Status of CUORE: an observatory for neutrinoless double beta decay and other rare events

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CUORE is a ton-scale neutrinoless double beta decay ($0\nu\beta\beta$) experiment based on TeO_2 cryogenic detectors that is in the last construction stage at the Laboratori Nazionali del Gran Sasso. Its primary goal is to observe $0\nu\beta\beta$ of ^{130}Te, with a projected sensitivity reaching the inverted hierarchy region of the neutrino mass. Thanks to the ultra-low background and large projected exposure, CUORE is suitable to other rare event searches, as solar axions or dark matter direct detection. CUORE-0, a single-tower prototype recently concluded, has served as a proof-of-concept of the CUORE technology. We present the final CUORE-0 results on $0\nu\beta\beta$ and discuss the status and the physics potential of CUORE on different rare event searches.

1 Introduction

CUORE (Cryogenic Underground Observatory for Rare Events) [1, 2] is a ton-scale experiment whose primary goal is to observe neutrinoless double beta decay ($0\nu\beta\beta$) of ^{130}Te using a large array of TeO_2 cryogenic detectors. This decay [3] is a second-order lepton number violating process in which a nucleus (A,Z) transforms into (A,Z+2) with the simultaneous emission of two electrons, that can occur only if the neutrino is a Majorana particle. Its observation would not only prove the neutrino nature (Dirac or Majorana) and confirm lepton number violation, but it could also assess the absolute neutrino mass scale. In CUORE, a TeO_2 crystal is simultaneously the source of the decay and the detector that measures the energy deposited by the two electrons, which results in a peak centered at the transition energy $Q_{\beta\beta}$ (around 2528 keV for ^{130}Te). The CUORE technology was proven by Cuoricino, that with 40 kg of TeO_2 and 19.75 kg×yr of ^{130}Te exposure set a lower limit to the $0\nu\beta\beta$ half-life of 2.8×10^{24} yr (90% C.L.) [4]. It also revealed that the background in the region of interest (RoI) around $Q_{\beta\beta}$ was dominated by surface contaminations in the crystals and near surfaces (mainly the copper structures that hold the crystals). Therefore, for CUORE we implemented very strict protocols for the materials cleaning and assembly. The first tower constructed according to the new standard CUORE procedures was operated in the Cuoricino cryostat as an independent experiment called CUORE-0, and served not only as proof-of-concept of the complete CUORE cleaning and assembling line, but was a $0\nu\beta\beta$ search on its own.
CUORE is currently in the last phase of construction at Laboratori Nazionali del Gran Sasso

(LNGS), in Italy, and is expected to start operations by the end of 2016. With its ultra-low background ton mass, it could also serve as an observatory for other rare searches like solar axions and dark matter (DM).
In the following we report on the CUORE-0 results (Sec. 2), we revise the CUORE physics potential on axions and dark matter searches (Sec. 3) and finally we give an update on CUORE status (Sec. 4).

2 CUORE-0 results

CUORE-0 is an array of 52 TeO_2 crystals of 750 g each, for a total mass of 39 kg (11 kg of ^{130}Te). It was operated in the same experimental setup that hosted Cuoricino, at LNGS, from March 2013 to March 2015 for a total exposure of 35.2 kg×yr. A complete description of the detector construction and experimental details can be found in [5].
The success of the new cleaning procedures was soon evidenced in the background spectrum (see it compared with the Cuoricino one in Fig. 1, left). The γ component, that is the major part of the background below 2615 keV, originates in the cryostat and so it is practically the same for both experiments. Above that energy, background is dominated by degraded α decays coming from surfaces near the detector. We measured the rate in the α region (evaluated from 2700 keV to 3900 keV, excluding the ^{190}Pt α line coming from a bulk contamination in the crystals) to be 0.016±0.001 counts/(keV×kg×yr). That means a factor of 6.8 improvement over Cuoricino. The energy resolution, evaluated on the ^{208}Tl line at 2615 keV during calibration runs with ^{232}Th source, was 4.9 keV FWHM.

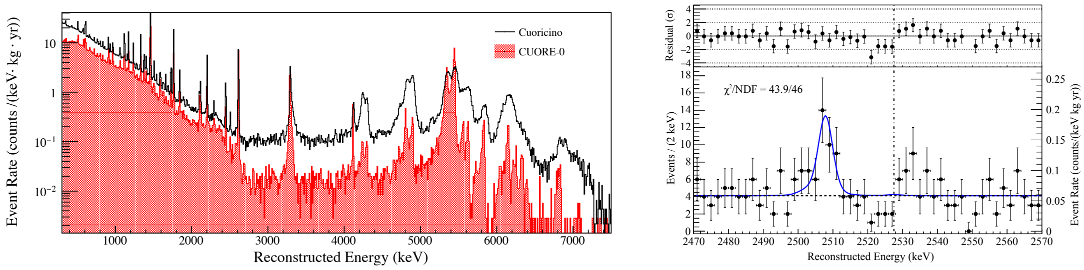

Figure 1: Left: CUORE-0 (red histogram) and Cuoricino (black line) backgrounds. The γ component, below 2615 keV, is originated in the cryostat, the same for both experiments, while there is a strong reduction in the α component above this energy. Right: CUORE-0 data and the best fit model (solid blue line) in the RoI. The normalized residuals are shown above. The peak at 2507 keV is due to ^{60}Co and the dash-dotted line indicates the $Q_{\beta\beta}$.

