PROCEEDINGS OF SCIENCE

CUORE

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Physicists have searched for Neutrinoless Double Beta Decay (0νββ) for about a half a century. Developed over the latest 20 years, the bolometric technique is today used by one of the most competitive experimentsin the field: CUORE, a ton-size detector aiming for a sensitivity of ~10^{26} yr on ^{130}Te 0νββ decay half-life. With the final step of its construction nearly completed, CUORE will start its operation by the end of the current year. Meanwhile, the first CUORE-like tower is operated at Laboratori Nazionali del Gran Sasso as an independent 0νββ experiment. Named CUORE-0, it represents the state of the art for large-mass, low-background, ultra-low-temperature bolometer arrays. Besides being a competitive 0νββ decay search, it has validated the ultraclean assembly techniques and radiopurity of materials for the upcoming CUORE experiment.

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1. Introduction

The Double Beta (ββ) decay is a transition in which an (A,~Z) nucleus transforms into its (A,~Z+2) isobar. The interest in ββ decay detection stands in the possibility that the transition goes through a channel in which no neutrinos are emitted, being one of the most powerful probe of Lepton Number non conservation. The Neutrinoless Double Beta (0νββ) decay is possible only if the neutrino is a massive Majorana particle and it appears today the only experimentally viable test of this hypothesis. If the 0νββ decay exists, its half-life is proportional to the square of the Majorana mass of neutrino, defined as $m_{ee}=|\sum U_{ei}^2 m_i|$ (where U_{ei} are the elements of the PNMS matrix and m_i are the three neutrino mass eigenstates). 0νββ searches probe therefore the neutrino mass hierarchy and their absolute mass scale [1].

The 0νββ decay is detected measuring the monochromatic energy deposition of the two electrons emitted in the decay: given the negligible energy of the recoiling nucleus the sum kinetic energy of the two electrons (E_{ee}) is equal to the Q-value of the ββ transition ($Q_{\beta\beta}$). The competing process of Two Neutrino Double Beta decay (2νββ) is on the other hand characterized by a continuum spectrum for E_{ee}. Events occurring near the end-point produce an irreducible background for the 0νββ decay signal spoiling the sensitivity of the experiment. This effect can either be mitigated with a careful choice of the candidate isotope or drastically reduced with the use of high resolution devices: germanium diodes, bolometers and few more.

Depending on the detector type and on the set-up features, other characteristic information of the process can be used to distinguish a 0νββ decay event from a background event (induced by radioactivity or cosmic ray interactions) of the same energy. The real challenge of any 0νββ decay experiment is to be able to control and reduce - ideally to zero - these sources.

Thanks to their high energy resolution (that allow to get rid of the irreducible background due to 2νββ decay), their mass scalability and their flexibility in the choice of the ββ decaying isotope (since this is contained in the molecule of the detector material and a wide choice of materials can be used) bolometers are today considered one of the the most powerful devices for the study of 0νββ decay. A number of successful experiments have been realized over the last 20 years using TeO_2 bolometers [2,3,4]. ^{130}Te, with a natural isotopic abundance of about 34%, is amongst the best candidate for 0νββ studies, the key points being its high $Q_{\beta\beta}$ (~2528 keV) and the not mandatory enrichment. The mentioned bolometric experiments, as it will be for CUORE [4], have been realized in the underground hall A of Laboratori Nazionali del Gran Sasso (L'Aquila, Italy) where cosmic ray flux is strongly suppressed. They have achieved a continuous improvement in mass, energy resolution, background level and ultimately in the 0νββ sensitivity. CUORE is the next step in this evolution toward largest scale experiments. With a completely new infrastructure conceived on a yearly experience in the field, CUORE will likely be the starting point of a new phase for 0νββ decay searches with bolometers. Indeed, as discussed at the end of this paper, a number of newly developed techniques are becoming available to exploit the CUORE facility with upgraded detectors that hopefully will allow to realize a *background free* experiment, where the sensitivity will be determined only by the exposure.

