The CUORE experiment: status and prospects

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Abstract. CUORE is a bolometric detector composed of 988 TeO$_2$ crystals, with a total mass of about 200 kg of $^{130}$Te, currently under construction at Laboratori Nazionali del Gran Sasso in Italy. It will probe the neutrinoless double beta decay (0$\nu$DBD) of $^{130}$Te, testing the neutrino nature and mass at the level relevant for exploring the inverted neutrino mass hierarchy. On the road towards CUORE, a first tower named CUORE-0, is being assembled and will be operated as an independent experiment in 2012. Detailed information on these detectors and on the expected performance are discussed.

1. Introduction
The search for neutrinoless double beta decay (0$\nu$DBD) has become in recent years extremely relevant in neutrino physics. The impressive massy of data on neutrino oscillations provides informations only on the differences between neutrino masses and on mixing angles. Informations on neutrino absolute mass scale and neutrino nature (Dirac or Majorana) can not be extracted form the present available data. 0$\nu$DB is a unique tool to add the missing informations.

The lepton number violating process 0$\nu$DBD can occur only if the neutrino is a massive Majorana particle and it is the only known probe to test whether the neutrino is a Majorana or Dirac particle. The 0$\nu$DBD half-life $\tau_{0\nu}^{1/2}$ is related to neutrino masses through $[\tau_{0\nu}^{1/2}]^{-1} \propto \left[\frac{\langle m_\nu \rangle}{m_e}\right]^2 \cdot |M^{0\nu}|^2 \cdot G^{0\nu}$, where $|M^{0\nu}|$ is the matrix element, $G^{0\nu}$ is the phase space factor, and $\langle m_\nu \rangle = |\Sigma_j m_j e^{i\delta_j} |U_{e,j}|^2|$ is the Majorana neutrino mass, where $m_j$ are the mass eigenvalues of the three neutrino mass eigenstates $\nu_j$, $e^{i\delta_j}$ are the CP Majorana phases, and $U_{e,j}$ are the elements of the electron sector of the neutrino mixing matrix. Therefore measuring $\tau_{0\nu}^{1/2}$ will provide valuable informations on the neutrino mass absolute scale and on the masses hierarchy.

The general approach in searching for 0$\nu$DBD is to detect the two final-state electrons and measure their energy. In CUORE we utilize a “source=detector” approach, where the detector is made from material (TeO$_2$) containing the isotope of interest ($^{130}$Te). In this technique the 2 electrons release all their energy in the detector resulting in an energy signal corresponding to the sum energy of the 2 electrons. The signature of 0$\nu$DB is an excess of events at the Q-value of the decay. The advantages of this technique are that it offers excellent energy resolution, a large source mass, and high efficiency; the primary disadvantage is that it does not offer the capability for identifying particles. A CUORE predecessor and feasibility study, named CUORICINO, concluded its activity in 2008 setting one of the best limits so far on 0$\nu$DBD at $\tau_{0\nu}^{1/2}(^{130}Te) > 2.8 \times 10^{24}$ y (90%C.L.) [2].

CUORE is the first of a new generation of experiments aiming to start the exploration of Inverted Hierarchy (IH) mass region for the Majorana neutrino.
2. The CUORE project

CUORE, the Cryogenic Underground Observatory for Rare Events [1], is an underground experiment under construction at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy and will search for the $0\nu$DBD of $^{130}$Te (Q-value: 2527 keV).

The CUORE detector (see Fig. 1) will be operated by cooling crystals of TeO$_2$ to $\sim$ 10 mK inside a dilution-refrigerator cryostat. At cryogenic temperatures a TeO$_2$ crystal has such a small heat capacity that an individual particle interaction inside it produces a measurable rise in its temperature – i.e., the crystal functions as a bolometer--. The temperature pulses are detected using special neutron-transmutation-doped (NTD) Ge thermistors which are glued to each crystal and whose resistance varies with the system’s temperature. The amplitude of a temperature pulse is proportional to the energy deposited in the crystal, so we look for an excess of pulses (i.e., above background) at 2527 keV, the Q-value for $0\nu$DBD in $^{130}$Te. The response of each crystal – namely, its energy scale and gain – is monitored via monthly calibrations with a $^{232}$Th gamma source and by injecting controlled amounts of energy into the crystals at 5-minute intervals using Joule heaters glued to the crystal surface.

Figure 1. Artistic view of the CUORE detector inside the cryostat; the different thermal shields of the cryostat and the internal Roman Pb shield are also visible.

The detector will consist of 988 TeO$_2$ crystals arranged in 19 towers of 52 crystals each, organized in 13 4-detectors modules. Each crystal measures $5\times5\times5$ cm$^3$ and weighs 750 g, resulting in a total mass of 740 kg of TeO$_2$, corresponding to 210 kg of $^{130}$Te. The background level is expected to be as good as 0.01 counts/keV/kg/y due to: improvements in the radiopurity 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 contributions can be
found in [3][5][6]).

