materials are acceptable.

3 CUORE-0

The final step before the start of the CUORE experiment is CUORE-0, a single CUORE-like tower that is now acquiring data in the former Cuoricino cryostat. CUORE-0 consists of 52 CUORE crystals with a total TeO_2 mass of 39 kg. It has been assembled accordingly to the same stringent protocols defined for CUORE. CUORE-0 represents an opportunity to evaluate the bolometric performances of a CUORE-like detector apparatus in a familiar cryostat, and it will be the first large-scale empirical test of the extensive background-reduction measures undertaken.

3.1 CUORE-0 Assembly

Tower construction is organized around two units: the gluing station, which provides all the tools needed for the gluing of thermal sensors onto the crystals, followed by the assembly line, an integrated set of tools devoted to the final assembly of the tower. Both units use N_2-fluxed glove boxes to provide a controlled radon-free environment [9]. The coupling of the sensors (thermistors and heaters) to the TeO_2 crystal absorbers affects the performance of the detector. Significant effort went into improving the totally manual gluing procedure used previously in Cuoricino and obtain a highly reproducible sensor-to-absorber coupling procedure. The sensor-to-absorber coupling is made by applying a matrix of glue dots using a semiautomated system involving robots which allows high repeatability.

The CUORE-0 tower has been assembled following strict protocols under extremely clean conditions. This not only requires that all assembly be performed inside glove-boxes flushed with nitrogen gas, but also that strict controls are implemented on all materials which come into contact with the tower components during assembly. The assembly line consists of five separate glove boxes for specialized operations on the detector components. The assembly includes also the system and procedures for the electrical connection of the sensors to the tower wires, consisting of PEN (Polyethylene naphthalate) strips with a copper deposition forming the wires. The connection is achieved by bonding four 25-micron wires from the sensor gold pads to the copper pads on the wire strips. During the bonding of the CUORE-0 tower connections, we were able to connect 51 out of 52 NTD thermistors and 51 out of 52 heater sensors.

3.2 Performances

The CUORE-0 detector was cooled down in September 2012. Unfortunately, due to problems with the old Cuoricino cryostat, the detector has achieved stable operation only since March 2013. During the first cool down we lost one electrical connection of one heater chip, reducing the number of active heaters to 50 out of 52 and bringing to 49 the number of fully active channels (crystals equipped with both working heater and NTD chips). However, we verified that no thermometer connections were lost during the multiple cool-downs, meaning that the new bonding system can easily tolerate thermal contractions.

After we reached base temperature of about 10 mK on all the detectors, we performed the optimization of the bolometers. Load curves were computed to determine the best configuration of the thermistor bias circuit and to have maximum pulse amplitudes. To evaluate the bolometric performances of the detectors we performed a calibration measurement, by inserting a gamma source (thoriated tungsten wires) outside of the cryostat. Figure 1 shows the energy spectrum of pulse amplitudes recorded by 49 fully active channels with the calibration sources in place. The statistics was acquired in 258.7 h. The peaks in Fig. 1 are identified as gamma lines from the decay of nuclei in the ^{232}Th decay chain.

The energy resolution is evaluated on the 2615 keV photo-peak from the decay of ^{208}Tl, very close to the ^{130}Te Q-value of 2,527.5 keV. Fig. 2 shows the gaussian fit

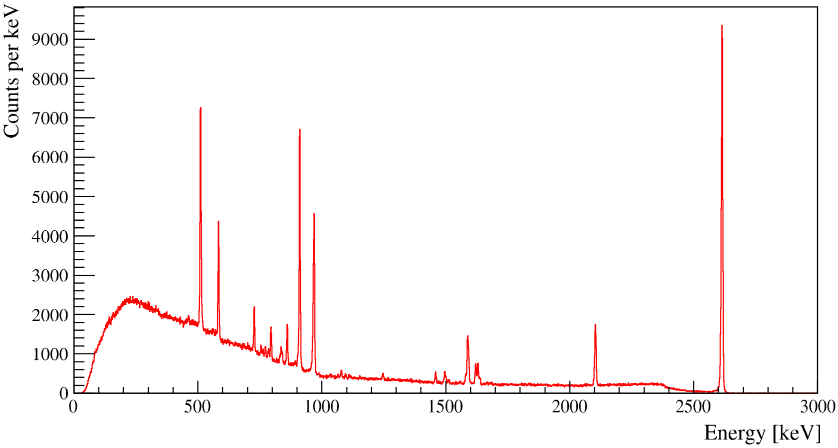

Fig. 1 The sum spectrum of the calibration run from 49 fully active channels of the CUORE-0 detector. The visible lines are due to γs from the ^{232}Th calibration source (Color figure online)

