New CUORICINO Results and Status of CUORE[*]

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Abstract—CUORICINO is an array of 62 TeO_2 bolometers with a total mass of 40.7 kg (11.2 kg of ^{130}Te), operated at about 10 mK to search for $\beta\beta(0\nu)$ of ^{130}Te. The detectors are organized as a 14-story tower and intended as a slightly modified version of one of the 19 towers of the CUORE project, a proposed tightly packed array of 988 TeO_2 bolometers (741 kg of total mass of TeO_2) for ultralow-background searches on neutrinoless double-beta decay, cold dark matter, solar axions, and rare nuclear decays. Started in April 2003 at the Laboratori Nazionali del Gran Sasso (LNGS), CUORICINO data taking was stopped in November 2003 to repair the readout wiring system of the 62 bolometers. Restarted in spring 2004, CUORICINO is presently the most sensitive running experiment on neutrinoless double-beta decay. No evidence for $\beta\beta(0\nu)$ decay has been found so far and a new lower limit, $T_{1/2}^{0\nu} \geq 1.8 \times 10^{24}$ yr (90% C.L.), is set, corresponding to $\langle m_\nu \rangle \leq 0.2-1.1$ eV, depending on the theoretical nuclear matrix elements used in the analysis. Detector performance, operational procedures, and background analysis results are reviewed. The expected performance and sensitivity of CUORE is also discussed.

1. INTRODUCTION

The existence of neutrino oscillations, well proven in recent years by the results of   neutrino oscil-

lation experiments, has stimulated great interest in neutrinoless double-beta decays. By demonstrating the finiteness of neutrino mass and mixing, neutrino oscillations have in fact provided us with the first clear evidence of phenomena beyond the reach of

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the Standard Model (SM). Other unsolved questions concerning neutrino properties have since become a subject of increasing interest and are considered a unique tool to see what new physics lies beyond SM predictions. We know in fact that neutrinos are massive, but we still ignore the absolute scale of their masses. Neutrino oscillations in fact depend only on the absolute value of the difference of the neutrino mass eigenvalues squared. Two possible hierarchies are then implied by current available data: the normal ($m_1 \approx m_2 \ll m_3$) and the inverted hierarchy ($m_1 \ll m_2 \approx m_3$).

The same ignorance holds for the neutrino nature. In the SM, neutrinos are Dirac particles by construction (i.e., in order to conserve lepton number L). In the limit of vanishing masses, however, lepton number conservation can be equivalently stated in terms of neutrino helicity properties and the Majorana or Dirac descriptions for the neutrino are equivalent (i.e., they do not change the physical content of the theory). For finite neutrino masses, however, the two descriptions are no longer equivalent and can give rise to different physical scenarios (e.g., mass generation mechanisms).

Only experiments sensitive to m_1 can aim at solving the mass hierarchy problem. This is the case for kinematic measurements of the β-spectrum end point, $\beta\beta(0\nu)$, and cosmological measurements. The sum of the masses of the neutrinos of the three flavors is constrained to values from 0.7 to 1.7 eV from the Wilkinson microwave anisotropy probe full sky microwave map together with the survey of the 2dF galaxy redshift [1−5]. A claim for a nonzero value of 0.64 eV has also been proposed [6]. Although these values are more constraining than upper limits of 2.2 eV for m_ν obtained so far in experiments on single-beta decay, they are strongly model dependent and therefore less robust with respect to laboratory measurements. On the other hand, the best sensitivity expected for next-generation single-beta decay experiments is of the order of $\sim$0.2 eV (KATRIN [7] and Re-μ bolometers [8]).

The measurement of neutrino masses, mixing angles, and phases and the assessment of the Dirac/Majorana character of neutrinos are going to be considered primary goals of the next-generation experiments. In this scenario, neutrinoless double-beta decay searches play a unique role giving the possibility to probe the Majorana character of neutrinos while obtaining information on the neutrino mass hierarchy and Majorana phases. If neutrinos are Majorana particles, more stringent constraints, or a positive value for the effective neutrino mass, can be obtained.

