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The CUORE cryostat and its bolometric detector

The CUORE collaboration

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2017 JINST 12 C02055

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2017 JINST 12 C02055

Abstract: CUORE is a cryogenic detector that will be operated at LNGS to search for neutrinoless double beta decay ($0\nu\beta\beta$) of ^{130}Te. The detector installation was completed in summer 2016. Before the installation, several cold runs were done to test the cryogenic system performance. In the last cold run the base temperature of 6.3 mK was reached in stable condition. CUORE-0, a CUORE prototype, has proven the feasibility of CUORE, demonstrating that the target background of 0.01 counts/keV/kg/y and the energy resolution of 5 keV are within reach.

Keywords: Calorimeters; Cryogenic detectors; Cryogenics and thermal models; Double-beta decay detectors

2017 JINST 12 C02055

Contents

1 Introduction **1**

2 CUORE experiment **1**

2.1 TeO_2 bolometer 2

2.2 CUORE assembly line 3

3 CUORE cryostat **3**

4 CUORE-0 experiment **6**

4.1 CUORE-0 detector performance 6

4.2 Search of neutrino-less double beta decay by ^{130}Te 7

5 Conclusion **7**

1 Introduction

Neutrinoless double beta decay $0\nu\beta\beta$ is an extremely rare process in which a nucleus undergoes two simultaneous beta decays without neutrino emission. Its evidence is a peak in the sum of energy spectrum of two emitted electrons [1]. This process has never been observed but its discovery would demonstrate the lepton number violation and the Majorana nature of neutrino (ν and $\overline{\nu}$ are the same particle); it also would constrain the neutrino mass absolute scale.

A good $0\nu\beta\beta$ experiment must have low level of background, high isotopic abundance of $\beta\beta$ candidate to increase the $0\nu\beta\beta$ signal event, and a possible good energy resolution.

CUORE (Cryogenic Underground Observatory for Rare Events), situated at Laboratori Nazionali del Gran Sasso, is the upcoming 1-ton bolometric $0\nu\beta\beta$ experiment.

2 CUORE experiment

CUORE consists in 988 TeO_2 crystals arranged in a modular structure in 19 towers. Each tower is an array of 52 TeO_2 crystals, disposed in 13 floors, on each floor there are four $5 \times 5 \times 5\,cm^3$ crystals with a mass of 750 g. The total mass of CUORE is 742 kg. In figure 1 the assembled CUORE towers are shown.

CUORE searches the neutrinoless double beta decay by the following reaction:

$$^{130}\text{Te} \rightarrow ^{130}\text{Xe} + 2e^-. \tag{2.1}$$

The Q-value is 2527.515 ± 0.013 keV [2]. It is between the Compton edge and the ^{208}Tl photo-peak, which is the highest line of natural radioactivity. Nevertheless ^{130}Te has a natural isotopic

2017 JINST 12 C02055

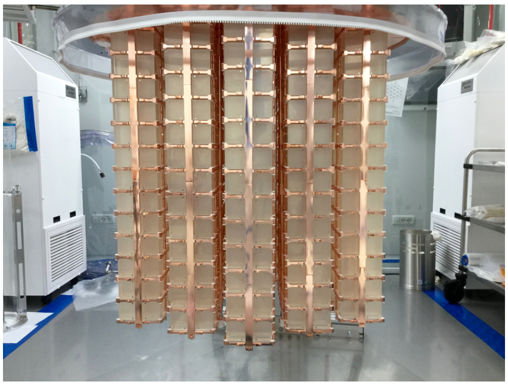


Figure 1. CUORE towers.

abundance of 34%, so the enrichment is not strictly required. This a great advantage because the enrichment process can cause crystal contamination and it is an expensive process.

CUORE bolometers will be operated at 10 mK temperature reached by custom-build cryogenic system. The expected energy resolution is 5 keV at the 2615 keV peak and the expected background level is 10^{-2} count/keV/kg/yr in the energy region around the Q-value of ^{130}Te (Region of Interest — ROI).

2.1 TeO_2 bolometer

A bolometer is a low temperature detector in which the energy released into the crystal is converted in thermal phonons. The good energy resolution, the low intrinsic background and the high detection efficiency make bolometer an ideal detector to search for rare events.

