The Cryostat of the CUORE Project, a 1-ton Scale Cryogenic Experiment for Neutrinoless Double Beta Decay Research

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Abstract.
CUORE is a new generation of 1-ton scale cryogenic detector for rare-events physics. CUORE, a detector to search Neutrinoless Double Beta Decay of $^{130}$Te, is an array of 988 $\text{TeO}_2$ crystals of a mass of 750 g each. To build the cryogenic system, where the CUORE detector will be installed in the Gran Sasso Underground Laboratory, is really a challenge. It is a large cryogen-free cryostat cooled by pulse tubes and by a high power dilution refrigerator. To avoid radioactive background, about 10000 kg of lead will be cooled to below 1 K and only few construction materials are acceptable. the detector will have a total mass of about 1500 kg and must be cooled to less than 10 mK in a vibration-free environment.
1. Search for a neutrinoless double beta decay with CUORE

Although the existence of neutrino oscillations (and consequently of massive neutrinos) are well proved, several properties of the neutrino family have still to be fixed. Measuring the masses, the mixing angles (and phases) as well as assessing the Dirac/Majorana character of neutrinos will be the goals of the next experiments in neutrino physics. In this scenario, a unique role is played by Neutrinoless Double Beta Decay ($\beta\beta^0\nu$) searches: these are the only experiments that can prove the Majorana character of neutrinos (as foreseen by the majority of theories) allowing in the meantime to obtain information on the neutrino mass hierarchy and scale.

CUORE is a low temperature detector designed in accordance with the so-called "source = detector" configuration that guarantees an high efficiency (ideally 100%). The use of the bolometric technique offers high energy resolution, needed to separate the $\beta\beta^2\nu$ contribution from the $\beta\beta^0\nu$ peak. Natural tellurium contains about 33.8% of the isotope $^{130}\text{Te}$ that, given its high Q-value ($\sim 2530$ keV) and its favorable nuclear factor of merit, is one of the more interesting candidates for $\beta\beta^0\nu$ study. The array of CUORE consists of 19 vertical towers, each tower consisting of 13 layers of 4 modules hosting 5x5x5 cm$^3$ crystals of TeO$_2$ (750 g) cooled at 10 mK, arranged in a cylindrical structure [1]. Each crystal is weakly coupled to the main bath thanks to small Teflon springs. The feasibility of the project is widely showed by the results of CUORICINO, a single CUORE tower running since 2003 in the Hall A of the Gran Sasso Underground Laboratory [2].

2. Requirements to build a cryostat for CUORE

The total mass to be cooled to about 10 mK, including the detector support structure made of copper (Electronic Tough Pitch, called also NOSV, chosen for its low hydrogen content) is about 1500 kg. Even if some others experiments has achieved to cool down such mass [3], the CUORE cryogenic system is therefore a new challenge in the field of large mass cooling.

The cryostat must satisfy the following requirements:

- the detector base temperature must be as less as 10 mK for optimal operation for the crystals as well as for the Ge NTD thermistors
- the CUORE detector array is about 1 meter high and 90 cm diameter
- the system "detector and cryostat" needs 2700 wires
- the thermistors having a very high impedance, the level of the vibrations transmitted to the detector has to be minimized to avoid microphonic noise.
- the achievement of the CUORE target requires a strong reduction of the background (specially in the energy range where $\beta\beta^0\nu$ of the $^{130}\text{Te}$ is expected (2530 keV), lower than $10^{-2}$ counts/keV/kg/y). The reduction of the environmental radioactivity is achieved by adding shields of 30 cm of lead in every direction.
- again for reduction of background, only radiopure materials can be used, all the more so inside the lead shielding
- CUORE measuring time can be as long as 10 years, the experiment needs to be stable, service-free, and hight duty cycle running. The cryostat has to be cryogen-free with at least one spare cryocooler.

3. Cryostat design description

A 3D view of the cryogenic apparatus is showed in fig. 1. It consists of 6 shields whose two are vacuum chambers, the Outer Vacuum Chamber at 300 K, and the Inner Vacuum Chamber at a temperature around 4 K, used to precool the detector and the shields at 4 K at the start of the cooling. The flange of the OVC is made of stainless steel 316LN for its robustness, contrary to the other flanges and shields, made of copper OFE (Oxygen Free Electrolytic), to avoid too high
thermal gradients. The mixing chamber plate is made of copper NOSV (for its low hydrogen content). Between the OVC and the IVC, a thermal shield is placed at a temperature around 45 K, made of copper.

Figure 1. Schematic of the CUORE cryostat.

Up to 5 pulse tubes (PTs) mounted on the OVC top flange provide the cooling of the 45 K shield (the first stages of PTs) and the IVC (the second stages of PTs). The PTs chosen are the PT415 made by Cryomech, which have a cooling power as high as 1.5 W at 4 K, each. The cooling of the experiment itself is provided by a high power cryogen-free Joule-Thompson $^3$He/$^4$He dilution refrigerator heat sunk on the IVC flange, made by Leiden Cryogenics. The mixing circulation should be as high as 2 mmol/s, the expected cooling powers are 1.5 mW at 120 mK and 6 $\mu$W at 10 mK, and the base temperature without loads should be as low as 6 mK. The three other shields are thermalized respectively on the still, on the cold plate (between the continuous and the discrete heat exchangers) and on the mixing chamber of the dilution unit.

To protect the experiment from environmental radioactivity and from contaminations in the building materials, a 300 mm thick lead layer outside the OVC shields the detector from the bottom and from the side of the detector. Inside the cryostat, there are three lead shields (cf fig. 1). A 300 mm thick, 900 mm diameter disc in lead is placed just above the detector, a shield 60 mm thick outside the vessel of the still and a ring-shaped placed on the still flange closing the gap between the disc and the room temperature shield.
To avoid vibrations on the detector, suspensions of the shields, suspensions of the detector and dilution unit are independent (cf fig. 2). The materials used for suspensions are 316LN tie bars from 300 K to the temperature of the still, Kevlar 49 ropes with thimble eyes from the still plate to just below the mixing chamber plate (to minimize the heat load on the cold plate), and a copper bar from the mixing chamber plate to below (for radiopurity requirements). As an exception, the cold plate of the dilution unit is suspended thanks to three Ti-6Al-4V alloy rods fixed on the still plate. The detector suspension is a two stage low-frequency isolator, fixed to a "Y" shaped structure above the cryostat (cf fig. 1). The first stage is a negative stiffness mechanism made by Minus-K, the second stage is provided by regular springs at the top end of the suspension bars (cf fig. 2). This low-pass filter has two poles at about 0.5 Hz and 3.4 Hz. In the horizontal direction, the structure is a pendulum with a frequency of 0.4 Hz.

4. Conclusions
The CUORE cryostat will have to be ready in 2010. We are currently testing individually the components of the cryostat, like the performances of the PTs, the heat leaks of the materials that will be used to build the experiment (already bought and placed in the Gran Sasso Underground Laboratories to prevent cosmic ray activation). The dilution unit will be test separately in Leiden in a dedicated cryogen-free test cryostat, with 3 PTs.

References
[1] Arnaboldi C et al. 2004 Nucl. Instrum. Methods A 518 775
[2] Arnaboldi C et al. 2005 Phys. Rev. Lett. 95 142501
[3] de Waard A et al. 2004 Class. Quantum Gravity 21 S465