IL NUOVO CIMENTO Vol. 37 C, N. 6 Novembre-Dicembre 2014
DOI 10.1393/ncc/i2015-11840-7

Colloquia: LaThuile14

Status of the CUORE and CUORE-0 experiments at Gran Sasso

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ricevuto il 31 Luglio 2014

Summary. — CUORE is a 741 kg array of TeO_2 bolometers for the search of neutrinoless double beta decay in ^{130}Te. The detector is being constructed at the Laboratori Nazionali del Gran Sasso, Italy, where it will start taking data in 2015. If the target background of 0.01 counts/(keV·kg·y) will be reached, in five years of data taking CUORE will have a half life sensitivity of $\sim 10^{26}$ y. CUORE-0 is a smaller experiment constructed to test and demonstrate the performances expected for CUORE. The detector is a single tower of 52 CUORE-like bolometers that started taking data in spring 2013. The status and perspectives of the CUORE and CUORE-0 experiments will be presented.

PACS 23.40.-s – β decay; double β decay; electron and muon capture.
PACS 14.60.Pq – Neutrino mass and mixing.

1. – Introduction

The interest in neutrino physics has increased in the past years since the discovery of neutrino oscillations. Thanks to oscillation experiments we know that neutrinos have a non-vanishing mass, and we could measure the angles of the lepton flavor mixing matrix. Future neutrino oscillation experiments are being designed to check whether CP violation takes place in the lepton sector, and to disentangle between the so-called normal and inverted hierarchy of the neutrino mass ordering. There are however some fundamental questions that cannot be addressed by oscillation experiments. Among them is whether the neutrino can be described as a Majorana particle, or if instead it behaves as a Dirac particle, in the same way as all the other elementary fermions in the standard model of particle physics. The only practical way to investigate this feature is to search for neutrinoless double beta decay (0νDBD) [1]. The observation of this process would prove that neutrinos are Majorana particles, and could provide other fundamental information about the neutrino mass.

The CUORE [2] experiment will search 0νDBD of the isotope ^{130}Te with a 741 kg array of cryogenic bolometers. The detector is being built at the Laboratori Nazionali del Gran Sasso (LNGS), Italy, and will start data taking in 2015. In the meanwhile a smaller scale prototype experiment named CUORE-0, with a 39 kg detector mass, is being operated at LNGS since March 2013. The main purpose of CUORE-0 is to check the effectiveness of the material cleaning and detector assembling procedures developed for CUORE, but it is a sensitive 0νDBD experiment as well.

After a brief introduction to double beta decay in sect. **2**, the bolometric technique will be described in sect. **3**. Then the CUORE and CUORE-0 experiments will be presented, in sect. **4** and sect. **5**, respectively.

2. – Neutrinoless double beta decay

Double beta decay is a rare process in which a nucleus changes its atomic number by two units:

$$(A, Z) \rightarrow (A, Z+2) + 2e^- .$$

It can be observed only in several nuclei with an even number of neutrons and protons, in which the single beta decay is energetically forbidden. The process can occur in two modes. In two-neutrino double beta decay (2νDBD) two electrons and two anti-neutrinos are emitted. This decay mode is allowed by the standard model and has been observed in all the double beta decay candidate nuclei that are considered interesting from an experimental perspective. It is in fact the rarest weak decay ever observed, with half lives ranging from 10^{19} to 10^{21} years. In neutrinoless double beta decay (0νDBD) only the two electrons are emitted. This decay mode is forbidden by the standard model, and has never been observed. It violates the lepton number conservation by two units, and its existence would imply that neutrinos are Majorana particles [3]. By making some assumptions on the underlying mechanism that drives this decay, some other important properties about neutrinos could be obtained from its observation. It is commonly assumed that the mechanism that dominates the 0νDBD decay rate is the exchange of a light Majorana neutrino. In this case the half life for the decay reads