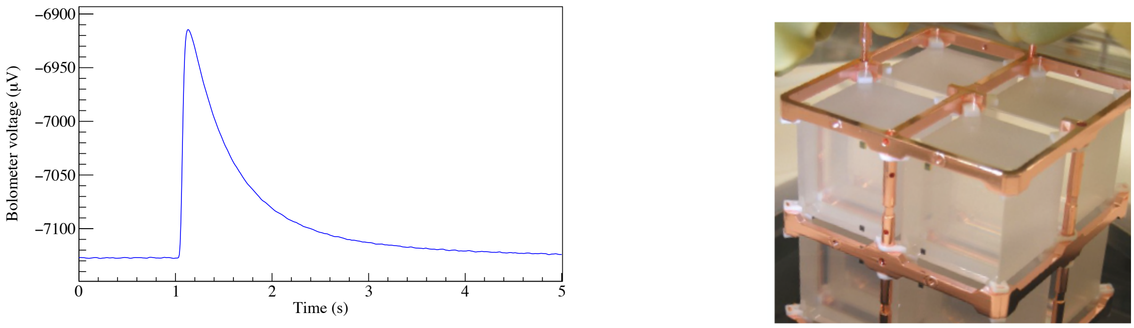
A bolometer consists in three principal parts: a diamagnetic and dielectric crystal as energy absorber, a thermistor that converts the thermal signal into an electrical one, and a thermal link between the crystal and the heat bath. The thermal signal is given by a pulse, its amplitude is proportional to $\frac{\Delta E}{C}$ and its decay time is $\tau \sim C/G$, where C is crystal thermal capacity and G is the thermal conductance between crystal and heat bath (see figure 2a). Since the amplitude of thermal signal is proportional to the ratio $\frac{\Delta E}{C}$, smaller C means higher thermal signal.

The basic elemenent of the CUORE bolometer is a TeO_2 crystal equipped with a NTD-Ge sensor and a silicon heater (see figure 2b). Four crystals are housed in a copper frame structure, acting as heat bath, and a Teflon support, acting as thermal link [3]. The TeO_2 crystal has good thermal and mechanical properties and its thermal capacity is $= 2.3 \times 10^{-9}$ J/K at 10 mK.

The CUORE sensor is an ultra-pure germanium crystal doped by neutron-transmutation technique (NTD-Ge). The NTD-Ge sensor operates in the Variable Range Hopping regime (VRH): the phonons are responsible of conduction regime and the charge migrates among far impurity sites at Fermi energy. The resistivity is correlated to temperature by the following relation:

$$R(T) = R_0 exp\left(\frac{T_0}{T}\right)^{\frac{1}{2}}, \tag{2.2}$$

where T_0 depends on doping level and R_0 depends on the doping level and on the sensor geometry. The measured values for CUORE-NTD are: $R_0 = 1.13\,\Omega$, $T_0 = 3.84$ K.



(a) **(b)**

Figure 2. On the left a typical 2615 keV CUORE-0 pulse. On the right a CUORE bolometer.

The heater is a silicon chip on which a heavily doped meander is realized through the standard processes of silicon planar technology. The meander has a low-mobility metallic behavior at low temperatures, providing a constant resistance of ~ 300 kΩ.

Since the thermal detectors are sensitive to temperature drift, which would spoil their intrinsic energy resolution, the heater is used to correct the signal for this problem during initial stage of data analysis. The heater periodically injects a fixed-energy pulse into each crystal to emulate particle interaction and bolometer response.

2.2 CUORE assembly line

In CUORE the dominant background is originated by the α particles, emitted from radioactive nuclei located on copper surface, that lose part of their energy in the copper before reaching the detector. The resulting is a continuum energy background spectrum from 4–5 MeV to zero.

The CUORE assembly line is based on strict selection of materials and an extremely careful radio-purity control during the assembly process to reduce the α background.

The assembly is done following a "zero contact" philosophy for the detector components, i.e. no exposure to air to prevent possible Radon contamination and minimized contact (in space and time) with other materials [3]. The assembly procedure uses two separate workstation, consisting in a glove boxes under nitrogen atmosphere. The two glove boxes are: a gluing box in which the sensor is coupled to the crystal and a glove box in which each tower is assembled (see figure 3). The sensor is coupled to the crystal by a semi-automatic system, consisting in a six-axis articulated robotic arm to lift and position the crystals, and a three-axis Cartesian robot to dispense glue dots on the semiconductor chips via a pneumatic dispenser, in order to guarantee reproducible sensor response.

All copper parts of detector (frame, columns, etc.) are cleaned by TECM technique for radio-purity requirements. The TECM cleaning consists in a sequence of different step of surface treatments: Tumbling Electopolishing, Chemical etching and Magnetron plasma cleaning.