In 2009 the production of CUORE crystals started at SICCAS Jiading with a production capacity of about 30 crystals/month [4]. The production of crystals is systematically controlled and each production phase is certified. Very strict certification conditions were applied for the dimensions of the crystals and for the quality of surface processing. Moreover, a dedicated cryogenic setup, the CUORE Crystals Validation Runs (CCVR), mounted and operated in Hall C of LNGS is used to test TeO$_2$ crystals. The tests are performed on crystals randomly chosen from each production batch and is aimed at checking the radioactive contamination level of crystals and their bolometric performance. Limits on crystals bulk contaminations obtained with these bolometric tests are well below the concentration limits requested for TeO$_2$ crystals to be used in CUORE experiment [5].

The CUORE cryostat (Fig. 1) is made of six nested vessels and its base temperature is expected to be as low as 6 mK. Three lead shields are used to protect the detector from environmental radioactivity and from contaminations in the building materials. A 25 cm thick octagonal lead layer outside the cryostat shields the detector from radiations coming from the bottom and from the sides. An equivalent shielding against radiation coming from the top is placed inside the cryostat, just above the detector. This is a 30 cm thick lead disk with a diameter of about 90 cm. Just below it, copper disks totaling an additional 8 cm shields are placed. An additional shielding of detector’s sides and bottom is provided by a 6 cm lead layer. Outside the external lead shield a 18 cm thick polyethylene layer will be added in order to thermalize environmental neutrons that will then be absorbed by a 2 cm layer of H$_3$BO$_3$ powder contained in the hollow space between the lead and the polyethylene itself.

The challenges in constructing CUORE are due largely to its size and the complexity of the engineering. Namely, it is difficult to prepare and maintain the cleanliness of such a large amount of radiopure material, and the apparatus involves many interconnected systems occupying the same space under unique conditions. Currently all the assembling lines for the production of the 988 CUORE detectors and their packing into 19 towers are installed and tested in the underground location at LNGS. All the assembling phases, including automatic gluing of the NTD thermistors on the TeO$_2$ crystals, assembling of the crystals in a copper and teflon structure, cabling of the towers, and bonding of the thermistors, are performed under nitrogen atmosphere in dedicated glove boxes to prevent Rn contaminations from air. For the same reason all the component of CUORE are stored in multiple layers radioclean plastic foils under nitrogen atmosphere. During 2011 all the assembling line where installed and tested in the CUORE clean room in the LNGS underground location.

The assembly of the 19 CUORE towers is expected to be completed in 2013 and data taking is expected to start in 2014.

3. The CUORE-0 prototype

The first tower from the CUORE assembly line, CUORE-0, will be cooled down in the former CUORICINO cryostat starting in 2012 in order to test the assembly line protocols and debug all the assembling procedure. This procedure, started in 2011 already produced several improvements in the assembling lines, allowing a complete test of all the procedure and protocols in real condition. Due to this effort, CUORE-0 will also represent a valuable measurement in its own right, as it will be comparable in size to CUORICINO but exhibit lower backgrounds due to the use of improved copper frames, radio clean material selection, and clean detector assembling.

The main difference between CUORE-0 and CUORE is the shielding from external radiation, which is limited by the dimensions of the CUORICINO cryostat to 2.5 cm of roman lead internal shield. Moreover the CUORE detector compact layout will guarantee that the inner TeO$_2$ crystals are shielded by the outer once form contaminations generated inside the roman lead
shield – i.e. on the cryostat copper shields –.

4. Sensitivity

![Figure 2](image)

**Figure 2.** Expected sensitivity for CUORE-0 (left) and CUORE (right) as a function of live time. An energy resolution of 5 keV is assumed. The main difference are due to the mass of the detectors and the background, which in CUORE-0 will be bigger due to worst shielding.

The expected sensitivity of the CUORE-0 is limited by the mass – a factor $\sim$20 less than CUORE – and by the background from external contaminations, as discussed in previous section. Background is expected to fall in 0.05-0.11 counts/keV/kg/y range, corresponding to the interval between the expect background only due to external contaminations – i.e. all the CUORE radioactivity-reduction upgrades being effective – and the CUORICINO background. With 0.05 counts/keV/kg/y, the expected 2-year 1$\sigma$ sensitivity is $\tau^{0\nu}_{1/2} = 9.4 \times 10^{24}$ y or $\langle m_{\nu} \rangle = 170$-390 meV (see Fig. 2).

Assuming to reach the CUORE background goal of $<10^{-2}$ counts/keV/kg/year, after 5 years of live time, CUORE will reach a 1$\sigma$ sensitivity to the 0$\nu$DBD half-life of $\tau^{0\nu}_{1/2} = 1.6 \times 10^{26}$ y and thus a potential to probe the effective Majorana neutrino mass down to 41-95 meV [6].

References

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