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu} \left| M^{0\nu} \right|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2} ,$$

where m_e is the electron mass, $G^{0\nu}$ is a calculable phase space factor, $M^{0\nu}$ is the nuclear matrix element (NME) for the transition, and $\langle m_{\beta\beta} \rangle$ is the effective Majorana neutrino mass, which is a function of the elements of the lepton mixing matrix, of the Majorana phases and of the three neutrino masses. Under the assumption that the NME is known, the observation 0νDBD half life would lead to a measurement of $\langle m_{\beta\beta} \rangle$. Because the elements of the lepton mixing matrix and the neutrino masses squared differences are known from oscillation experiments, $\langle m_{\beta\beta} \rangle$ can be expressed as a function of three unknown parameters, the mass of the lightest neutrino, and two Majorana phases. Therefore a measurement of the 0νDBD half life could also give information on the mass hierarchy, on the absolute neutrino mass scale and on the Majorana phases.

Because no neutrinos are emitted, in 0νDBD all the energy is shared between the two electrons. Therefore in a calorimetric detector this process gives rise to a monochromatic energy release centered at the Q-value of the decay, which is in the few MeV region. Current 0νDBD half life lower limits range from 10^{21} to 10^{25} years for the most interesting nuclei. The observation of a decay with such a large half life requires a very large number of source isotopes and an extremely low background level. For example CUORE will have $\sim 10^{27}$ nuclei (or 206 kg) of source isotope. For what concerns the background it is preferable to study isotopes with high Q-values. The higher the Q-value, the lower the background induced by natural radioactivity. In particular, if the Q-value is higher than 2615 keV, most of the natural γ radioactivity does not affect the measurement. It should be noted however that even if all the background sources could be rejected, the end tail of the 2νDBD spectrum represents a background that cannot be avoided. The only way to deal with this background is to use detectors with high energy resolution. The above considerations are summarized by the sensitivity $S^{0\nu}$, that expresses the half life corresponding to the minimum number of signal events that an experiment can detect above the background at a given confidence level:

$$S^{0\nu} \propto \eta \cdot \varepsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \Delta E}}\,.$$

In the above formula η is the isotopic abundance of the double beta decay candidate nucleus, ε is the detection efficiency, M is the total detector mass, t is the live time of the experiment, ΔE is the energy resolution and b is the background index expressed in counts/(keV·kg·y). Although all the above parameters must be optimized for an experiment to be competitive, the reduction of the background represents the most challenging aspect from a scientific perspective.

3. – The CUORE bolometers

CUORE will use the bolometric technique to search for 0νDBD in ^{130}Te. A CUORE bolometer is essentially a calorimeter where an energy release induces a measurable temperature rise of an absorber crystal. In a simplified model a bolometer is composed by an absorber, a sensor, and a weak thermal link towards a constant temperature heat bath. The temperature rise ΔT is related to the energy release E by the formula $\Delta T = E/C$, where C is the heat capacity of the absorber crystal. In order for the temperature rise to be measurable, the heat capacity and the base temperature of the absorber crystal must be very small. Bolometers are usually operated at a temperature around 10 mK and are made of dielectric materials, so that only the lattice heat capacity plays a role. Large mass bolometers can achieve excellent energy resolution, comparable to that obtained with germanium detectors. However they have the advantage that they can be built with a wide range of materials, so that in principle many isotopes could be studied with this technique. Their main drawback is that the thermal origin of the signal makes them intrinsically slow.

The CUORE bolometers are cubic TeO_2 crystals with 5 cm side and a mass of 0.75 kg. Being made with natural tellurium (the isotopic abundance of ^{130}Te is 34%) they have a $\sim 28\%$ mass fraction in ^{130}Te. They are held in a copper structure that serves both as mechanical support and as constant temperature heat bath. The weak thermal link between the crystals and the support frame is made with small PTFE supports that also compensate the different thermal contractions of the copper and of the TeO_2. The readout of the thermal signal is performed by mean of a neutron transmutation doped (NTD) germanium thermistor that is glued on the absorber crystal. The resistance of the NTD sensor has a steep dependence on the temperature. By inserting the sensor in a proper polarization circuit the thermal pulses can be converted into voltage signals that can be handled with conventional electronics. When operated at ~ 10 mK the CUORE bolometers have an heat capacity of $\sim 10^{-9}$ J/K, and the NTD sensors have a resistance