3 CUORE cryostat

CUORE towers will be housed in a dedicated custom-built cryogenic free dilution refrigerator [4], that must satisfy the following requirements:

2017 JINST 12 C02055

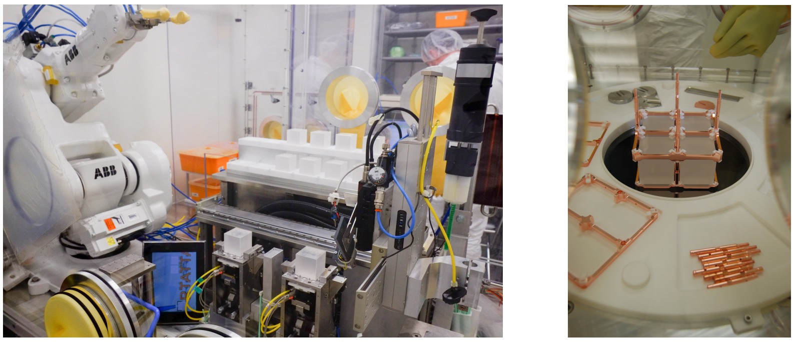


Figure 3. On the left the gluing box. On the right the tower box. Both of them are under nitrogen atmosphere to minimize radioactive re-contamination.

- reaching base temperature of 10 mk;
- the cooling power of the refrigerator will have to account for the thermal load produced by the $\sim$ 2600 read-out wires running from room temperature to 10 mK;
- mechanical decoupling between detector and cryogenic system to minimize the noise induced by cryostat vibrations;
- stringent radio-purity control on the cryostat components and properly shielding to reduce the background coming from natural radioactivity;
- since CUORE is expected to collected data for a period of five years, the cryogenic system must be stable, service-free and capable to operate with high duty-cycle.

The CUORE cryostat consists of six copper vessels thermalized to different temperature stages (see figure 4): 300 K, 40 K, 4 K, 600 mK (Still plate), 50 mK and 10 mK (Mixing chamber plate). The 40 K stage is an intermediate radiation shield between the Outer Vacuum Chamber (OVC) thermalized to room temperature and the Inner Vacuum Chamber (IVC) thermalized to the 4 K temperature. The 40 K and 4 K vessels are wrapped by in multi-layer insulation (MLI) to reduce the heating from thermal radiation. The amount of MLI is limited by radioactivity constraints.

The copper is chosen in order to preserve the radio-purity requirement in the rare event search.

The CUORE cryogenic system is a dilution unit refrigerator pulse-tube assisted:

1. the temperature of 4 K is reached by five two-stage pulse tubes (PT) coolers mounted on the room temperature OVC top flange. The total cooling power of the five pulse-tubes are 200 W at 40 K and 7.5 W at 4 K.
2. the base temperature is reached by ^{3}He/^{4}He custom dilution unit designed by Leiden Cryogenics (DU). It is capable to circulate more than 8 mmoles/s of ^{3}He/^{4}He mixture in order to guarantee high cooling power, that is 2 mW at 100 mK and 4 μW to 10 mK.

The choice of PT arise from the fact that, unlike conventional cryogen based dilution unit, the PT based dilution refrigerator does not require frequent interruption for replenishing the cryogen, thus prolonging the live time of the experiment.

2017 JINST 12 C02055

Inside the cryostat there are two additional lead shields to protect the detector from environmental radioactivity and from contamination in the building materials. There is 2.5 tons lead shield on the tower support plate thermalized to 50 mK and there is 4.5 tons of Ancient Roman shield[1] thermalized to 4 K to protected the detector from the contamination of the cyostat itself. The whole cryogenic structure is shielded by an external modern lead shield.

The CUORE cryostat used the fast cooling system (FCS), to reach the temperature of 4 K from room temperature. The FCS used a closed loop cycle to have forced convection of cold gas in the IVC. The total mass to be cooled at 4 K is about 15 tons. The pulse tubes alone will take about five months to cool down this mass, instead with the FCS the cool down period is reduced to three weeks. The detector calibration system (DCS) consists of 12 Kevlar string and 25 Teflon-coated copper capsules for string, which contain small thoriated tungsten wire. Each source string is wound-up on a spool that is connected to a motor on the top of the cryostat, which turns the spool to raise and lower the source string.

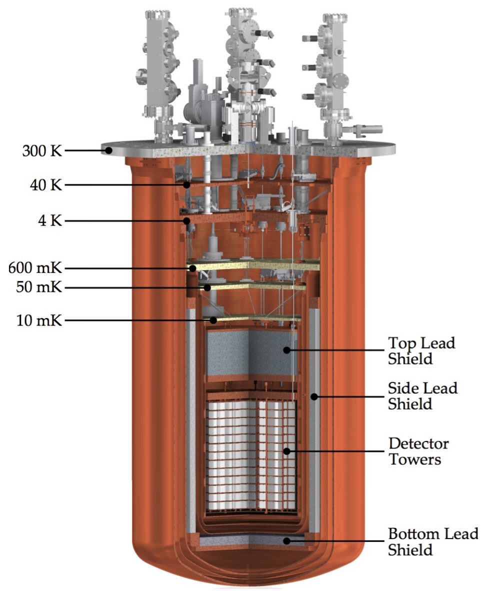


Figure 4. The CUORE cryostat on the right.