Double-beta decay (DBD) can occur in a number of even−even nuclei and can be experimentally studied for a consistent fraction of them for which single-beta decay to the intermediate nucleus is energetically forbidden. Its transition rate can be written as

$$\lambda_{\beta\beta}^{0\nu} = G^{0\nu}(E_0, Z)|\langle m_\nu \rangle|^2 |M_{\mathrm{F}}^{0\nu} - (g_A/g_V)^2 M_{\mathrm{GT}}^{0\nu}|^2, \tag{1}$$

where $G^{0\nu}$ is the phase-space factor, $M_{\mathrm{F}}^{0\nu}$ and $M_{\mathrm{GT}}^{0\nu}$ are the Fermi and Gamow−Teller nuclear matrix elements, and g_A and g_V are the axial-vector and vector weak coupling constants. $\langle m_\nu \rangle$ is the effective Majorana electron neutrino mass, which can be expressed in terms of the elements of the neutrino mixing matrix as follows:

$$\langle m_\nu \rangle \equiv |U_{e1}^L|^2 m_1 + |U_{e2}^L|^2 m_2 e^{i\phi_2} + |U_{e3}^L|^2 m_3 e^{i\phi_3}, \tag{2}$$

where $e^{i\phi_2}$ and $e^{i\phi_3}$ are the Majorana CP phases (± 1 for CP conservation), $m_{1,2,3}$ are the Majorana neutrino mass eigenvalues, and the coefficients U_{ej}^L are the elements of the first row of the Pontecorvo−Maki−Nakagawa−Sakata (PMNS) neutrino mixing matrix. Taking into account the results of all oscillation experiments [9−18], we have then

$$|\langle m_\nu \rangle| = |(0.70 \pm 0.030)m_1 \tag{3}$$
$$+ (0.30 \pm 0.030)m_2 e^{i\phi_2} + (<0.05)m_3 e^{i\phi_3}|,$$

which, in the case of the inverted hierarchy, implies that $|\langle m_\nu \rangle|$ could have a minimum value as large as 0.055 eV. This is a very important result for $\beta\beta(0\nu)$ since it implies that next-generation experiments could have the required sensitivity to probe the inverted mass hierarchy.

Equation (1) for the $\beta\beta(0\nu)$ rate implies an explicit dependence on the square of the nuclear matrix elements whose calculation is still quite uncertain. This is one of the most severe problems in $\beta\beta(0\nu)$ result interpretation. As a consequence, it is imperative to search for $\beta\beta(0\nu)$ in different nuclei. Another reason for this request is an intrinsic weakness of the $\beta\beta(0\nu)$ signature in the calorimetric approach: in fact, the sharp line at the transition energy could in principle be mimicked by a radioactive background line. Only the discovery of the transition lines at the energies expected for $\beta\beta(0\nu)$ in two or more candidate nuclei would therefore definitely prove its existence.

No evidence has been obtained for $\beta\beta(0\nu)$ so far, with the only exception of an indication reported by a subset of the Heidelberg−Moscow Collaboration headed by Klapdor-Kleingrothaus [19, 20] which, in our opinion, needs, however, a deeper and more statistically significant verification, possibly through the study of candidate isotopes different from ^{76}Ge.
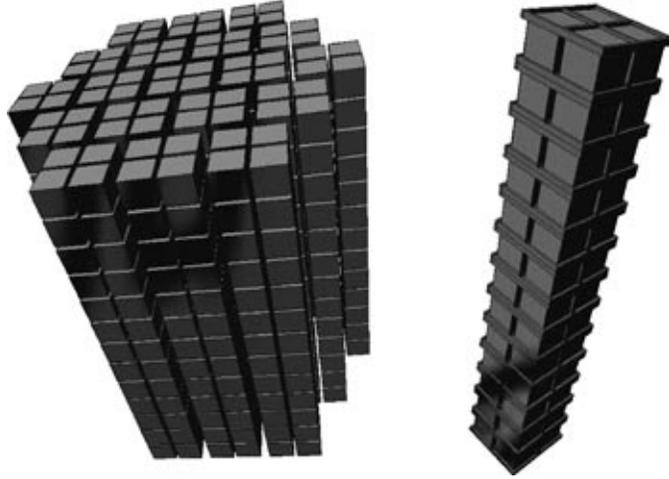
Fig. 1. Scheme of the CUORE array (left) and of one of the 19 towers (right).