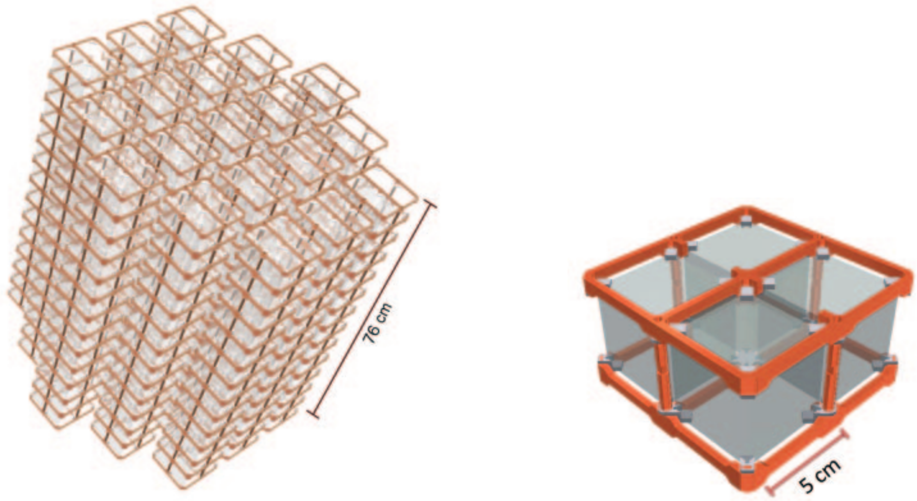

Fig. 1. – Pictorial representation of the CUORE detector structure. Left: arrangement of the 988 bolometers composing the CUORE array. Right: the four bolometers composing a single floor of a CUORE tower.

of few tens of MΩ. An energy release of 1 MeV produces a temperature rise of $\sim 100\,\mu$K, which translates into a resistance variation of about 3 MΩ, or a voltage variation of $100\,\mu$V at the ends of the sensor. The signal has a typical time evolution of ~ 5 s, with a rise time of few tens of ms and a decay time of about one order of magnitude larger. Each CUORE crystal has also a Si resistor glued on it, that can be used to inject a known amount of energy in the bolometer. The signals induced by these Joule heaters are very similar in shape to those produced by particle interactions, and are used offline to correct the detector gain variations induced by the thermal instabilities of the cryogenic system.

4. – The CUORE experiment

The CUORE collaboration is building an array of 988 TeO_2 bolometers to search for 0νDBD of ^{130}Te ($Q \simeq 2528$ keV [4-6]). The experiment will be operated at the Laboratori Nazionali del Gran Sasso (LNGS), in Italy, under a mountain that provides a 3650 m w.e. shield against cosmic rays. Assuming a background in the signal region of 0.01 counts/(keV·kg·y), and an energy resolution of 5 keV FWHM, CUORE will reach a 90% C.L. sensitivity of 9.5×10^{25} y in five years of live time [7]. The CUORE detector mass is of 741 kg, or 206 kg in ^{130}Te. The bolometers are arranged in 19 towers, each tower being composed by 13 floors of 4 crystals each (see fig. 1). The tower structure is made of ultra pure copper and the crystals are coupled to it by mean of small PTFE supports. The CUORE detector is enclosed in a custom made, cryogen-free dilution refrigerator with a base temperature of about 10 mK. The CUORE towers are mechanically decoupled from the cryostat structure by mean of a suspension system that has the purpose of dumping the external mechanical vibrations, which would otherwise spoil the resolution of the detectors. The energy calibration is performed by exposing the bolometers to radioactive source wires about once per month. In order to guarantee a uniform irradiation, some of the source wires must be inserted between the CUORE towers. This requires to cool the wires to 10 mK and bring them back outside the cryostat at room temperature before and after each calibration. A careful design of the heat loads was needed in order to minimize the heating of the system during the insertion of the sources, and to reduce the thermalization times as much as possible.