Before the detector installation, there where several cold runs to test the DU performance and to study the thermal load introduced by the different cryogenic system components (wiring, shielding, DCS, FCS, . . .). In the last commissioning run the whole system without the detector reached a base temperature of (6.3 ± 0.04) mK in stable condition.

In the last cold run also a mini-tower, composed by 8 TeO_2 crystal,was inserted into the cryostat to test the bolometric performance, the DAQ system and the calibration system. In figure 5 the energy spectrum obtained by mini-tower is shown. The reached energy resolution of mini-tower bolometers is 10 keV.

[1]It is from a ship that sunk between 50 and 80 B.C. off the coast of Sardinia.

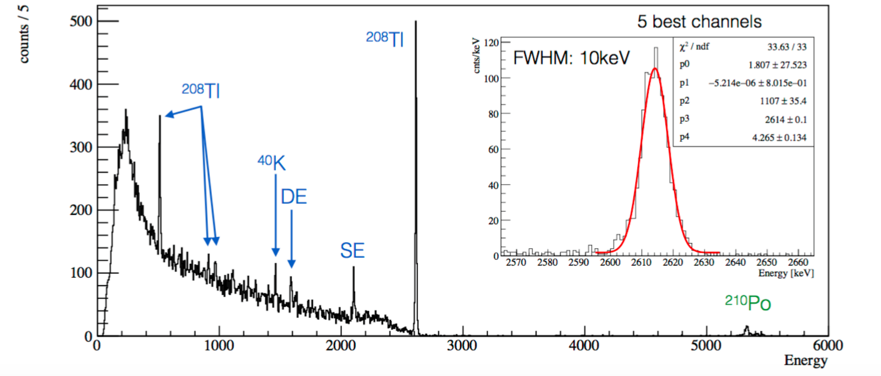


Figure 5. Background energy spectrum and energy resolution obtained by mini-tower on the left.

4 CUORE-0 experiment

CUORE-0 is an array of 52 TeO_2 crystals disposed in the CUORE tower style. The total mass is 39 kg of TeO_2. It is the first tower produced using CUORE low-background assembly line.

On the contrary of CUORE towers, CUORE-0 was surrounded by a lateral copper shield and it was cooled by a commercial cryostat. CUORE-0 was operated between 2013 and 2015 as CUORE prototype in order to:

- test the validity of bolometric technique for $0\nu\beta\beta$ search;
- test the CUORE DAQ and analysis framework;
- test and debug of the CUORE tower assembly line;
- check the background reduction thanks to the assembly line designed for CUORE towers.

4.1 CUORE-0 detector performance

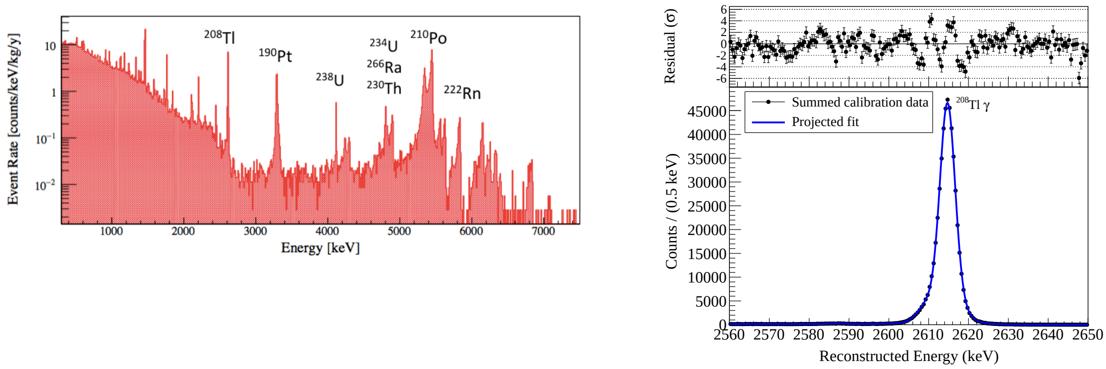
The background rate measured by CUORE-0 is $0.058\pm0.004(\text{stat})\pm0.002(\text{syst})$ count/(keV·kg·yr), in the ROI. In figure 6a the background spectrum is shown, two principal components are present:

- *gamma background*: multi Compton event originated from 2615 keV peak originated from a ^{232}Th contamination of cryostat itself;
- *alpha background*: ^{232}Th and ^{238}U chain contamination that comes from surface contamination of crystal and copper frame.