Lacking any evidence for $\beta\beta(0\nu)$ in all the experimentally studied candidate isotopes, only upper limits on its half-life can be obtained. These limits directly translate, through the nuclear matrix elements evaluations, into lower limits of the order of $0.3-1$ eV on $\langle m_\nu \rangle$ [21]. On the other hand, the above-cited theoretical considerations on the neutrino properties based on present results coming from atmospheric, reactor, and solar neutrino experiments seem to indicate that $\langle m_\nu \rangle$ should lie in the range between 0.1 and 1 eV [22]. This reinforces the importance of designing and building experiments that could explore this mass range, and indeed several second-generation experiments (e.g., EXO, GENIUS, MAJORANA, MOON, and CUORE) [21] have been proposed during the last few years to search for the $\beta\beta(0\nu)$ decay of various nuclei. The challenge of these experiments consists in the construction of a large mass (of the order of tons) counting facility with extremely low background. This can be easily deduced from the following simplified expression for the 1σ sensitivity:

$$S_{1\sigma}^{0\nu} = \ln(2) N_A \frac{\epsilon\eta}{A} \sqrt{\frac{MT}{B\Delta}}, \qquad (4)$$

from which the explicit dependence on the relevant experimental parameters (e.g., detector mass M, measurement time T, background rate B, energy resolution Δ, detection efficiency ϵ, and isotropic abundance η) is apparent.

Another DBD mode, characterized by the emission of two neutrinos ($\beta\beta(2\nu)$), is usually considered in $\beta\beta$ searches. Although allowed in the framework of the Standard Electroweak Model (second-order transition) and characterized by very long half-lives (of the order of $10^{19}-10^{20}$ yr), $\beta\beta(2\nu)$ still represents one of the primary goals of $\beta\beta$ experiments (e.g.,

NEMO3) since it could represent a unique tool to test nuclear matrix calculations [23].

2. CUORE

The CUORE Project [24–26] aims at the construction of a DBD experiment based on the low-temperature detector (LTD) technique and characterized by an active mass of the order of 1 t. The main advantages of the LTD approach with respect to other conventional techniques (e.g. Ge diodes) are a sensitivity to low- or nonionizing events and a material choice flexibility. Besides allowing an experimental investigation on any DBD active isotope, LTDs allow therefore a $\beta\beta(0\nu)$ experimental study based on the use of materials characterized by a large natural isotopic abundance (a crucial parameter showing a linear dependence in the DBD lifetime sensitivity).

The CUORE setup (Fig. 1) will consist of 988 natural TeO_2 bolometers arranged in a cylindrical configuration of 19 towers (each made of a stack of 13 four-detector modules). Each bolometer will consist of a temperature sensor (NTD thermistor) glued to a cubic $5 \times 5 \times 5$-cm TeO_2 crystal with a mass of about 750 g. ^{130}Te is in fact one of the best candidates for DBD searches. Owing to its high transition energy (2528.8 ± 1.3 keV), the favorable nuclear matrix elements, and the large natural isotopic abundance (33.8%), it is possible to perform a sensitive experiment even using natural tellurium. ^{130}Te is moreover characterized by a favorable neutrinoless DBD rate and large TeO_2 single crystals can be grown with excellent features as thermal detectors.