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2. The CUORE project

The CUORE project [4] foresees the realization of a 0νββ decay experiment with an active mass of the order of 1 ton. CUORE will employ 988 natural TeO_2 bolometers, each made of a cubic crystal (5 cm on the side and 750 g in mass). The goal is to reach, in the energy region of interest (ROI), a background level lower than 10^{-2} counts/(keV·kg·yr) and a FWHM energy resolution of ~5 keV. With this figure of merit, the sensitivity on the 0νββ decay of ^{130}Te will be of the order of 10^{26} yr ($9.5 \cdot 10^{25}$ yr at 90% C.L. in 5 yr exposure).

The CUORE array is designed to have a compact structure, minimizing the distance between the crystals and the amount of inert material interposed in-between them. This will exploit one of the most powerful characteristics of the experiment: background reduction by anticoincidence operation. Indeed, while a 0νββ decay in ~90% of cases involves only one bolometer (producing a *single-hit* signal), most background events that are induced by radioactive contaminations (and seldom by cosmic rays interactions) are very likely *multi-hit* signals (more than one bolometer records an energy deposition), therefore they can be identified and rejected by coincidence studies.

The 988 TeO_2 bolometers of the array are held in an ultra-pure copper frame by polytetrafluoroethylene (PTFE) supports and arranged in 19 towers each with 13 floors, with 4 crystals per floor. Each crystal is instrumented with a neutron-transmutation-doped Ge thermistor to record thermal pulses and a silicon resistor to generate reference pulses. The entire array, surrounded by a 6 cm thick lead shield, will be operated at about 10 mK in a He^3/He^4 dilution refrigerator specially designed and constructed for CUORE. A further thickness of 30 cm of low activity lead will be used to shield the array from the dilution unit of the refrigerator and from the environmental radioactivity. A borated polyethylene shield and an air-tight cage will surround externally the cryostat.

At the time of writing all the 19 towers of CUORE - fully assembled - are stored underground, the dilution refrigerator is in the final phase of its commissioning while the infrastructure (hut, external shields …) is almost completed. Tower installation in the refrigerator is forseen for the end of 2015.

3. From Cuoricino to CUORE

The strategy of the CUORE project is based on the experience collected over the years in the operation of - increasingly in mass - bolometric arrays. The more recent was Cuoricino [3], an array of 62 detectors (40.7 kg of total mass) of TeO_2 operated between 2003 and 2008 in the Oxford Instruments low temperature refrigerator of Hall A at LNGS. With an exposure of ~20 kg(^{130}Te)·yr Cuoricino set a lower limit on the ^{130}Te half-life of $2.8 \cdot 10^{24}$ y at 90% C.L. More relevant for the CUORE project, Cuoricino was the test bench for the construction of large scale bolometric arrays, providing a number of information about detector performances and background sources that have formed the basis for the design of the CUORE detector.

Indeed, to ensure the achievement of the CUORE target sensitivity, the increase in the isotope mass, from the 11.3 kg(^{130}Te) of Cuoricino to the 206 kg(^{130}Te) of CUORE is not enough. Both the detector performances and the background level need to be improved. In numbers, this is translated in a design FWHM energy resolution of 5 keV at $Q_{\beta\beta}$ over the 988 bolometers (in Cuoricino the energy resolution was ~7 keV) and a reduction of the background level in the ROI from the (0.153 ± 0.006) counts/(keV·kg·yr) measured by Cuoricino to the 10^{-2}

counts/(keV·kg·yr) forseen for CUORE. This implied an intense R&D program pursued over the last decade and concluded with the construction of the first CUORE tower: CUORE-0.

One of the challenges in CUORE construction was the realization of a detector assembly chain able to ensure reliability and reproducibility over large number of bolometers, with the additional complexity of respecting all the constraints coming from radioactivity control [5].

The background reduction effort was even more challenging [6,7]. On one side, highly radiopure materials were selected for all the elements used in the construction (detectors cryostat, shields …). For each of them a protocol for surface cleaning and for component handling during construction was developed. On the other, specific actions were defined for the mitigation and reduction of the main sources responsible of the Cuoricino background counting rate in the ROI. These sources are:

- a ^{232}Th contamination localized in the Cuoricino cryostat thermal shields. This is an irreducible background source for any detector operated in the same set-up but an avoidable problem in CUORE, thanks to strict requirements on the radiopurity of the materials used in the construction and instrumentation of the new refrigerator;
- a surface contamination of the TeO_2 crystals and/or the mechanical structure holding the detectors (mainly made of copper) in ^{232}Th and ^{238}U progenies. This contamination is particularly pernicious since has a specific activity well below the detectable limits of the standard techniques for contaminant measurements (from γ or α spectroscopy with solid state devices to NAA or ICPMS).

