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Abstract. Since the discovery of neutrino, many of its properties have been studied. The flavor oscillations recently revealed that, contrary to the Standard Model assumptions, neutrinos have a finite mass. Other neutrino characteristics are still to be investigated, such as its Dirac or Majorana nature: experiments are currently searching for a rare phenomenon, the neutrinoless double beta decay ($0\nu\beta\beta$), whose observation would solve this issue. The Cryogenic Underground Observatory for Rare Events (CUORE) at Gran Sasso National Laboratories focuses on the search of $^{130}\text{Te}$ $0\nu\beta\beta$ and it is the first ton-scale bolometric experiment ever realized for this purpose. The detector is hosted inside a custom cryostat and consists of 988 TeO\textsubscript{2} crystals, operated at a temperature of $\sim 10 \text{mK}$. The CUORE goals in 5 years of data taking are an energy resolution of $5 \text{keV}$ FWHM and a background level of $0.01 \text{counts/keV/kg/y}$ in the $^{130}\text{Te}$ $0\nu\beta\beta$ region of interest. This corresponds to a sensitivity on the $^{130}\text{Te}$ $0\nu\beta\beta$ half life of $9 \cdot 10^{25} \text{y}$ (90\% C.L.) and an upper limit to the effective Majorana mass of $50^{-130} \text{meV}$. The CUORE commissioning has been recently completed; the experiment has just concluded the pre-operation phase and data taking is currently ongoing.

1. Introduction
The experimental observation of neutrinos flavor oscillations is one of the most important results achieved in neutrino physics. The occurrence of this phenomenon implies that neutrinos are not massless; in this scenario, flavor and mass eigenstates are not coincident, since one can be expressed as linear combination of the others. Flavor oscillation can only happen if their masses are non-zero and different among each other [1]. This is the first experimental evidence of a physics beyond the Standard Model. There are many neutrino’s characteristics which are still unknown, such as their absolute mass scale, the direct or inverse mass hierarchy, their Dirac or Majorana nature. Oscillations experiments cannot investigate on neutrino mass, since they are sensitive only to the mass difference, and not even on its nature, as the Majorana phases have no effects in neutrino oscillations [2]. An interesting approach for studying the neutrino nature is to search for the occurrence of the neutrinoless double beta decay ($0\nu\beta\beta$): it is a hypothesized decay mode of the double beta decay, a rare process in which the nucleus decays through a second order $\beta$ such that two neutrons simultaneously go into protons. In the Standard Model, this is admitted with the emission of two neutrinos ($2\nu\beta\beta$), so that symmetries such as the lepton number are conserved regardless of the neutrino nature; this process has been already observed. However, if the neutrino were a Majorana particle, that is to say, if neutrino and antineutrino were coincident particles, the double beta decay would be allowed without neutrino emission.
The physical parameter involved in this process is the effective Majorana mass, defined as [3]:

$$\langle m_{\beta\beta} \rangle = \left| \sum_{j=1}^{3} U_{e j}^2 m_j \right|$$

(1)

where $\phi_j$ are the Majorana phases, and the $0\nu\beta\beta$ decay rate can be written as [3]:

$$[T_{1/2}^{0\nu}]^{-1} = G_{0\nu}(Q, Z)|M_{0\nu}|^2 (m_{\beta\beta})^2$$

(2)

where $G_{0\nu}$ is the phase space factor, $|M_{0\nu}|$ is the nuclear matrix element, $m_{\beta\beta}$ is the effective Majorana mass. This expression reveals that when lower limits on the lifetime are available, it is possible to set upper limits on $m_{\beta\beta}$.

The experimental approach for the detection of the double beta decay consists of measuring the energy of the emitted electrons. In case of a $2\nu\beta\beta$ event, there are overall four decay products, namely the two electrons and the two neutrinos: since the two neutrinos carry away a fraction of the energy, the spectrum of the sum of the two electrons energies turns out to be a continuum between 0 and the Q-value of the reaction. Conversely, in the $0\nu\beta\beta$ decay, there would be only two electrons in the final state, therefore they will carry the total amount of the decay energy (the kinetic energy due to the nuclear recoil is neglected). It immediately follows that the expected sum energy spectrum of the emitted electrons is a monoenergetic peak at the energy defined by the Q-value, and it has a non-zero width due to the finite detector resolution.

An essential parameter for the comparison of different experiments is the sensitivity $S$ [3]. This quantity is defined as the half life corresponding to the minimum number of observable signal events above the background at a given statistical significance, or, in other words, to the maximum number of signal events hidden by the background fluctuations:

$$S_{0\nu}(n_\sigma) = T_{1/2}^{0\nu}(n_\sigma) = \frac{ln 2}{n_\sigma} \frac{\epsilon N_a \eta A}{b \Delta E} \sqrt{\frac{M t}{\Delta E}}$$

(3)

being $n_\sigma$ the number of the standard deviations corresponding to a given confidence level (C.L.), $\epsilon$ the detection efficiency, $N_a$ the Avogadro number, $\eta$ the emitter isotopic abundance, $A$ its mass number, $M$ the total mass of the detector, $t$ the experiment live time, $b$ the background and $\Delta E$ the instrumental spectral width related to the energy resolution in the Region of Interest (ROI), that is an energy range around the Q-value of the $\beta\beta$ emitter.

