Journal of Low Temperature Physics manuscript No.
(will be inserted by the editor)

A. Nucciotti[1,2,10] · **F. Alessandria**[2] ·
M. Ameri[6] · **C. Bucci**[4] · **A. Bersani**[6] ·
L. Canonica[6] · **R. Cereseto**[6] · **G. Ceruti**[2] ·
O. Cremonesi[2] · **A. Dally**[8] · **V. Datskov**[2] ·
S. Dossena[2] · **L. Ejzak**[8] · **M. Faverzani**[1,2] ·
E. Ferri[1,2] · **A. Franceschi**[5] · **G. Gregerson**[8] ·
K. Heeger[8] · **C. Ligi**[5] · **T. Napolitano**[5] ·
D. Orlandi[4] · **M. Sisti**[1,2] · **L. Taffarello**[7] ·
L. Tatananni[4] · **T. Wise**[8] · **A. Woodcraft**[9]

Status of the cryogen-free cryogenic system for the CUORE experiment

17.07.2011

Keywords Dilution refrigerator; Pulse tube; Cryostat; Double beta decay

Abstract The CUORE detector will be made of 988 TeO2 crystals and will need a base temperature lower than 10 mK in order to meet the performance specifications. 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 ton and uses a vibration decoupling suspension system. Because of the stringent requirements regarding radioactivity, about 12 tons of lead shielding need to be cooled to 4 K and below, and only a limited number of construction materials are acceptable. The eight retractable radioactive sources for detector calibration and about 2600 signal wires add further complexity to the system. The many stringent and contrasting requirements together with the overall large size made the design of the CUORE cryogenic system a real mechanical and cryogenic engineering challenge. The cryogenic system is expected to be fully operational in the Gran Sasso Laboratory in July 2013. We report here about the current status of the cryogenic system construction, which has started about one year.

PACS numbers: 74.70.Tx,74.25.Ha,75.20.Hr

1:Dipartimento di Fisica “G. Occhialini”, Univ. Milano-Bicocca, Milano, Italia
2:INFN, Sez. di Milano-Bicocca, Milano, Italia
3:INFN, Sez. di Milano, Milano, Italia
4:INFN, Laboratori Nazionali del Gran Sasso, Assergi (AQ), Italia
5:INFN, Laboratori Nazionali di Frascati, Frascati (Roma), Italia
6:INFN, Sez. di Genova, Genova, Italia
7:INFN, Sez. di Padova, Padova, Italia
8: Department of Physics, Wisconsin University, Madison, USA
9: Astronomical Instrumentation Group, Cardiff, UK
10:Tel.: +390264482428 Fax:+390264482463 E-mail: angelo.nucciotti@mib.infn.it

1 Introduction

The CUORE experiment[1] is being built at the National Gran Sasso Underground Laboratory (LNGS, Assergi, L'Aquila, Italia) to search for the neutrinoless double beta decay ($\beta\beta$-0ν) of ^{130}Te using an array of 988 thermal detectors. Each detector is made of a 750 g TeO_2 crystal. The CUORE cryogenic system where the 1.5 ton detector will be installed has been designed to satisfy a set of experimental requirements:

- the detector base temperature must be less than 10 mK for optimal operation;
- the 988 detector array requires an experimental space at least 1000 mm high and 940 mm wide;
- about 2000 high impedance sensors and heaters must be read with about 2600 wires;
- the level of the vibrations transmitted to the detectors has to be minimized.

The achievement of the CUORE target background in the energy range where the $\beta\beta$-0ν of ^{130}Te is expected ($Q_{\beta\beta}$= 2528 MeV) requires a strong reduction of environmental radioactivity (especially ^{232}Th). This has added more requirements:

- the experiment must be shielded by at least 30 cm of lead in every direction;
- inside the lead shielding only selected radiopure materials can be used;

Finally, since the CUORE measuring time may be as long as 10 years, to comply with the need for a stable and service-free operation with high duty-cycle running, a cryogen-free system was chosen. Much progresses has been made since our previous paper[2]; in the following we describe the present status of the project.