In the energy region where the 0νDBD signal is expected, the background is dominated by natural radioactivity. In order to reach an adequate level of background suppression the CUORE cryostat will be surrounded by a $\sim$ 25 cm thick lead shield to absorb γ-rays and by a $\sim$ 20 cm thick borated polyethylene shield to slow down and absorb neutrons. Moreover a Faraday cage will protect the experimental apparatus from electromagnetic disturbances. Inside the cryostat, two additional cold lead shields will be present. A 6 cm thick layer of low radioactivity Roman lead [8] thermalized at 4 K will shield the detectors from the radioactive contaminations in the outer vessels of the cryostat. Another 31 cm thick disc of Roman lead will be thermalized at 10 mK and will shield the detectors from the radioactivity in the mixing chamber and in the cryogenic apparatus. Overall, about 20 ton of material will be cooled below room temperature. Dedicated measurements [9] demonstrated that the muon-induced background can be neglected in CUORE.

Stringent radiopurity constraints must be imposed on all the materials facing the detectors and on the detectors themselves, as shielding cannot be applied in this case. The radiopurity of these materials was verified with low background measurement techniques. The TeO_2 crystals were manufactured by the Shanghai Institute of Ceramics, Chinese Academy of Science (SICCAS), following a strict procedure defined by the CUORE collaboration [10]. A few crystals were chosen from each batch delivered at LNGS, and were promptly operated as bolometers to verify their radiopurity and to check their performance as detectors [11]. Dedicated procedures were developed for the handling and cleaning of each detector component. In particular the cleaning procedure for the copper frames was verified with a dedicated bolometric measurement [12]. To avoid possible recontamination after cleaning, all the detector assembling procedures are performed in glove boxes flushed with nitrogen. The tower assembling procedure consists essentially in three steps. First, the NTD sensor and the heater are glued on the crystal. Then the crystals are assembled together in a single CUORE tower, and wire trays are mounted on the sides of the tower to bring the signals from the crystals to the mixing chamber of the dilution refrigerator. Finally, for each bolometer the sensor and the heater are bonded to the pads on the wire trays with 50 μm thick gold wires. To guarantee high success rate and reproducibility, all the above steps are performed with properly designed tools that make the whole assembly procedure semi-automatic.

The CUORE experiment is currently in the construction phase at LNGS, the detector cool down is scheduled for the beginning of 2015. All the crystals are already at LNGS. The tower assembly is ongoing, 12 out of 19 towers are ready and put to storage, and the remaining 7 towers will be completed by summer 2014. All the components of the cryostat were delivered at LNGS, where they are being tested. The cryostat was cooled down to 4 K by mean of pulse tubes, and leak checks were performed successfully. The detector calibration system was installed and tested down to 4 K. The dilution unit was tested in its own custom cryostat, it reached a base temperature of 5 mK, with a cooling power of 5 μW at 12 mK. In summer 2014 the first bolometric tests of the cryostat will be performed, by cooling down and measuring a mini tower made of CUORE-like crystals. After that, in fall 2014, the mounting of the towers on the cryostat will take place and the signal wires will be connected. In parallel, the readout electronics and the data acquisition system will be installed.