Since this process is extremely rare, the awaited rate of events is very low, of the order of $10^{25} - 10^{26}$ years. This is the main issue that makes its identification so difficult: in fact, experiments searching for rare events are strikingly sensitive to the background, and it is very difficult to discriminate it from signal events. There exist many different background sources that can hide a hypothetical $0\nu\beta\beta$ signal: the internal background sources coming from the detector itself, such as $2\nu\beta\beta$ spectrum or crystals radioactive contaminations, and the external ones, like muons, neutrons and $\gamma$ from cosmic rays or rocks natural radioactivity. The background sources minimization therefore plays a crucial role in a detector searching for rare events.

2. **The CUORE experiment**

The Cryogenic Underground Observatory for Rare Events (CUORE) is currently the largest cryogenic bolometric detector searching for the $0\nu\beta\beta$ decay, in particular of the $^{130}$Te isotope [4]. It is located at the Gran Sasso National Laboratories (LNGS) of INFN in Assergi (AQ), Italy, built under 1400 m of rock inside the Gran Sasso mountain. This allows to considerably reduce the rate of cosmic rays background. The muon flux is reduced by about six orders of magnitude, as it is $\sim 1 \mu/(h \cdot m^2)$. 

2.1. Bolometric technique & setup

A bolometer is a Low Temperature Detector (LTD) that exploits the temperature variation induced by a particle passing through it, in order to measure the amount of energy lost by the particle itself. The amplitude of the thermal signal $\Delta T$ can be expressed as a function of the deposited energy $\Delta E$ and the heat capacity $C$:

$$\Delta T = \frac{\Delta E}{C}$$ (4)

It is clear from this expression that the smaller is $C$, the higher is the signal amplitude; therefore, in order to have a good resolution, it is necessary to get a small value of $C$. It is well known that, being the absorber a dielectric and diamagnetic crystal, its thermal capacity follows the Debye law:

$$C(T) = \beta \frac{m}{M} \left( \frac{T}{T_D} \right)^3$$ (5)

where $\beta = 1944 \, J/(K \cdot mol)$, $m$ is the crystal mass, $M$ is the molecular weight and $T_D$ is the Debye temperature. This expression tells us that the heat capacity $C$ decreases as $T^3$ as the temperature also decreases; this means that a low temperature provides a low value of $C$, and therefore a higher signal amplitude. Thanks to this detector characteristic, it is possible to get a measurable temperature variation although the amount of energy deposition is very small: at room temperature, the thermal variation would be of the order of $10^{-18} - 10^{-15} \, K$, so it would be impossible to detect. The working temperature that allows bolometers to measure $\Delta T$ of the order of $\sim 10 - 100 \, \mu K$ usually lies in the range $10 - 100 \, mK$.

The CUORE experiment is based on the use of TeO$_2$ cryogenic bolometers, which represent both the source and detector of the $^{130}$Te $0\nu\beta\beta$ decay; the isotope $^{130}$Te is characterized by a natural abundance of 34.2%, which is a very important feature since it allows to realize an experiment by using only natural Te, avoiding to carry out expensive enrichment procedures that may also introduce radioactive contamination into the crystal. The searched process is described by the following reaction:

$$^{130}\text{Te} \rightarrow ^{130}\text{Xe} + 2e^-$$ (6)

that has a $Q$-value of $2527.515 \pm 0.013 \, keV$ [5].

The CUORE setup consists of 988 TeO$_2$ crystals, which are arranged in 19 towers of 52 absorbers each [6] for a $^{130}$Te mass of $206 \, kg$ out of $742 \, kg$ of total Te mass. A copper structure, working as heat bath, is mechanically and thermally coupled to the crystals through Teflon (PTFE) links. The temperature variation of the CUORE bolometers is converted into an electrical signal by Neutron Transmutation Doped (NTD) germanium semiconductor thermistors, which are glued on the crystals’ surface. Bolometers are strikingly sensitive to thermal drifts, that can affect the detectors response and worsen their energy resolution. In order to avoid this phenomenon in CUORE, a $2.3 \times 2.4 \times 0.5 \, mm^3$ silicon resistor glued on each crystal, the heater, is used to periodically inject a well known energy pulse into the crystals, in order to simulate physics events. Being the energy of the injected pulse constant, it allows to control the gain of every bolometer and correct the effects of thermal drifts during the first level of the offline data analysis through a stabilization procedure.