The main goal of CUORE is to reach, in the energy region of interest, a background level lower than 10^{-2} counts/keV/kg/yr, obtaining hence a sensitivity on the effective Majorana mass of the neutrino

Table 1. Expected CUORE 5-yr $\beta\beta(0\nu)$ sensitivities under different possible performance and background scenarios ($|\langle m_\nu \rangle|$ ranges are evaluated according to QRPA calculations of nuclear matrix elements)

B, counts/keV/kg/yr	Δ, keV	$T_{1/2}$, 10^{26} yr	$|\langle m_\nu \rangle|$, meV
0.01	10	1.5	23−118
0.01	5	2.1	19−100
0.001	10	4.6	13−67
0.001	5	6.5	11−57

lower than 50 meV (Table 1). The CUORE array (Fig. 1) is designed in order to have the most compact structure, reducing to a minimum the distance between the crystals and the amount of inert material between them.
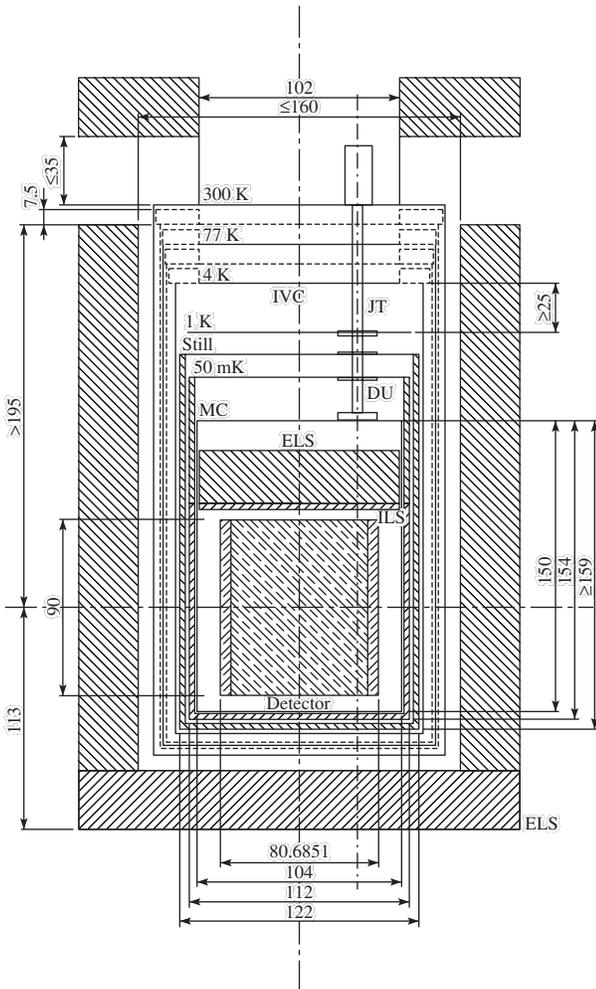
The entire array, surrounded by an ancient Roman

Fig. 2. Scheme of the CUORE cryostat and radiation shields (dimensions are in mm).

lead shield 3 to 6 cm thick, will be operated at about 10 mK in a powerful ^{3}He/^{4}He dilution refrigerator (Fig. 2). A further thickness of 30 cm of low-activity lead will be used to shield the array from the dilution refrigerator setup and from the environment. A borated polyethylene shield and an air-tight cage will surround the cryostatn externally. The experiment will be installed underground in the LNGS at a depth of 3400 m w.e. The CUORE will be by far the largest array of low-temperature detectors ever realized.

In order to demonstrate the feasibility of such a project, an intermediate detector (named CUORICINO and consisting of a single tower of CUORE) was proposed some years ago, to be housed in the same refrigerator already used for the MiDBD experiment. Such an array, built and installed at LNGS in 2001, is now taking data (Section 3). Following the successful operation of CUORICINO, CUORE was approved in 2004 by the LNGS and INFN scientific committees. It is now under construction at LNGS in the underground experimental Hall A. First data taking is expected in 2010.