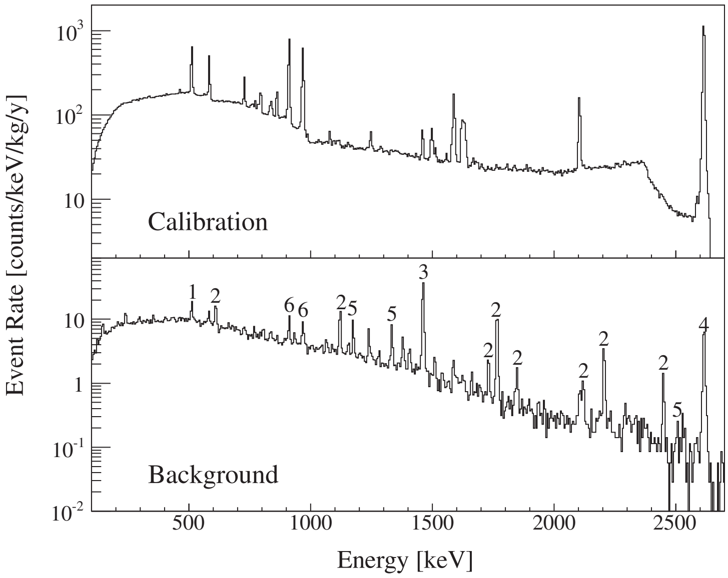

Fig. 2. – Top panel: CUORE-0 calibration spectrum. Bottom panel: CUORE-0 background spectrum; the labels in the plot correspond to identified radioactive peaks: e^+e^- annihilation (1), ^{214}Bi (2), ^{40}K (3), ^{208}Tl (4), ^{60}Co (5) and ^{228}Ac (6). Figure reprinted from [13].

5. – CUORE-0

CUORE-0 [13] is a single CUORE-like bolometer tower that is being operated at LNGS since March 2013. This pilot experiment was meant as a test for the cleaning and assembling procedures designed for CUORE, and as a high statistics test of the improvements achieved in the background reduction with respect to the past Cuoricino [14] experiment. The tower is composed by 52 cubic natural TeO_2 bolometers with 5 cm side, with a total detector mass of 39 kg ($\sim$ 11 kg in ^{130}Te). The experiment is hosted in the former Cuoricino cryostat. To suppress the background from environmental radioactivity, the apparatus is surrounded by a 20 cm thick lead shield and by 20 cm of borated polyethylene. The detector is protected from radioactive contaminations in the cryostat materials by a 1 cm thick low activity lead thermalized to the 600 mK radiation shield. The whole apparatus is enclosed in a Faraday cage that suppresses electromagnetic disturbances. The bolometers are calibrated about once per month by inserting a pair of ^{232}Th source wires between the cryostat walls and the external lead shield. The calibration spectrum is shown in fig. 2, top panel. The average energy resolution, measured on the 2615 keV photoelectric peak from ^{208}Tl, is of 6.3 keV FWHM. The background spectrum in the γ region, acquired between March and September 2013, and summed over all the detectors, is shown in fig. 2, bottom panel. It corresponds to a TeO_2 exposure of 7.1 kg·y. In the background spectrum the energy resolution measured on the 2615 keV peak is of 5.7 keV FWHM.

From a thorough study of the Cuoricino data it turned out that the background in the 0νDBD region was dominated by three components: γ events from ^{232}Th contaminations in the cryostat materials (about 30%), contaminations from the crystal surfaces (about

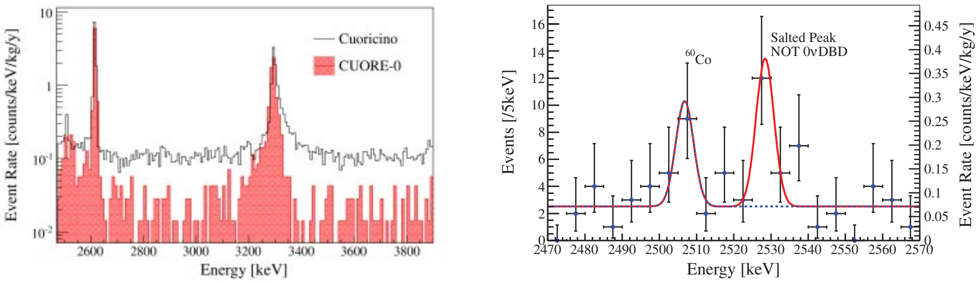

Fig. 3. – Left: CUORE-0 (red filled histogram) and Cuoricino (black histogram) background in the α region; figure reprinted from [13]. Right: blinded CUORE-0 background spectrum in the signal region; the peak at 2505 keV is produced by the sum energy of the two γ-rays emitted in the β-decay of ^{60}Co while the peak at the 0νDBD Q-value is an artifact used to blind the energy spectrum in the signal region (see text); figure reprinted from [13].