The CUORE towers have been assembled and installed in a clean room in the underground LNGS laboratories. The most delicate operations, such as the towers assembly, have been carried out into specific glove boxes kept under Nitrogen atmosphere to further reduce the contamination; a view of the CUORE towers storage and their completed installation are shown in Figs. 1 and 2, respectively.
2.2. The CUORE cryostat

The CUORE detector, operating at a temperature of $\sim 10 \text{ mK}$, is housed into a dedicated custom-built cryostat, that is one of the largest ever realized [7]. In order to avoid material damages as consequences of the sudden thermal jump, the base temperature is reached through different stages of cooling. The CUORE cryostat is therefore composed of six copper shieldings that are thermalized to decreasing temperatures: $300 \text{ K}$, $40 \text{ K}$, $4 \text{ K}$, $600 \text{ mK}$, $50 \text{ mK}$, $10 \text{ mK}$ (Mixing Chamber). The intermediate vessels work as radiation shields, so that thermal radiations from the warmer stages cannot affect the detectors. In order to further strengthen this thermal insulation, the $40 \text{ K}$ and the $4 \text{ K}$ vessels are both vacuum tight at $< 10^{-8} \text{ mbar}$, moreover they are wrapped in the so-called superinsulation, which is a multi-layer mylar insulation.

Vacuum and superinsulation minimize the heat radiation reaching the detector, but do not protect it from the external radioactivity: lead shields housed inside the cryostat aim at this task. A 30 cm thick top shield of 2745 kg lead is placed above the Tower Support Plate (TSP) and is thermalized to 50 mK, while a 5562 kg lateral shield of ancient Roman lead envelopes the cryostat between the 4 K and the 600 mK vessel and is thermalized to the 4 K vessel because of stronger cooling power. In 1988, 120 lead ingots were recovered from a Roman shipwreck that sank around 80-50 B.C. off the coast of Sardinia. The relic was preserved at the National Archeological Museum in Cagliari, and in 2010 30 ingots were transferred at LNGS thanks to an agreement between the INFN and the Italian cultural heritage Ministry [8]. This ancient lead has spent 2000 years under the sea, so nowadays it has almost completely lost its natural radioactivity: this makes it the perfect material for a CUORE shielding.

Two different techniques are used for the CUORE cryostat cool down [4]. The Outer Vacuum Chamber (OVC), namely the 40 K and 4 K vessels, is cooled by 5 Pulse Tubes (PTs) coolers: with respect to conventional cryogenic dilution refrigerators, the PTs have no need of cryogenic liquids, therefore they do not require periodical refilling interruptions that affect the experiment live time.
From 4 K, the base temperature is reached through a continuous-cycle Dilution Refrigerator (DR), a cooling system that exploits the properties of the $^3$He-$^4$He mixture: at few degrees above the absolute zero, $^3$He and $^4$He cannot arbitrarily mix, they instead spontaneously separate into two phases: the concentrated phase, mainly containing $^3$He, and the dilute phase, mostly containing $^4$He. The DR uses a pump external to the cryostat that pulls $^3$He from the concentrated phase to the dilute phase, and this produces an endothermic process that, absorbing the energy, allows the cryostat to achieve the base temperature. The $^3$He is finally returned to the dilute phase, closing the cycle. This cool down system requires about 2 days for a 15 tons total mass such as that of the CUORE cryostat.

A schematic image of the CUORE cryostat is shown in Fig. 3.

![Figure 3. A scheme of the internal structure of the CUORE cryostat. The copper shields and their temperatures are shown, the towers being hosted into the inner one; the lead shields for the radiation protection are also represented.](image)

3. CUORE goals
Thanks to the CUORE experimental characteristics such as its large exposure, the appropriate TeO$_2$ crystals features at cryogenic temperatures and the specific procedures adopted for cleaning and assembling the detector components, in order to minimize the internal background, a competitive result will be likely set for the $0\nu\beta\beta$ decay of $^{130}$Te. CUORE aims at obtaining a FWHM energy resolution of $\sim 5$ keV at the $0\nu\beta\beta$ energy region of interest of $^{130}$Te. The dedicated cleaning operations and the new cryostat, built starting from radiopure selected materials, will allow to reduce the background level to $10^{-2}$ counts/keV/kg/y in the same energy region; the $^{130}$Te half life sensitivity for CUORE is expected to be $9 \cdot 10^{25}$ y (90% C.L.), which corresponds to an upper limit range for the Majorana neutrino mass of $50 - 130$ meV. Fig. 4 shows the sensitivity that CUORE would be able to reach for $^{130}$Te.
Figure 4. Effective Majorana mass $m_{\beta\beta}$ vs lightest neutrino mass [9]. On the right side of the plot, limits set by other experiments on other isotopes are also shown.

4. Conclusions
The CUORE commissioning phase started in spring 2016, with the cryostat operations; just few months later, in July - August, the towers installation was completed and the cryostat copper shields were closed in November. The cooldown phases started in December 2016 and were successfully completed with the reach of the base temperature at the beginning of January 2017; just a few days later, the first CUORE pulses have been observed, confirming the proper functioning of the detectors. Pre-operation procedures, such as working parameters optimization followed, and the calibration phase took place in April. The commissioning phase has then been completed within the end of April; CUORE data taking has started and will continue for 5 years.

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