We kept the CUORE-0 RoI blinded until the sensitivity surpassed the Cuoricino one. Then, after fixing the data selection cuts and the $0\nu\beta\beta$ analysis procedure, we unblinded the RoI and performed an unbinned extended maximum likelihood fit. The final results can be found in [6] and a detailed revision of the analysis procedures in [7]. The result is displayed in the right panel of Fig. 1: There is no excess of events in the RoI, and our best fit limit on the $0\nu\beta\beta$ half-life of ^{130}Te is $T_{1/2} > 2.7\times10^{24}$ yr at 90% C.L. This is consistent with our median expected 90% C.L. sensitivity of 2.9×10^{24} yr. Combining this result with that of Cuoricino, we obtain the best limit up to now for ^{130}Te: $T_{1/2} > 4.0\times10^{24}$ yr at 90% C.L. Using recent nuclear matrix elements (NME) calculations (see [6] and references therein) this limit is converted onto an upper limit on the effective Majorana mass $m_{\beta\beta}$ <270-760 meV (see Fig. 2).

3 Other rare event searches with CUORE

Other rare event searches, like solar axions or DM direct detection, demand an energy threshold ≤10 keV. In Cuoricino, it was of the order of several tens of keV. Since then, we have done a large effort to reduce the threshold in CUORE-like crystals. In [8], we developed a new trigger based on the continuous application of the optimum filter [9] to the data stream. The filtered data has improved signal-to-noise ratio, so the trigger level can be notably decreased. This procedure was applied to one of the test runs that were performed on the CUORE crystals in order to asses their background and performances [10], carried out in an R&D cryostat not specially design for low background measurements. The result was 3 keV threshold in 3 over 4 crystals and a background at low energy ranging from 25 counts/(keV×kg×day) at 3 keV to 2 counts/(keV×kg×day) at 25 keV, with a peak of unknown origin at 4.7 keV [11].

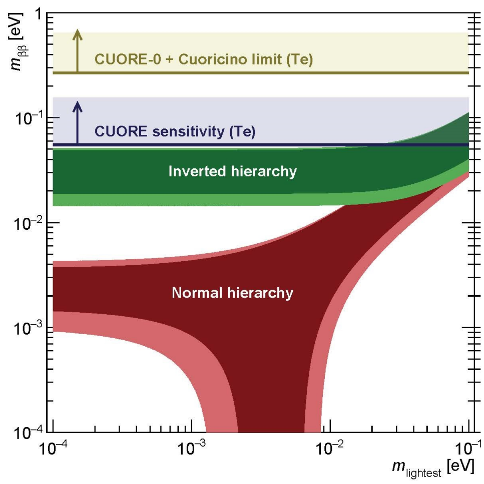

Figure 2: Allowed regions for the effective Majorana neutrino mass for the normal and inverted hierarchies, CUORE-0+Cuoricino 90% limit and expected CUORE 90% sensitivity (5 years live time).

TeO_2 is not a scintillator, so it is not possible to reduce background by electron vs nuclear recoil event-by-event discrimination based on the different light yield, but annual modulation analysis is possible thanks to the large exposure and projected stable condition over at least 5 years of data-taking. The projection of the measured background and threshold to the exposure of the whole experiment [11] indicates that CUORE could explore the parameter region pointed out by the positive result of the DAMA experiment [12]. CUORE could also look for solar axions through the Primakoff effect in the electric field of the crystal. We envisage two detection strategies: to search for the 14.4 keV peak coming from the iron M1 line [13], and to use the coherent Primakoff conversion that appears when the incident angle of the axion flux with respect to the crystalline plane fulfils the Bragg condition as the Earth rotates, producing a variable counting rate. CUORE prospects for both strategies can be found in [14] and [15] respectively. Currently we are working on the analysis of CUORE-0 data with the optimum trigger. Preliminary results [16] indicate a background in the low energy region of about 1-2 counts/(keV×kg×day) and thresholds of the order of 10-20 keV.

4 CUORE status and prospects

CUORE is currently in the last stage of construction at LNGS. The cryostat commissioning was completed on March 2016. The 19 towers, that were assembled and instrumented by 2014 and since then stored underground inside nitrogen flushed bags, have been installed in the cryostat in August 2016, so we hope CUORE to start operations by the end 2016. The background reduction measured in CUORE-0 demonstrates the validity of our cleaning procedures. Thanks to the closed-packed structure of CUORE with respect to CUORE-0, our background models predict that the 0.01 counts/(keV×kg×yr) background goal in the RoI is within reach. This corresponds to a sensitivity of 9.5×10^{25} yr at 90% C.L. in 5 years, and a range in $m_{\beta\beta}$ of 50-130 meV (see Fig. 2). CUORE could also look for solar axions and explore the parameter region pointed out by the DAMA positive annual modulation signal.

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