Specific markers for these two sources are the ^{208}Tl peak at 2615 keV clearly visible in Cuoricino bolometer spectra and the flat counting rate recorded by the detectors above this same line. The 2615 keV is the highest energy (intense) γ line due to environmental radioactivity (i.e. the dominant source of γ background in underground experiments). Multi Compton events induced by this photon can populate the ROI producing events that mimic a $0\nu\beta\beta$ decay. In Cuoricino about 30% of the ROI counting rate is ascribed to this source that Monte Carlo simulations localize in the cryostat thermal shields. The residual 70% of the events recorded in the ROI is ascribed to the same process that populates the energy region immediately above the 2615 keV peak, namely to degraded α particles. ^{232}Th and ^{238}U contamination in the TeO_2 crystal surfaces or in the materials directly facing the crystals[2] produce - in their decays - α particles with energies between 4 and 7 MeV. When the α particle deposits only a fraction of its energy in the crystal - either because the decay originated in a facing material or in a nearby crystal - it contributes to the background below 4 MeV. Such contribution can extend down to the lowest energies and certainly in the ROI.

Special surface treatments of both holder copper elements and TeO_2 crystals were developed by the CUORE collaboration to get rid of the latter source of background and specific bolometric tests with small crystals arrays have been pursued to validate these techniques [6,7]. However the final answer on the achievement of this important goal could come only from a long run with a Cuoricino-size tower.

[2]The array is held in vacuum and bolometers are fully active i.e. they do not have any dead layer at their surface. Crystal surface contamination can be identified and rejected by coincidence analysis (since they produce double hit events). Therefore the most pernicious source is the contamination of the holder.

4. CUORE-0

CUORE-0 is a single CUORE-like tower built using the low-background assembly techniques developed for CUORE. The tower is deployed in Hall A of LNGS. The cryogenic system, shielding configuration, and front-end electronics are the same used for Cuoricino. The purpose of CUORE-0 is to prove that all CUORE requirements concerning detector performances and background level are fulfilled. Moreover, despite the mentioned ^{232}Th contamination of the Cuoricino cryostat, the improvements on background counting rate make CUORE-0 a competitive 0νββ decay experiment [8].