3. CUORICINO

The CUORICINO detector is a slightly modified version of a CUORE tower, enlarged in order to exploit all the available cryogenic experimental chamber of the dilution refrigerator installed in Hall A of LNGS. Eleven of the 13 storys of the CUORICINO tower are four-crystal modules identical to those foreseen for CUORE (Fig. 3). The remaining ones are made of nine-crystal modules, where 18 of the 20 crystals used for the MiDBD experiment have been housed. CUORICINO contains therefore 44 TeO$_2$ crystals of size $5 \times 5 \times 5$ cm (790 g each) and 18 TeO$_2$ crystals of size $3 \times 3 \times 6$ cm (340 g each). The total mass of TeO$_2$ in CUORICINO is about 41 kg (11 kg of ^{130}Te). All the crystals are made of natural tellurium except for four of the small-size ones. Two of these are isotopically enriched to 75% in ^{130}Te, while the remaining two are isotopically enriched to 82.3% in ^{128}Te. Particular care was dedicated to the selection and treatment of the materials used for the construction of the CUORICINO array: the crystals were grown with radiopure materials in China (SICCAS) and shipped to Italy, where they were optically polished with specially selected low-contamination powders and stored underground at LNGS. The mechanical structure of the array was made exclusively of OFHC copper and PTFE, both with an extremely low radioactive content. All the copper and Teflon components of the mounting structure were separately processed with acids to remove any possible surface contamination. Finally, the array was assembled in an underground clean room, inside
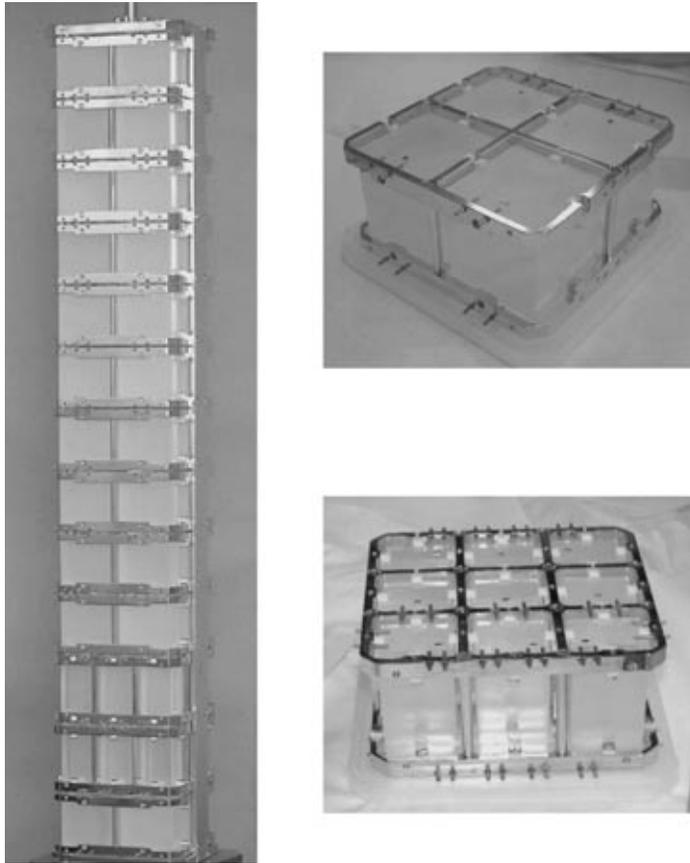
Fig. 3. The CUORICINO tower (left) and details of the two CUORICINO modules (right).

boxes flushed with clean N_2 in order to avoid Rn contamination. Once closed inside its copper box, the array was mounted in the dilution refrigerator installed in Hall A of LNGS. An inner Roman lead shield kept at low temperature (a ∼1-cm-thick tube with bottom (top) discs 7.5 (10) cm thick) completely surrounds the detector. The refrigerator itself is shielded with a 20-cm thickness of low-activity lead and a 10-cm thickness of borated PET. Nitrogen from a dedicated evaporator is flushed between the external lead shield and the cryostat to avoid any Rn contribution to the detector background.