2 CUORE Cryogenic System design and status

Cryostat

The CUORE cryostat is made of six closed vessels cooled by five Pulse Tubes (PT) and one Dilution Unit (DU) (Fig. 1). They include two vacuum chambers: the Outer Vacuum Chamber (OVC) at room temperature and the Inner Vacuum Chamber (IVC) kept a temperature of about 4 K by the 2*nd* stage of the PTs. The OVC is about 3090 mm high and has an outer diameter of about 1620 mm. A thermal radiation shield between the OVC and the IVC chambers is maintained at a temperature of about 40 K by the PT 1*st* stages. Because of its radioactive contamination, only 30 layers of specially selected Multilayer Insulation (MLI) will cover the 40 K shield. Additionally, 10 layers will protect the IVC shield. Inside the IVC there are two radiation shields connected respectively to the Still (a thermal stage at about 0.5-0.9 K) and to the Heat Exchanger stage (HEX) (at about 50-100 mK) of the DU. The innermost shield is connected to the DU Mixing Chamber (MC) to protect the experimental space. Its temperature is expected to be lower than 10 mK. The IVC volume is accessed through ten ports with different diameter made out of 316LN stainless steel tubes with thin walled bellow sections. The cryostat contains also two lead shields against radioactivity. A 60 mm thick lead layer between the IVC and Still vessels at 4 K will protect the detectors from the radioactivity of the outer vessels and of the MLI. A 300 mm lead disk between

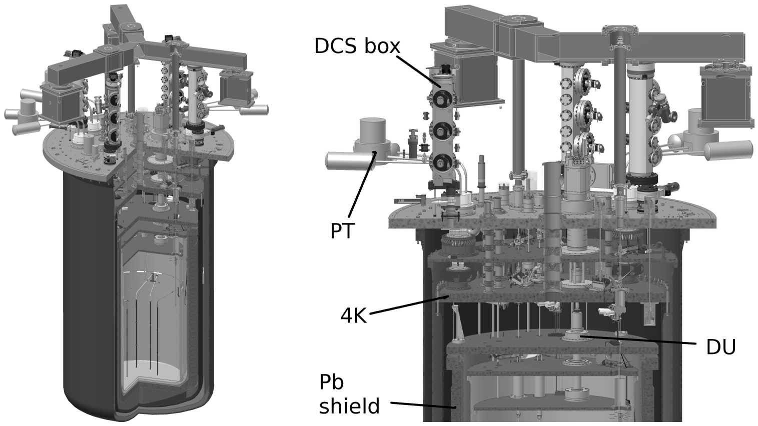

Fig. 1 CUORE Cryostat cross section (left) and details of the upper part (right)

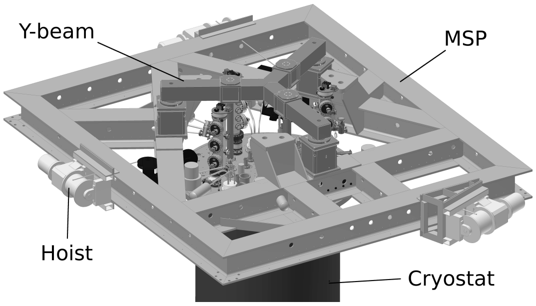

Fig. 2 The Main Support Plate (MSP)

