Status of the CUORE experiment

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Abstract. One of the fundamental open questions in elementary particle physics is the value of the neutrino mass and its nature of Dirac or Majorana particle. Neutrinoless double beta decay (DBD0ν) is a key tool for investigating these neutrino properties and for finding answers to the open questions concerning mass hierarchy and absolute scale. Experimental techniques based on the calorimetric approach with cryogenic particle detectors are proved to be suitable for the search of this rare decay, thanks to high energy resolution and large mass of the detectors. The CUORE (Cryogenic Underground Observatory for Rare Events) experiment will search for DBD0ν in 130Te. The CUORE setup consists in an array of 988 tellurium dioxide crystals, operated as bolometers, with a total mass of about 230 kg of 130Te. The experiment is under construction at the Gran Sasso National Laboratory in Italy. As a first step towards CUORE, a tower prototype (CUORE-0) has been assembled and is running. In this talk a detailed description of the CUORE-0 tower, its performances and the expected sensitivity will be given. The status of the CUORE experiment, its critical points and its expected sensitivity on the base of what we will learn with CUORE-0 will then be discussed.

1. Introduction
Double beta decay (DBD) is a second order weak process in which a nucleus changes its atomic number by two units (A,Z)→(A,Z±2). It occurs for some even-even nuclei for which the single beta decay is energetically forbidden, or suppressed by large change in angular momentum. Two different DBD modes are usually considered: the decay with the emission of two neutrinos (DBD2ν), which is allowed in the Standard Model, that is described by the reaction

\[ (A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e \]  \hspace{1cm} (1)

and the neutrinoless decay (DBD0ν) given by

\[ (A,Z)(A,Z+2) + 2e^- \]  \hspace{1cm} (2)

This transition, which does not depend on the Dirac or Majorana nature of the neutrino, can be modeled as two successive single beta decays (see Fig. 1). DBD2ν was observed for many different nuclei [1], and the computed half-lives are of the order of 10^{18}-10^{24} y.

The DBD0ν is instead forbidden in the Standard Model, since it violates the lepton number by two units, moreover it has never been observed (except for one controversial claim [2]). DBD0ν decay can proceed through many different mechanisms, the simplest way to obtain it is by the exchange of a massive Majorana neutrino: one can think of the virtual neutrino in the diagram of Fig. 1 as being produced as an antineutrino at one vertex and absorbed as an neutrino at the
other vertex. In addition to the Majorana equivalence of neutrino and antineutrino, a not zero neutrino mass is required to flip the helicity since antineutrinos are right-handed and neutrino are left-handed. The helicity flip and the smallness of the neutrino mass cause the rate of DBD0$\nu$ to be much lower than the rate of DBD2$\nu$.

The rate of DBD0$\nu$ decay driven by the exchange of light Majorana neutrinos can be written as:

$$\left[ T_{1/2}^{0\nu} \right]^{-1} \propto G_{0\nu} \cdot |M_{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

where $G_{0\nu}$ is the phase space factor, $M_{0\nu}$ is the nuclear matrix element (NME), and $m_{\beta\beta}$ is the effective Majorana mass defined as:

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

with $U_{ej}$ as the mixing parameters of the PMNS matrix and $m_j$ the neutrino mass eigenstates. So, if neutrinos are Majorana particles, measuring or constraining the effective Majorana mass provides information on the neutrino mass scale and hierarchy.

2. The CUORE experiment

The use of bolometric detectors for the search of neutrinoless double beta decay was proposed by Fiorini and Niinikoski in 1984 [3]. Since almost thirty years his research group has been developing cryogenic detectors of increasing mass. The choice of a pure calorimetric approach was supported by the very good energy resolution achievable and the large choice of absorber materials containing DBD candidates.

2.1. Working principle

Bolometers are calorimeters operating at low temperature, in which the energy deposited by a particle is converted into phonons and is detected as a temperature variation. Almost the total released energy can be detected in this device. The energy deposited by a single particle in the device (connected to a heat sink) produces an increase of the temperature $T$ in the absorber. This variation corresponds to the ratio between the energy released by the interacting particle and the heat capacity of the absorber. The only requirements needed for running this type of devices are therefore to operate the detector at low temperatures (mK scales), in order to reduce the value of the heat capacity (large temperature variations), and to have a sensitive thermometer coupled to the absorber. The thermometer is usually a thermistor, a Neutron
On the left the entire CUORICINO tower and two modules are shown. On the right a sketch of the apparatus is depicted.