The γ contribution is expected be reduced in CUORE thanks to the roman lead shield and radio-purity control on the cryogenic system components.

The energy resolution is an important parameters in the $0\nu\beta\beta$ search because it determines the power to discriminate the $0\nu\beta\beta$ peak from the background.

The energy resolution has been evaluated on ^{208}Tl photo-peak (2615 keV) because it is the closest high-statistic signal to the ROI (2527.515 keV). The effective mean FWHM value in CUORE-0 is 4.9 keV (see figure 6b), so the CUORE goal of 5 keV is successfully reached.



(a) **(b)**

Figure 6. On the left the background energy spectrum: the 2615 keV given by cryostat contamination, and the flat α continuous background given. On the right CUORE bolometer energy resolution estimated on the 2615 peak, the average energy resolution is 4.9 keV [5].

4.2 Search of neutrino-less double beta decay by ^{130}Te

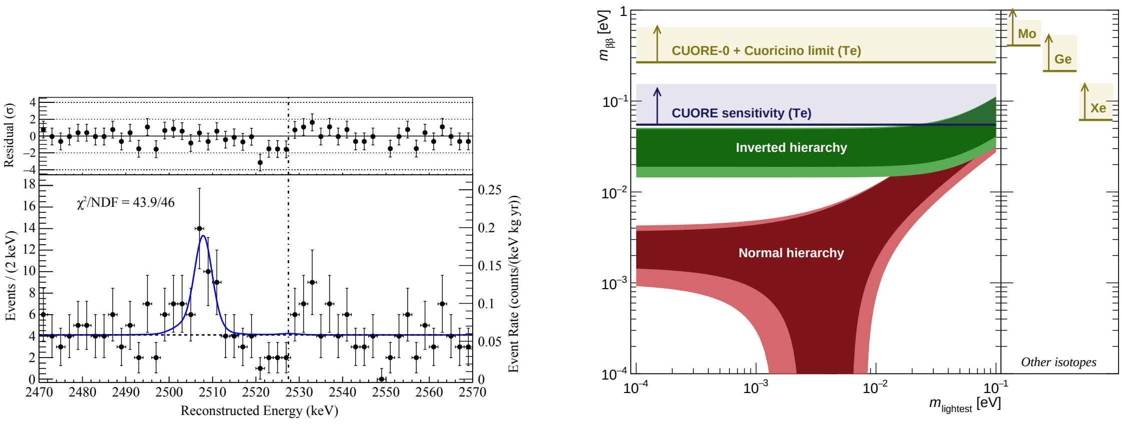
CUORE-0 sets a good limit on the half-life of $0\nu\beta\beta$ and on effective Majorana mass. In figure 7a is shown the best-fit in the energy region of 2470–2570 keV. This energy interval contains 233 candidates in the total exposure of 35.2 kg · yr exposure of TeO_2 or in 9.8 kg · yr of ^{130}Te considering the natural abundance 34.167%. The fit parameters are: signal peak fixed at $Q_{\beta\beta}$ of TeO_2, the double peak at ∼ 2507 keV of ^{60}Co (product of copper cosmogenic activation); continuous background given by ^{208}Tl peak and degraded alphas. The upper limit on half-life at 90% C.L. is $T^{0\nu}_{1/2} > 2.7 \times 10^{24}$ yr.

The limit on $T^{0\nu}_{1/2}$ can be translated into a limit on effective Majorana mass of 270–650 meV [5]. The sensitivity on $m_{\beta\beta}$ reached by CUORE-0 and the expected CUORE sensitivity are shown in figure 7b. The expected CUORE sensitivity is 9.5×10^{25} yr at 90% C.L. for five years of data-taking, given an energy resolution of 5 keV and a background level of 10^{-2} count/(keV · kg · yr). CUORE will be able to investigate a range of $m_{\beta\beta}$ of 40–100 meV [6].

5 Conclusion

CUORE-0 obtained a good bolometric performance: the 5 keV energy resolution was successfully reached and the tower assembly line designed for CUORE guarantees a low level of α contamination of copper structure.

The CUORE cryostat commissiong was concluded in March 2016 and a temperature of 6.3 mK was reached in stable condition. After that the CUORE tower installation was started and it was completed by the summer 2016.



(a) **(b)**

Figure 7. On the left the best-fit in the CUORE ROI. On the right the CUORE-0/CUORE sensitivity on effective Majorana mass.

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