10%) and from the surfaces of the copper structure (about 50%). The first of these three components will be made negligible in CUORE thanks to better shielding of the detectors from the cryostat, but it is expected to be in CUORE-0 comparable to that of Cuoricino, because the two experiments are hosted in the same cryostat. The other two background components originate from α-decays taking place on the surface of the crystals or of the copper structure surrounding them. If the decays occur very close to the surface, the decay products can escape and hit a facing crystal. This gives rise to a continuous flat spectrum that extends from the Q-value of the decay down to the energy region where the 0νDBD signal is expected. This kind of background was expected to be reduced in CUORE-0 with respect to Cuoricino thanks to the improvements in the material cleaning procedures developed for CUORE. It can be quantified by studying the energy spectrum above the 2615 keV peak. Above this energy the γ background becomes negligible, and the α background dominates. For comparison, the CUORE-0 energy spectrum in the α region is shown in fig. 3, left, superimposed to the Cuoricino spectrum. The plot demonstrates the effectiveness of the new surface cleaning procedures developed for CUORE. The flat α background index is (0.019 ± 0.002) counts/(keV·kg·y) in CUORE-0 while it was (0.110 ± 0.001) counts/(keV·kg·y) in Cuoricino. 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, to avoid taking into account the peak from ^{190}Pt α-decay, originating from Pt contaminations in the crucibles used to grow the crystals. The CUORE-0 blinded energy spectrum in the 0νDBD signal region is shown in fig. 3, right. The peak at 2505 keV is produced by the sum energy of the two γ-rays originating from ^{60}Co contaminations in the copper. The peak at the 0νDBD Q-value is an artifact used to blind the energy spectrum in the signal region. It is obtained by exchanging a blinded fraction of the events at (2615 ± 10) keV with an equivalent fraction of events within ± 10 keV around the 0νDBD Q-value. The flat background in the signal region is (0.071 ± 0.011) counts/(keV·kg·y). It is obtained with a maximum-likelihood unbinned fit whose free parameters are the flat background index and the intensities and positions of the ^{60}Co peak and of the salted 0νDBD peak. The FWHM energy resolution of the two peaks is fixed to the value measured on the 2615 keV peak (5.7 keV). With such a background index, the CUORE-0 sensitivity will overcome the Cuoricino half life limit (which is of 2.8×10^{24} y at 90% C.L. [14]) within about one year of live time.

6. – Conclusions

The bolometric technique is among the most promising approaches for rare-event searches. After the successful operation of Cuoricino, the CUORE collaboration is building a 741 kg array of TeO_2 bolometers to search for neutrinoless double beta decay in ^{130}Te. The detector is being constructed at LNGS and the cool down is expected to take place at the beginning of 2015. The potential of CUORE is demonstrated by the pilot CUORE-0 experiment, a 39 kg array of TeO_2 bolometers that is being operated at LNGS since March 2013. The CUORE-0 detectors showed a FWHM energy resolution of 5.7 keV at 2.6 MeV, and a flat background of (0.071 ± 0.011) counts/(keV·kg·y) in the signal region. The background above 2.6 MeV, originating from α-decays occurring on the surfaces of the crystals and of the copper constituting the tower structure, was measured to be (0.019 ± 0.002) counts/(keV·kg·y), a factor of six better than in Cuoricino. The background above 2.6 MeV gives an estimation of what is expected to be the main background contribution in the signal region in CUORE. By combining the CUORE-0 background measurement with Monte Carlo simulations of the CUORE geometry, it is possible to extrapolate that after five years of live time CUORE will reach a 90% C.L. sensitivity of 9.5×10^{25} y on the 0νDBD half life of ^{130}Te.

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