Transmutation Doped germanium sensor (Ge-NTD). The resistivity of the thermistor has a steep dependence on the temperature:

\[ R(T) = R_0 e^{\left(\frac{T_0}{T}\right)^\gamma} \]  

(5)

where \( R, T \) and \( \gamma \) are parameters that depends on the doping level of the sensors. Typical parameters for CUORE NTDs are:

\[ R_0 = 1.15 \, \Omega, \quad T_0 = 3.35 \, K, \quad \gamma = 0.5 \]  

(6)

2.2. From CUORICINO to CUORE

The CUORE experiment will look for DBD0ν in \(^{130}\text{Te}\) using TeO\(_2\) absorbers. It will use the bolometric technique established with its predecessor, CUORICINO, and should be able to achieve an improvement of almost two orders of magnitude in sensitivity to the DBD0ν half-life over Cuoricino’s current limit.

CUORICINO was the first CUORE prototype, the largest cryogenic detector ever assembled. The detector was an array of 62 TeO\(_2\) crystals, for a total active mass of 40.7 kg. The detectors were made of 5 × 5 × 5 cm\(^3\) crystals (44 absorbers) with a mass of about 790 g, the rest were 3 × 3 × 6 cm\(^3\) crystals with a mass of about 330 g (see Fig. 2). Four of the 330 g crystals were made of enriched Te: two were enriched in \(^{130}\text{Te}\) and two in \(^{128}\text{Te}\).

All the detector components: TeO\(_2\) crystals, the copper structure and the PTFE holders facing the detectors were treated to remove any possible radioactive impurities. The detectors were then assembled in a clean room with special care to avoid any recontaminations (e.g. Radon exposure). The CUORICINO tower was installed in a dilution refrigerator in the Underground Gran Sasso Laboratory, in order to reduce the background induced by cosmic rays. The detector was operated at a temperature of about 10 mK. The refrigerator was surrounded by a shield made of 10 cm of regular lead in addition with 10 cm of ancient Roman lead (with low 210\(^{\text{Pb}}\)
Figure 3. CUORICINO single-hit background spectrum (black) and CUORICINO sum calibration spectrum (red).

Figure 4. ROI of the CUORICINO single-hit background (black) and calibration (red) energy spectrum. The DBD0ν signal is expected at 2527 keV.

The total analyzed exposure was 19.75 y×kg of 130Te [5]. The average FWHM energy resolution of the array was 6.3 keV at the 130Te Q-value at 2527 keV. The final sum spectrum is obtained with the detectors operated in anticoincidence (see Fig. 3), to reduce background contributions from the crystal surfaces and from external γ’s. The achieved background level in the DBD0ν energy region is 0.169 counts/keV/kg/y (see Fig. 4), which translates into a sensitivity on the 130Te half-life and effective neutrino Majorana mass of:

\[ T_{1/2}^{0ν} > 2.8 \times 10^{24} \text{ y}, \quad \langle m_{ββ} \rangle < 0.3 - 0.7 \text{ eV}. \tag{7} \]

In CUORICINO, the main sources of background were the natural 238U and 232Th decay chains from detector material contaminations. By means of Monte Carlo simulations [6] two main background sources were identified: surface contaminations of the detector parts, and bulk contaminations of the surrounding materials (e.g. cryostat components). Surface contaminations produced a flat background in the region of interest [7]; the main components were the surfaces of the copper structure facing the detectors and the crystals themselves (~30% of the total background in the DBD0ν region).

The knowledge acquired with CUORICINO helped the design and construction of CUORE, this was done by optimizing each of the parameters of the sensitivity. The most critical parameter is the background level, this needs to be improved by more than a factor of 10 with respect to CUORICINO, reaching a goal of 0.01 counts/keV/kg/y. With a series of thorough studies on
the background abatement a special detector structure has been designed in order to reduce the overall copper surfaces facing the detectors. New surfaces cleaning techniques have been defined so that the surface contaminations are reduced and the induced background in the region of interest is minimized. All possible recontaminations of radio-cleaned materials are continuously kept under control.