CUORICINO was cooled at the beginning of year 2003. After a stop in November 2003 to fix a technical problem responsible for the disconnection of part of the readout wires, data taking restarted in spring 2004 with the full operation of all the detectors. Total statistics of 1.04 and 3.84 kg yr of ^{130}Te were collected in the 2003 (Run 1) and 2004 runs (Run 2, up to April 3, 2004). Starting from October 2004, the original embedded He liquefier was disconnected and manual He refilling started. Since then, the average duty cycle has improved abruptly to about 64%. Data taking is currently divided in background runs lasting

about four weeks, each starting and ending with a 2–3 d calibration with a gamma source (a ^{232}Th source placed in contact with the outer vacuum chamber of the cryostat). A number of gamma lines due to
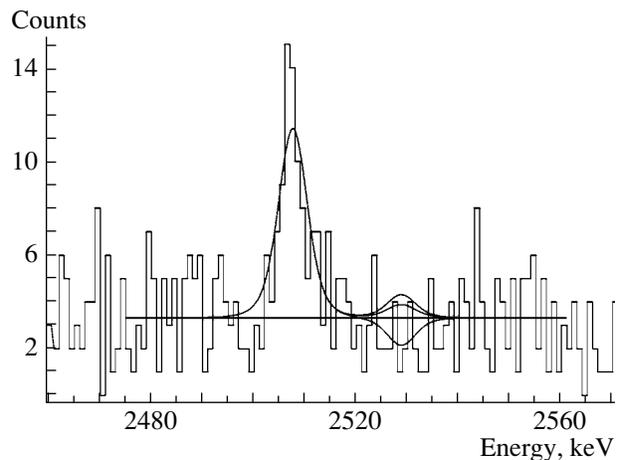

Fig. 4. Summed background spectrum from all the operating CUORICINO crystals in the region of $\beta\beta(0\nu)$ of ^{130}Te ($\beta\beta(0\nu)$ best fit, 68 and 90% C.L. curves are shown).

Table 2. Effective Majorana mass of the electron neutrino $|\langle m_\nu \rangle|$ corresponding to $T_{1/2}^{0\nu}(^{130}\text{Te}) = 1.8 \times 10^{24}$ yr derived from various nuclear (QRPA) models

Reference, author, year	Method	$\langle m_\nu \rangle$, eV
[28], Staudt et al., 1992	Pairing (Paris)	0.21−0.22
	Pairing (Bonn)	0.22−0.24
[29], Pantis et al., 1996	No $p-n$ pairing	0.66
	$p-n$ pairing	1.05
[30], Vogel et al., 1986		0.61
[31], Civitarese et al., 1987		0.54
[32], Tomoda, 1991		0.54
[33], Barbero et al., 1999		0.43
[34], Simkovic, 1999	pn RQRPA	0.88
[35], Suhonen et al., 1992		0.83
[36], Muto et al., 1989		0.51
[37], Stoica et al., 2001	Large basis	0.77
	Short basis	0.72
[38], Faessler et al., 1998		0.72
[39], Engel et al., 1989	Seniority	0.37
[40], Aunola et al., 1998	WS	0.50
	AWS	0.54