the MC plate and the detectors at the HEX temperature will protect them from the radioactivity of all cryostat components above. The two shields have total masses of about 7 and 3.3 tons, respectively. The OVC top plate and flange are made of specially selected 304L stainless steel. To accomplish the radiopurity requirements, the rest of the cryostat is entirely made of selected high purity copper and only e-beam welding is used. The copper has been already procured and stored at LNGS to prevent cosmic ray activation. The base temperature components will be made out of ETP1 alloy (Electronic Tough Pitch also called NOSV). The NOSV copper has been chosen for its low hydrogen content and measurements of the residual heat-leak due to hydrogen ortho-para conversion gave only an upper limit of about 4 pW/g.[3] The remaining copper is the OFE (Oxygen Free Electrolytic) alloy. In 2009 an extensive seismic analysis of the whole CUORE set-up has been performed by consultants from the Dipartimento di Ingegneria Strutturale of Politecnico di Milano. Actions were suggested to make the whole structure safer: in particular, for what concerns the cryostat, the design of the internal tie rods was improved and stoppers between the vessels were introduced to limit their displacement. To ensure people safety, as prescribed by Italian control regulation, the whole cryostat is suspended to a steel I-beam structure (Main Support Plate or MSP) (Fig. 2) by means of three stainless steel chains loaded with about 6 tons each and dimensioned to withstand safely the strongest expected earthquake with a peak ground acceleration (PGA) of about 0.26*g* (intensity VII on the Modified Mercalli (MM) scale, expected once in 475 years). The internal tie rod configuration has been modified with respect to our previous work[2]: the 40 K, 4 K and Still plates are now suspended from the OVC top plate by means of three independent sets of 316LN stainless steel tie rods and special tilting CuBe supports for the rods ends have been designed to prevent damages to the loaded rods in case of a shield displacement caused by a seismic event. On the 4 K plate, the vacuum tight access of the Still tie rods is allowed by metallic bellows welded on the rods. The 40 K, 4 K and Still tie rods are designed to be loaded each with about 0.33, 0.66 and 3.2 tons, respectively, and to resist without damage only to more frequent and weaker earthquakes with PGA of about 0.08*g* (intensity V on the MM scale, expected once in 35 years). The HEX and MC plates have 316LN stainless steel tie rods connected to the plates just above – i.e. to the Still and HEX plate, respectively – and will have tilting CuBe supports as well. The design of all parts at 4 K and above is now complete and the cryostat construction started beginning of 2010. The vessels and their top plates are being produced by Simic (Camerana, Cuneo, Italia). Presently, the 300, 40 and 4 K cryostat plates have been completed and the corresponding vessels are being e-beam welded by Pro-Beam (Burg, Germany). The production of all other cryostat components, such as the 316LN stainless tie rods, the IVC access ports and the thermal links, is in progress as well. The design of the inner cryostat parts is almost complete and the construction of the inner shields will start soon after the outer vessels will be successfully tested at 77 K by Simic. The full commissioning at LNGS of the three outer chambers is expected by the end of 2011. Presently at LNGS the MSP, with the integrated hoist system for lifting the cryostat plates and vessels, is already in place.

The DU cooling system

The cooling power to operate the CUORE detectors at temperatures in the 10 mK range, is provided by a custom cryogen-free high-power ^{3}He/^{4}He Dilution Unit (DU) developed by Leiden Cryogenics (Leiden, The Netherlands). The DU includes a Joule-Thompson condensing stage specially designed for high circulation rates and fitted with two spring loaded variable flow impedances. Thanks to two magnetically levitated turbo pumps (about 1850 l/s each), the ^{3}He Gas Handling System (GHS) can provide a ^{3}He flow rate up to about 6 mmoles/s. In order to prevent excessive thermal loading of the 4 K cryostat stage at high circulating rates, the incoming ^{3}He gas is pre-cooled thanks to tubes soldered on the PT bodies. The minimum cooling power specifications on the MC are 5 μW at 12 mK and 1.5 mW at 120 mK during continuous operation in a test cryostat. Presently the DU with its GHS is being characterized and optimized at Leiden Cryogenics in a standard test cryostat with two PTs. Preliminary runs showed a base temperature as low as 5.3 mK (with no external load) and a cooling power of about 3 mW at about 120 mK. Leiden Cryogenics is also developing a system (Fast Cooling System or FCS) for a quick pre-cooling of the IVC and of the whole experimental mass from room temperature to less than 30 K. The FCS will consists of an external vessel with heat exchangers, three Gifford-McMahon cryo-coolers (each with a cooling power of about 600 W at 77 K), a helium blower and double-walled pipes. Helium gas, progressively cooled in the external vessel, will be circulated and routed to three location at the bottom of the cryostat IVC. A preliminary estimate for the pre-cooling time of the complete cryogenic system by means of the FCS with the help of the five PTs gives less than 4 days to reach 4 K.

