The CUORE cryostat: a 10 mK infrastructure for large bolometric arrays

S Dell’Oro$^{1,2}$, F Alessandria$^{3}$, C Bucci$^{2}$, A Caminata$^{4}$, L Canonica$^{2,5}$, L Cappelli$^{2,4,6}$, R Cereseto$^{7}$, N Chott$^{7}$, S Copello$^{1,8}$, O Cremonesi$^{9}$, A D’Addabbo$^{2}$, M A Franceschi$^{10}$, P Gorla$^{2}$, M Guetti$^{2}$, C Ligi$^{10}$, T Napolitano$^{10}$, A Nuccioni$^{9,11}$, D Orlandi$^{2}$, C E Pagliarone$^{2,12}$, L Pattavina$^{2}$, D Santone$^{2,12}$, V Singh$^{13}$, L Taffarello$^{14}$ and F Terranova$^{9,11}$

$^1$ INFN, Gran Sasso Science Institute, 67100 L’Aquila, Italy
$^2$ INFN, Laboratori Nazionali del Gran Sasso, 67100 Assergi, L’Aquila, Italy
$^3$ INFN, Sezione di Milano, 20133 Milano, Italy
$^4$ INFN, Sezione di Genova, 16146 Genova, Italy
$^5$ Massachusetts Institute of Technology, Cambridge, MA 02139, USA
$^6$ Dipartimento di Ingegneria Civile e Meccanica, Università degli Studi di Cassino e del Lazio Meridionale, 03043 Cassino, Italy
$^7$ Department of Physics and Astronomy, University of South Carolina, Columbia, SC 29208, USA
$^8$ Dipartimento di Fisica, Università di Genova, 16146 Genova, Italy
$^9$ INFN, Sezione di Milano-Bicocca, 20126 Milano, Italy
$^{10}$ INFN, Laboratori Nazionali di Frascati, 00044 Frascati, Roma, Italy
$^{11}$ Dipartimento di Scienze Fisiche e Chimiche, Università dell’Aquila, 67100 L’Aquila, Italy
$^{12}$ Dipartimento di Scienze Fisiche e Chimiche, Università dell’Aquila, 67100 L’Aquila, Italy
$^{13}$ Department of Physics, University of California, Berkeley, CA 94720, USA
$^{14}$ INFN, Sezione di Padova, 35135 Padova, Italy

E-mail: stefano.delloro@gssi.infn.it

Abstract. The Cryogenic Underground Observatory for Rare Events (CUORE) experiment is presently in the final phases of its commissioning at the Gran Sasso Underground Laboratory (Italy). The CUORE cryogenic system will have to guarantee the optimal operation temperature of the detector ($\sim 10$ mK) for a live-time of 5 years. Furthermore, to avoid radioactive background, about 7 tonnes of lead are cooled to below 4 K and only few construction materials are acceptable. The CUORE detector will be by far the largest mass ever cooled to 10 mK. A description of the CUORE cryostat is presented and the specific characteristics and the performances are illustrated. The results of the (recently concluded) cryostat commissioning are also reported. They show that the CUORE cryostat is now ready to host the detector, thus confirming the possibility of realizing large bolometric arrays for rare event physics.

1. Introduction
Neutrinoless double beta decay ($0\nu\beta\beta$) [1] is a key tool to address some of the major outstanding issues in particle physics, such as lepton number conservation and the Majorana nature of neutrinos. Its discovery could also provide precious information on neutrino masses [2].
The Cryogenic Underground Observatory for Rare Events (CUORE) experiment will search for the $0\nu\beta\beta$ of $^{130}$Te with an array of 988 bolometers. Each bolometer consists in a 750g $5 \times 5 \times 5 \text{cm}^3 \text{TeO}_2$ crystal, for a total mass of over 740kg for the whole detector [3].

Bolometers are calorimeters in which the energy released in an absorber by an interacting particle is converted into phonons and measured via temperature variation. These detectors can only be operated at cryogenic temperatures, in our case of about $\sim 10\text{mK}$. In fact, on the one side, we must prevent the thermal generation of excitations that would cover any interaction signal. On the other, since the intrinsic response of a calorimeter is dependent on its heat capacity and the operating temperature [4], this requirement is needed in order to achieve high sensitivity and good energy resolution.

The CUORE cryogenic system will have to guarantee a stable operation temperature for a live-time of 5 years. The recently concluded cryostat commissioning at the Laboratori Nazionali del Gran Sasso ($\sim 3600\text{m.w.e.}$) confirm that this apparatus is now ready to host the detector. This success is opening the way for large bolometric arrays (ton-scale) for rare event physics.