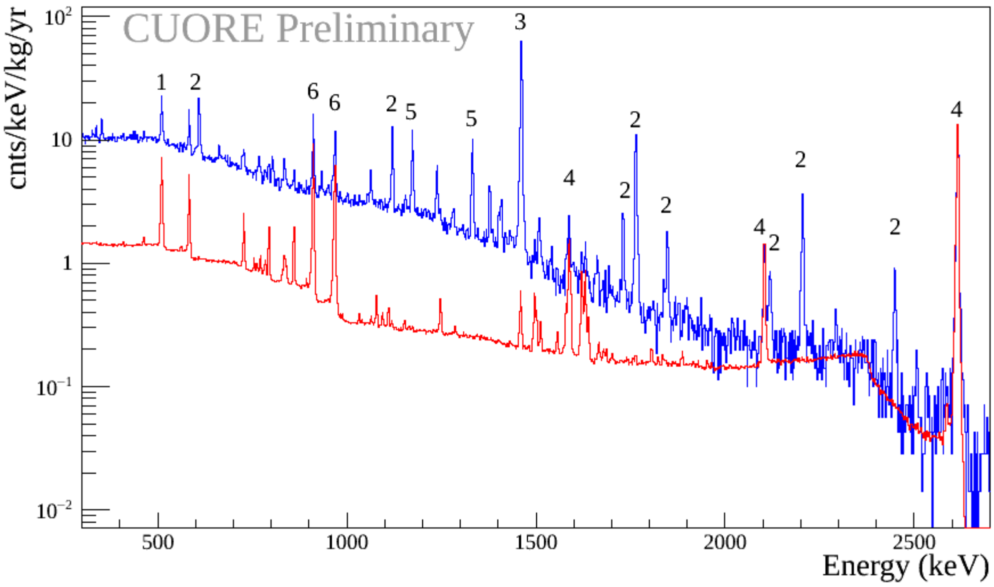

Figure 1: CUORE-0 energy spectra measured in calibration (red) and physics (blue) data. The calibration is normalized to have the same intensity at the 2615 keV peak. The labeled lines are identified as follows: (1) e+ e− annihilation, (2) ^{214}Bi, (3) ^{40}K, (4) ^{208}Tl, (5) ^{60}Co, and (6) ^{228}Ac. ^{214}Bi is the most intense γ emitter in the ^{238}U while ^{208}Tl and ^{228}Ac are the most intense in the ^{232}Th chain.

The characteristic energy resolution measured with CUORE-0 detectors is 5.1 ± 0.3 keV FWHM demonstrating the achievement of CUORE goal for what regards detector performances.

Similarly succesfull are the results on background reduction. Figure 1 shows the comparison between physics data (corresponding to 32.5 kg·yr exposure) and calibration data coming from the periodic exposure of the detectors to a ^{232}Th source (this is a tungsten thoriated wire periodically deployed in between the external lead shield and the cryostat). The ^{232}Th source produce an energy spectrum that is very similar to the one predicted by Monte Carlo simulations for the contamination of the thermal shields of the cryostat. As it can be appreciated by the plot, once normalized to have the same intensity at 2615 keV the two spectra exhibit a very similar counting rate also at lower energies (i.e. from the 2615 keV line down to its Compton edge) which provides a further evidence that the counting rate in the ROI is higly influenced by the ^{232}Th activity.

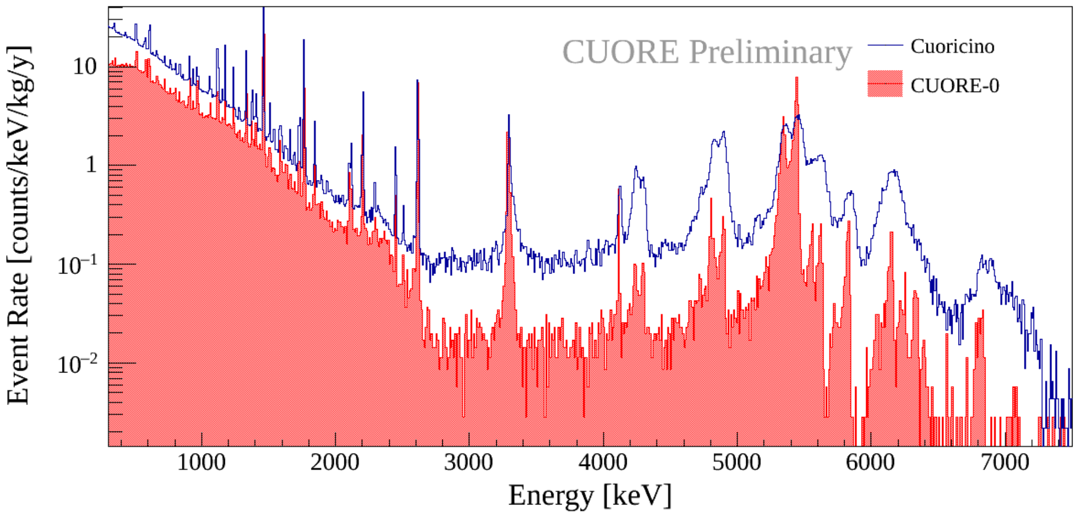

Figure 2: Comparison of the energy spectra of physics data collected in Cuoricino (blu line) and CUORE-0 (red filled histogram).

Fig. 2 shows a comparison of the energy spectra of physics data collected in Cuoricino and CUORE-0. An overall decrease of the background counting rate is observed, with a major effect above 3 MeV. Here the flat continumm, that the Cuoricino background model ascribes to degraded α particles, is reduced by a factor ~6. This improvement is attributed to the surface cleaning protocols adopted in CUORE-0 for crystals and for the copper holder.