The detector and cold lead shield suspension system

The detector suspension has been designed to minimize the transmission of mechanical vibrations both due to ambient micro-seismic noise and to the operation of the PTs and DU. It is a two-stage low-frequency isolator, in the vertical direction, and a pendulum with a natural frequency of about 0.4 Hz, in the horizontal direction. It must provide load path for the detector while minimizing the heat input and the vibration transmission. The suspension is made by several parts: three Minus-K springs and the Y-beam positioned on top of them are already mounted in the CUORE hut on top of the MSP. The detector will be suspended to the Y-beam through three composite rods. The system formed by the Minus-K springs and the rest of the detector will behave like a spring-mass system with a cut-off frequency of 0.5 Hz. The composite rods will be made of several 316LN stainless steel rods, with three copper thermal links connecting to 40 K, 4 K and Still plates. Below the Still thermal link there is a Kevlar rope section, which strongly reduces the thermal conductivity of the suspension. For the inner top lead shield assembly a similar suspension scheme has been designed: the lead suspension will be hung to the 300 K top plate and not to the Y-beam to guarantee the best mechanical decoupling of the detector from the cryostat assembly. Both suspensions have been designed and the detector suspension parts have been built and are ready to be pre-assembled in the CUORE cryostat after commissioning of the cryostat three outer chambers at LNGS. The pre-assembly will allow to characterize the suspension through an extensive campaign of vibration transmission measurements. Preliminary vibrational mode measurements on the Y-beam structure have been already performed. The Kevlar section of the suspension is still under careful investigations in Genova for what concerns the Kevlar creeping at low temperature.

The detector calibration system (DCS)

The energy response of the CUORE bolometer array will be calibrated with regular exposure of the detectors to γ-sources. To overcome the detector self-shielding, calibration sources will be placed between the individual towers of the CUORE detector array. The CUORE detector calibration system (DCS) consists of 12 radioactive source strings that are able to move, under their own weight, through a set of guide tubes that route them from outside the cryostat at 300 K to their locations between the bolometers in the detector region inside the cryostat.[4] The radioactive sources strings are fabricated from Teflon-coated copper capsules containing thoriated tungsten wire crimped onto a Kevlar string. A system of four vacuum boxes with a computer-controlled, spool-based deployment mechanism stores the calibration sources above the cryostat’s 300 K flange during regular data taking of the experiment. For the monthly detector calibration, strings of radioactive sources are moved through ports and a low-friction guide tube system into the cryostat. Solenoid-activated clamps provide an effective heat sink at 4 K for the source strings. Heat load due to thermal conduction on the lower temperature stages is dominated by the guide tubes, while radiation from the strings is negligible. The largest – but still manageable – heat load is expected from friction during source string extraction. Prototype components have been tested for many hundreds of deployment cycles at room temperature in the laboratory at Madison and a redundant set of instrumentation to monitor the motion and position of the source strings has been integrated into the deployment mechanisms. In 2010 the design of the motion box was completed and fabrication of the first deployment system started. Once the outer cryostat vessels will be commissioned at LNGS, one motion box and a representative set of guide tubes along with the thermalization mechanism will be installed in the empty cryostat for testing thermal and mechanical functionality.

Other components

The CUORE cryogenic system includes two other important components whose design is only partly completed: the Wiring System (WS) and the cold lead shields. For what concerns the latter the design is still very preliminary: work is in progress at LNGS to investigate the lead pieces production. More advanced is the WS which routes the detector signals from the MC plate to room temperature. It consists of independent modules which will be assembled and tested before being introduced in the CUORE cryostat through seven dedicated 40 mm ID access ports. Five ports are used for detector signal wires, while one is dedicated to heater and diagnostic wires. The seventh port is left as spare. The WS uses 100 μm NbTi wires with CuNi clad in 100 ribbons, each with 13 twisted pairs – without guard and shielding. Ribbons are 2400 mm long with connectors only at room temperature and at the MC, where junction boxes connect to the detector wiring system. The ribbons with the connectors at the end have already been produced. The preliminary design of the thermal stages below the 4 K plate, on the Still, HEX and MC plates is presently under review. Tests are in progress in Milano to validate the design of the most critical 300 K – 4 K section of the wiring, using one of the five CUORE PTs and one of the stainless steel access ports.

3 Conclusions

The design of most of the CUORE cryostat components is completed and the production has started. The first three vessels (300, 40 and 4 K) will be commissioned at LNGS by end of 2011. Test at low temperature will start soon after the commissioning. The full CUORE cryogenic system will be ready for detector integration by mid 2013.

References

1. L. Gironi, this issue.
2. A. Nucciotti et al., J. Low Temp. Phys. **151**, 662, (2008).
3. M. Martinez et al., AIP Conference Proceedings, **1185**, 693, (2009).
4. S. Sangiorgio et al., AIP Conference Proceedings, **1185**, 677, (2009).