^{60}Co and ^{40}K and of the ^{238}U and ^{232}Th chains are clearly visible in the background spectrum obtained in operating all the detectors in anticoincidence. It should be stressed that these lines are not visible in the spectra of the single detectors: they grow only by summing the spectra from all the detectors and are a good check of the calibration and stability of the detectors along the background measurement. The ^{208}Tl gamma line at 2615 keV, being clearly visible in the background summed spectrum, is used to evaluate the energy resolution in the $\beta\beta(0\nu)$ region. The FWHM measured value is 7 keV for the $5 \times 5 \times 5$-cm bolometers and 12 keV for the $3 \times 3 \times 6$-cm ones. Smaller values are measured at lower energies (3.6- and 4.4-keV FWHM at the 120- and 583-keV lines for the $5 \times 5 \times 5$-cm bolometers). The background rate in the region of interest for $\beta\beta(0\nu)$ is 0.18 ± 0.02 counts/keV/kg/yr. No peak appears (Fig. 4) at the ^{130}Te double-beta decay transition energy (2528.8 keV). A maximum likelihood procedure used to establish the maximum number of $\beta\beta(0\nu)$ events compatible with the measured background allows one to set an upper limit on the ^{130}Te $\beta\beta(0\nu)$ half-life of 1.8×10^{24} yr at 90% C.L.

The corresponding upper bound on the Majorana effective mass ranges from 0.2 and 1.1 eV depending on the nuclear model used to interpret the data [27] (see Table 2).

4. CUORICINO RESULTS AND CUORE PERSPECTIVES

While being a self-consistent experiment on $\beta\beta(0\nu)$ (actually the most sensitive currently running), CUORICINO must be considered as a first step towards CUORE. It is in fact an effective test facility intended to verify the technical feasibility of the parent project. Indeed the good results concerning the detector performance obtained with CUORICINO show that the construction of CUORE could be more straightforward than expected. The results of the ongoing R&D actually show that the increase in the number of bolometers and in the total mass do not substantially affect the experimental sensitivity. They also show that the mass of the inert materials (mainly copper and PTFE) can be reduced without any loss of performance. Results of crucial importance are also being obtained for what concerns background sources [27]. CUORICINO data analysis shows in fact that a dominant contribution to the background level originates from radioactive contaminations of the TeO$_2$ crystals and Cu holders distributed over a shallow layer whose thickness is of the order of a few micrometers. This clearly results from the comparison with detailed Monte Carlo simulations, but is also apparent from the naive observation that the background rate does not decrease above the 2615-keV line of ^{208}Tl. An intensive program aimed at the reduction of such a contribution, based on dedicated surface cleaning procedures, has therefore been started. Active methods aimed at identifying events originating from surface events have also been successfully developed [41].

On the other hand, the residual contribution observed in CUORICINO and attributed to "external" gamma sources (cryostat setup and radiation shields) should be a minor problem for CUORE. Indeed, the CUORE lead shield design was optimized in order to practically cancel the background coming from outside contributions (this optimization was not possible in CUORICINO, which had to be housed in a preexisting cryostat).

The surface processing of the CUORICINO TeO$_2$ crystals and mounting structure (copper and PTFE) was recently improved in the framework of the above-mentioned R&D. A reduction by approximately a factor of 5 in the $\beta\beta(0\nu)$ background contribution from the crystal surface was in fact obtained by a careful cleaning of the TeO$_2$ crystal surface by means of radioclean powders and chemicals. More

detailed knowledge on the background origin and location is expected from the systematic study of the CUORICINO background with larger statistics (single crystal background distributions, time coincidences, etc.). It will definitely help us in disentangling the background sources and finally reducing the CUORE background level below the sought level of 0.01 counts/keV/kg/yr.

5. CONCLUSIONS

With a 5-yr sensitivity of about 10^{25} yr (68% C.L.) for the ^{130}Te $\beta\beta(0\nu)$, CUORICINO is the presently running experiment with the best sensitivity on the effective Majorana neutrino mass $\langle m_\nu \rangle$ (100−500 meV, according to extreme nuclear matrix evaluations in [28] and [29], respectively). Moreover, thanks to the CUORICINO results, the LTD technology is now proven and a second-generation experiment (CUORE) is under construction at LNGS. It will represent by far the most cost-effective next-generation DBD experiment able to reach the desired levels of sensitivity to probe the neutrino mass inverted hierarchy.

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