2. Cryostat overview
A scheme of the CUORE cryostat is shown in Fig. 1. The cryostat consists of six nested vessels, the innermost of which encloses the experimental volume ($\sim 1\text{m}^3$). The different stages thermalize at about $300\text{K}$, $40\text{K}$, $4\text{K}$, $600\text{mK}$ (Still), $50\text{mK}$ and $10\text{mK}$ (Mixing Chamber, MC). Of these, the $300\text{K}$ and the $4\text{K}$ vessels are vacuum-tight: they enclose the Outer Vacuum Chamber (OVC) and the Inner Vacuum Chamber (IVC), respectively. The cryostat also contains the Detector Calibration System that will allow in situ calibration with known $\gamma$-ray sources [5].

Since the cryostat design is targeted for rare event detection, in order to preserve radio-purity, the $^{232}\text{Th}$ and $^{238}\text{U}$ contaminations must be $< 2 \cdot 10^{-8}\text{Bq/kg}$ and $< 10^{-4}\text{Bq/kg}$ respectively. The use of copper instead of stainless steel is therefore mandatory for both plates and vessels [6].
The IVC contains the detector shields: the top lead (30 cm thick) and the lateral lead (6 cm thick). In particular, the latter is made of ancient Roman lead (≈ 2000 years old) practically free of $^{210}\text{Pb}$ [7]. The 4 K and the 40 K vessels are externally covered with a multilayer aluminized superinsulation that acts as a thermal radiation shield.

Five pulse tubes (PTs) are mounted on the 300K top plate. They provide the cooling for the 40 K radiation shield (PT first stages) and for the 4 K vessel (PT second stages). PTs are cryocoolers and therefore they avoid the need of a liquid helium bath cryostat with its infrastructure, guarantee a high reliability and, due to the absence of cryogens to refill, increase the total duty cycle of the experiment, thus allowing a longer live-time. In particular, a remote motor option has thus to be used in order to reduce the vibrational noise, otherwise too high to allow the functioning of the detector.

The core of the CUORE cryostat is a custom designed Dilution Unit (DU) from Leiden Cryogenics. The nominal cooling power is of 2 mW at 100 mK and of 3 μW at 10 mK. The minimum reached temperature was ≈ 5.3 mK. The CUORE DU is able to sustain the high mixture flow ($\geq 8\text{ mmol/s}$) needed to cool down the several tons of mass to the respective operating temperature of each stage. At the same time, the mixture flow can be reduced to $< 1\text{ mmol/s}$ during the detector operation. A low mixture flow is required once the base temperature is reached, when most of the heat on the MC stage comes from the incoming mixture itself.

PTs alone would take months to cool the full mass inside the IVC from room temperature. The enthalpy difference from 290 K to 40 K is in fact $\sim 8 \times 10^8\text{ J}$. Therefore, a Fast Cooling System (FCS) has been developed. Helium gas is circulated through a separate cryocooler, where a system of heat exchangers powered by 3 Gifford-McMahon heads cools the gas down to less than 40 K. The He flow is injected inside the IVC and regulated to maintain a maximum temperature gradient of 40 K inside the cryostat in order to avoid any thermal shock. The PTs are turned on when the cryostat temperature is around 200 K and they work together with the FCS until the temperature reaches $\sim 70\text{ K}$, then the latter is turned off. With the FCS, the cool down period is reduced to about (2−3) weeks.

3. Commissioning results

The DU was first characterized in a dedicated test cryostat and then integrated in the CUORE cryostat. Positive results were obtained during the commissioning and the compliance with the nominal performances was verified also after the installation of the lead shields and the insertion of the whole wiring for the detector readout.

During the latest long-term cool down, a stable temperature was maintained for about three months. In particular, a value of (6.32 ± 0.04) mK was registered for a 48h interval of “undisturbed” cryostat. The measured cooling power was of 3 μW on the MC plate. Finally, the cool down time to 4 K with the FCS was also successfully tested, with about 16 days required to reach the target temperatures with the fully-loaded cryostat (apart from the detector).

At present, the cryostat commissioning is concluded, with the CUORE detector already installed, and ready for the final cool down.

References

[1] Furry W H, Phys. Rev. 56, 1184 (1939).
[2] Dell’Oro S, Marcocci S, Viel M and Vissani F, Adv. High Energy Phys. 2016, 2162659 (2016).
[3] Artusa D R et al. (CUORE Collaboration), Adv. High Energy Phys. 2015, 87987 (2015).
[4] Enss, C and McCammon D, J. Low Temp Phys. 151, 5 (2008).
[5] Cushman, J S et al., arXiv:1608.01607 [physics.ins-det] (2016).
[6] Alessandria F et al., Nucl. Instrum. Meth. A 727, 65 (2013).
[7] Alessandrello A et al., Nucl. Instrum. Meth. B 142, 163 (1998).