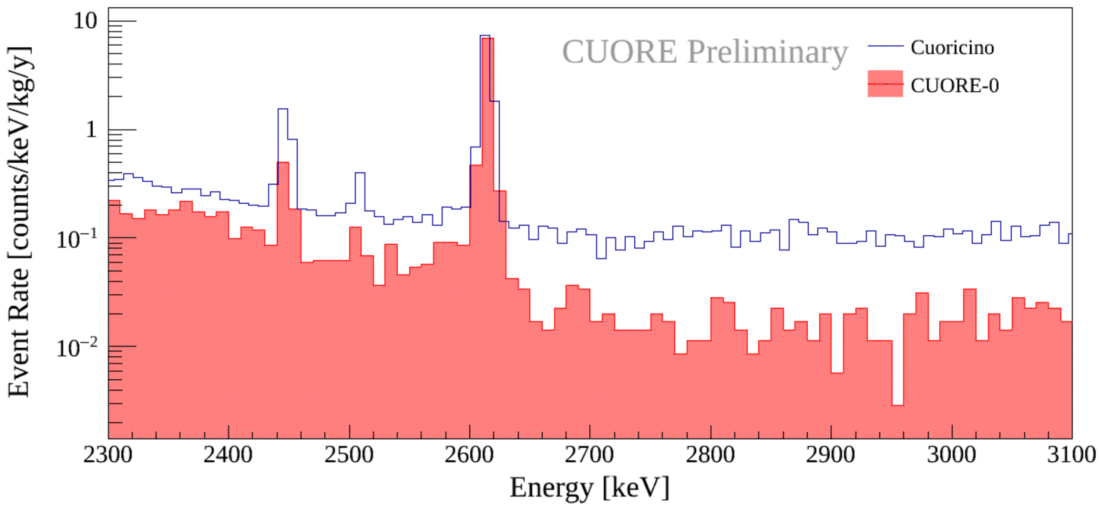

Figure 3: Zoom of the spectra shown in Figure 2 in the energy region across the ^{208}Tl peak.

The α peaks appearing between 4 and 7 MeV, besides being narrower thanks to the improved energy resolution and calibration procedure[3], exhibit a similar reduction. CUORE-0 counting rate in the ROI (i.e. in the region just below the ^{208}Tl line) is 0.058 ± 0.004 (stat.) ± 0.002 (syst.) c/(keV·kg·yr) therefore reduced by a factor ~2.6 with respect to Cuoricino.

It is clear from Figure 3 that two contributions are present: the flat background visible on the right-hand side of the 2615 keV peak (ascribed - following Cuoricino experience - to

[3]Energy non linearities influence the widths of the α peaks because the calibration of this energy region is extrapolated from that obtained at lower energies using the γ lines of the ^{232}Th source.

degraded α particles) and the additional background responsible of the *knee* observed when crossing (toward the left-hand side) the ^{208}Tl line. The latter contribution is that already discussed and due to multi Compton events. This same *knee* is not appreciated in Cuoricino data, since there degraded α particles produced a dominant contribution on both sides of the ^{208}Tl peak.

The demonstrated reduction of detector surface radioactivity, once scaled to the CUORE geometry (where anticoincidences are more efficient in reducing the effects of crystal surface contaminations and the amount of copper faced by crystals is reduced) is exactly what needed to prove the achievement of CUORE requirement on background level.