The CUORE detector will be a tightly packed array of 988 TeO$_2$ bolometer modules, each $5 \times 5 \times 5$ cm$^3$ and 750 g, for a total mass of 741 kg of TeO$_2$. Since the tellurium is unenriched, 204 kg of the total mass is the isotope of interest, $^{130}$Te. The bolometer modules will be arranged in 19 towers of 13 floors each, with 4 crystals per floor (see Fig. 5). The CUORE detector will be housed in a specially built cryostat and cooled to about 10 mK by a pulse-tube-assisted dilution refrigerator.

CUORE will reach a sensitivity two orders of magnitude better than CUORICINO: $\sim10^{26}$ y. Thus it will be the first experiment able to probe the inverted hierarchy of neutrino mass. In order to introduce all the improvements in the detector design and construction, going towards CUORE, a step in between CUORICINO and CUORE is needed: CUORE-0.

2.3. CUORE-0

The final step before the start of the CUORE experiment will be CUORE-0, a single CUORE-like tower that will operate in the former CUORICINO cryostat and it is now acquiring data. CUORE-0 will consist of 52 CUORE crystals mounted in CUORE-style single tower with a total TeO$_2$ mass of 39 kg. It will be assembled with detector components manufactured, cleaned, and stored following the same stringent protocols defined for CUORE. The preparation of CUORE-0 is thus aimed to confirm the efficacy and feasibility of the CUORE production and assembly procedures. In addition, 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 undertaken extensive background-reduction measures.
The assembly of the CUORE towers must follow very strict prescriptions, due to the extraordinary level of radio-purity needed for the success of the experiment. The assembly is conducted following a zero contact philosophy for the detector components. For these reasons, the whole assembly procedure will be performed inside dedicated glove boxes, in a clean-room recently built in the CUORE hut in the Hall A of LNGS. Moreover, to reduce the cosmogenic activation, the exposure of detector parts to cosmic rays has to be minimized. The detectors parts, after having been produced, are packed and then stored in the so called Permanent Storage Area (PSA), located in the underground Laboratories, inside stainless-steel cabinets, which are continuously flushed with Nitrogen until the time when they will be used for the CUORE construction. The tower construction is conducted around two units: the gluing station (see Fig. 7), which provides all the tools needed for the gluing of thermal sensors on the crystals, and the assembly line, an integrated set of tools devoted to the final assembly of the tower. Both units use glove boxes to provide a controlled Radon-free environment. Each glove box has been specifically designed in order to meet the requirements of each single operation.

3. CUORE and CUORE-0 sensitivity to neutrino Majorana mass

CUORE-0 tower was cooled down in August 2012, and it started the pre-operation phase and optimization of 51/52 detectors. Unfortunately these operations were not completed due to 2 vacuum leaks in the system which deteriorated the system stability. We were able to perform calibrations despite the leaks, showing reasonable detector performances. We can not give an
exact estimation on the background rate. Based on simple scaling arguments, on the amount of copper surfaces and surface treatments CUORE-0 is expected to have a background reduction at least of a factor 2 in the DBD0\(\nu\) region compared to CUORICINO.

After a calibration of the detectors with an external \(^{232}\)Th source, we have evaluated a preliminary energy resolution. The best detector showed an energy resolution at 2615 keV of about 5 keV.

CUORE-0 is operating in the CUORICINO cryostat and consequently the \(\gamma\) 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, an upper limit of 0.11 counts/keV/kg/y follows from scaling the CUORICINO background in the conservative case of a factor of 2 improvement in the crystal and copper contamination.

A plot of the expected 1 \(\sigma\) sensitivity of CUORE-0 as a function of live time in these two bounding cases is shown in Fig. 8.

In the case of CUORE, the expected background rate is 0.01 counts/keV/kg/y, an energy resolution of 5 keV and a live time of the data taking of 5 y CUORE are foreseen. The achievable sensitivity to DBD0\(\nu\) is \(2.1\times10^{26}\) y (see Fig. 8), that corresponds to a lower limit on the neutrino Majorana mass of \(\langle m_{\nu}\rangle < (35-82)\) meV using the following nuclear matrix elements [8, 9, 10, 11].

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