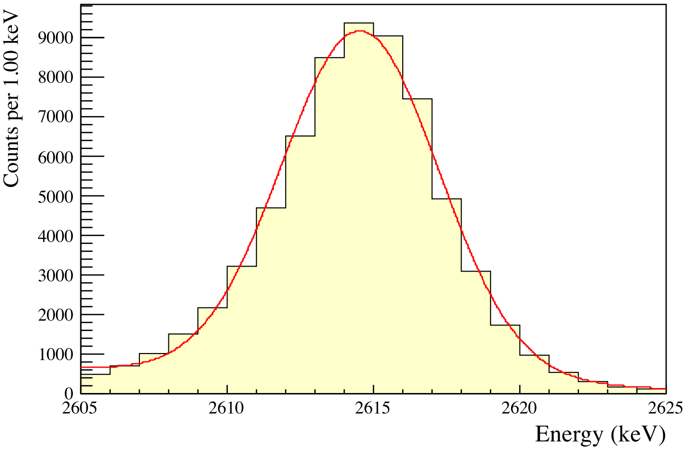

Fig. 2 Fit of the 2615 keV ^{208}Tl γ peak in the sum spectrum of the calibration runs from the 49 fully active channels of the CUORE-0 detector (Color figure online)

superimposed on a linear flat background to the 2,615 keV calibration peak for the sum spectrum of all the 49 fully active channels; the energy resolution is (6.3 ± 2.7) keV. For several months CUORE-0 has been acquiring background data.

CUORE-0 is operating in the cryostat used for Cuoricino and consequently the γ background from contamination in the cryostat shields will remain approximately the same as in Cuoricino. Considering that the irreducible background for CUORE-0 comes from the 2615 keV ^{208}Tl line due to ^{232}Th contaminations in the cryostat, in the case that all other background sources (e.g. surface contaminations) will be negligible, this would imply a lower limit of 0.05 counts/keV/kg/y on the expected background.

Similarly, a conservative upper limit of 0.11 counts/keV/kg/y follows from scaling the Cuoricino background by a factor of 2, proven to be at reach in dedicated

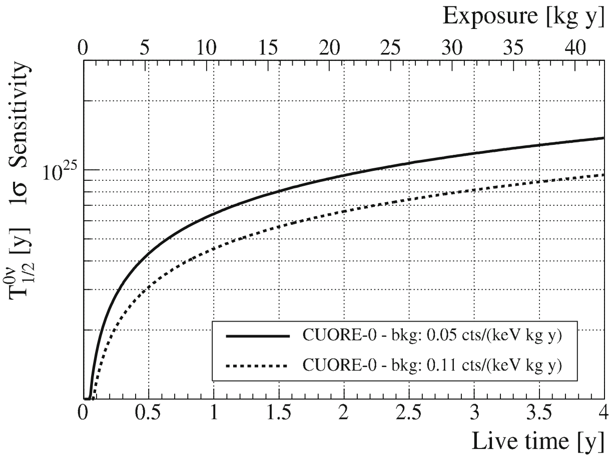

Fig. 3 CUORE-0 sensitivity at 1σ for two different values of the background rate in the ROI: 0.05 counts/keV/kg/y (*solid line*) and 0.11 counts/keV/kg/y (*dotted line*). The CUORE-0 background is expected to fall within this range.

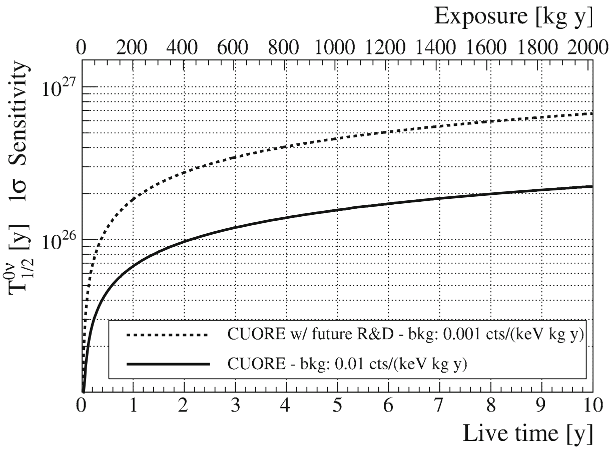

Fig. 4 Expected sensitivity for CUORE as a function of live time and exposure.

R&D bolometric measurements in which the contamination of the crystals and copper surfaces was reduced by means of new surface treatments [7], [8]).

A plot of the expected 1σ sensitivity of CUORE-0 as a function of live time in these two bounding cases is shown in Fig. 3.

4 CUORE Status and Sensitivity

The commissioning of the CUORE cryostat started during summer 2012 and is currently ongoing. All the crystal have been delivered to LNGS and the first six towers of the CUORE array have been assembled.The installation and cool down of the CUORE detector and the start of detector operations are foreseen for the end of 2014. A plot of the CUORE experimental sensitivity as a function of the live time and exposure is shown in Fig. 4. Assuming a background of 0.01 counts/keV/kg/y and five years of live time, the CUORE half-life sensitivities at 1σ would be 1.6×10^{26} years. This would mean sensitivity to an effective Majorana neutrino mass in the range 51 and 133 meV (90 % C.L.) depending on nuclear matrix elements considered. The predicted sensitivity of CUORE would allow the investigation of the upper region of the effective Majorana neutrino mass phase space for the inverted hierarchy of neutrino masses.

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