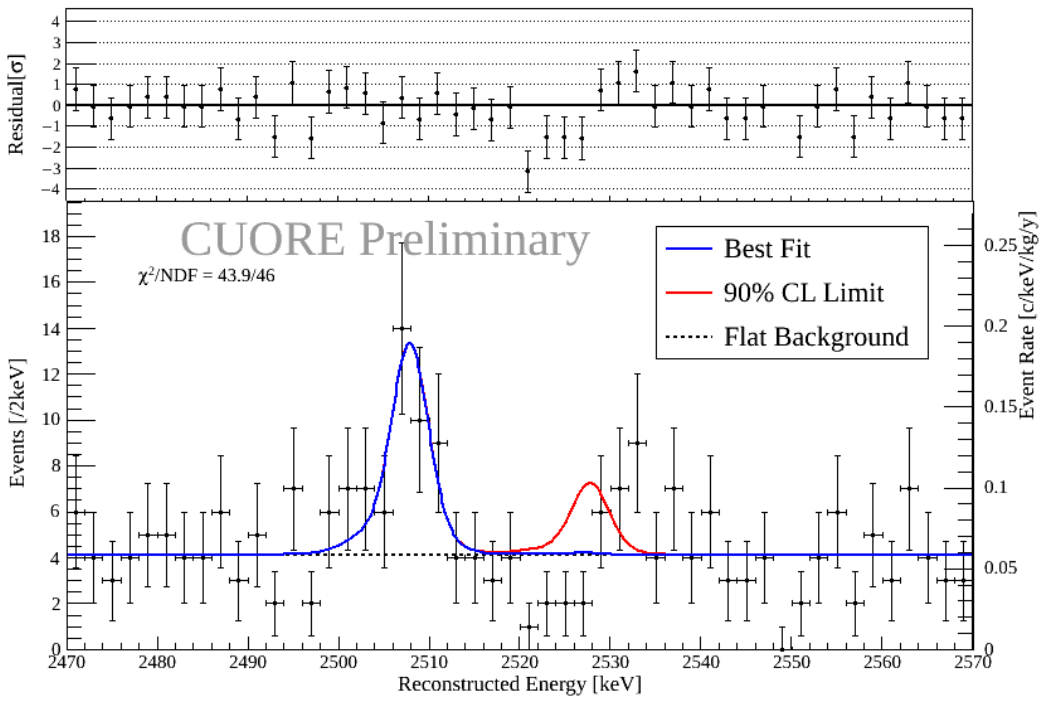

Figure 4:. Bottom: Energy spectrum of 0νββ decay candidates in CUORE-0 (data points) and the best-fit model from the unbinned maximum likelihood analysis (solid blue line). The peak at ∼2507 keV is attributed to ^{60}Co; the dotted black line shows the continuum background component of the best-fit model. The red line is the 0νββ peak that would correspond to the 90% C.L. limit. Top: The normalized residuals of the best-fit model and the binned data.

Unblinded after Neutrino Telescope conference, CUORE-0 data showed no evidence of 0νββ decay peak in the ROI (Figure 4). Here are the preliminary results, presently under publication [8]. With a total exposure of 9.8 kg(^{130}Te)·yr the median 90 % C.L. lower-limit sensitivity of the experiment is 2.9×10^{24} yr and surpasses the sensitivity of previous searches. The Bayesian lower bound on the decay half-life, is $T_{1/2}^{0\nu} > 2.7 \times 10^{24}$ yr at 90 % C.L. Combining CUORE-0 data with the 19.75 kg(^{130}Te)·yr exposure from the Cuoricino experiment we obtain $T_{1/2}^{0\nu} > 4.0 \times 10^{24}$ yr at 90 % C.L. (Bayesian), the most stringent limit to date on this half-life [8].

5. Beyond CUORE

The CUORE project has considered since its very first proposal the possibility of using the same infrastructure with different detectors, either to study a different physics or simply to upgrade the ββ detectors to a new design capable of enabling a more sensitive research.

Today the future of the CUORE infrastructure is being discussed [9] and while details and collaboration have still to be defined the evolution path is rather clear: exploit an improved technology able to provide additional tools for background suppression and meanwhile maximizing the number of 0νββ decay candidates. A viable and not excessively expensive isotopic enrichment, a high $Q_{\beta\beta}$ and the existence of easily grown, radiopure crystals instrumentable as bolometer are among the factors that are taken in consideration for isotope choice. Active background suppression based on particle identification or interaction localization are on the other hand the features required for the new bolometer technology.

With this constrains a few isotopes look extremely promising: ^{130}Te, ^{100}Mo, ^{82}Se and ^{116}Cd. With all of them except Te, scintillating crystals can be efficiently grown and operated as scintillating bolometers, devices where particle identification is based on the different light yield of α particles with respect to β/γ ones. In the case of Te, the read-out of the Cerenkov light is one of the possible solutions for the rejection of α induced background.

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