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Present and future of double-beta decay searches with bolometric detectors

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Summary. — Thanks to the excellent energy resolution, high efficiency and versatility, bolometric detectors are primed for the search of neutrinoless double-beta decay (0νDBD). The most advanced bolometric experiment, CUORE, is studying the 0νDBD of ^{130}Te using a 741 kg array of TeO_2 crystals. CUORE points to a 90% CL sensitivity on the half-life of 0νDBD of 9.5×10^{25} yr in 5 yr, corresponding to an upper limit on the neutrino Majorana mass of 50–130 meV. This sensitivity will allow to touch, but not to explore, the region corresponding to the inverted hierarchy mass scenario. In this document I present the status of CUORE and the possible upgrades of the bolometric technology in view of a next generation experiment.

1. – Introduction

The search for neutrinoless double-beta decay (0νDBD) is one of the most interesting open problems in the physics of rare events. The detection of this nuclear transition would prove the existence of a process that violates the total lepton number conservation, and would allow to determine the nature of neutrinos, as it can occur only if neutrinos coincide with their own antiparticles. Finally, the main observable of the 0νDBD, *i.e.* its half-life, could give an insight in the scenario of neutrino masses, as it can be related to the neutrino Majorana mass $m_{\beta\beta}$.

Since no neutrinos are emitted in the 0νDBD, the entire energy of the transition is shared between the two electrons. Therefore, the process should produce a very clear experimental signature: a monochromatic peak at the Q-value of the decay (a few MeV) in the sum energy spectrum of the emitted electrons.

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In the last decades, several collaborations proposed different technologies to investigate some of the isotopes that could undergo 0νDBD. Apart from a controversial claim [1], not confirmed by more recent experiments [2], no evidences for the decay were found.

The goal of next-generation projects is the full coverage of the region corresponding to the inverted hierarchy mass ($m_{\beta\beta} \sim$ 10–50 meV). Future detectors will have to operate about 10^{27} emitters (100–1000 kg of mass source) with background close to the zero-level, in order to achieve a sensitivity higher than $T^{0\nu}_{1/2} \sim 10^{27}$ yr. It should be observed that most of next-generation projects will have to deal with the irreducible background produced by the two-neutrino double-beta decay (2νDBD), a rare process allowed by the Standard Model that could spoil the sensitivity on 0νDBD.

These considerations set stringent requirements on the design of next-generation detectors. Thanks to the possibility of investigating different $0\nu\beta\beta$ emitters, as well as their excellent energy resolution and efficiency, bolometric detectors are primed for the high-sensitivity study of rare events. In this contribution I will describe the CUORE experiment, and discuss the possible upgrades of the bolometric technology for the realization of an experiment that could investigate the entire region of the inverted hierarchy mass.

2. – Bolometers

A bolometer can be sketched as a crystal coupled to a temperature sensor, and operated as calorimeter at cryogenic temperature ($\sim$ 10 mK) [3]. The crystals are grown starting from the emitter of interest, meaning that different isotopes can be investigated. In this approach source and detector coincide, thus large crystals can reach a high efficiency in the containment of the two 0νDBD electrons. Furthermore, the calorimetric technique provides an energy resolution of 0.1%, which is fundamental to reject the background due to 2νDBD.

CUORE [4], that will study the $0\nu\beta\beta$ of ^{130}Te (Q-value = 2528 keV) using 988 TeO_2 crystals of 750 g each, is the most advanced bolometric experiment for the search of 0νDBD. The TeO_2 crystals, equipped with Neutron Transmutation Doped (NTD) Ge thermistors, have been arranged in 19 towers with a total active mass of 741 kg (206 kg of which are ^{130}Te), and are currently stored in the underground Laboratori Nazionali del Gran Sasso (LNGS) in Italy. The collaboration is completing the commissioning of the detector, which is expected to be fully deployed and in operation by the end of 2016.

The expected background for CUORE has been predicted starting from the data collected by its ancestor Cuoricino, an array of 62 TeO_2 crystals. The analysis of the large statistics collected with Cuoricino allowed to determine that the background of CUORE will be dominated by α-decaying isotopes located in the surface of the detector materials (mainly in the copper structure in which the crystals are arranged). The emitted α's can lose a variable fraction of their energy in the inert material before interacting in the active detector, producing a flat background that limits the sensitivity on $0\nu\beta\beta$ decay.

An extensive R&D activity was carried out to suppress this background in view of CUORE: the tower design was modified in order to reduce the amount of copper, the surface of each detector component was cleaned with more effective procedures, the exposure to radon was minimized through a dedicated storage system and assembly-line.

In March 2013 a single CUORE-like tower, CUORE-0, started data-taking with the purpose of validating all the procedures developed for the low-background assembly line of CUORE. CUORE-0 is an array made by 52 TeO_2 crystals ($\sim$ 11 kg of ^{130}Te), each of them equipped with an NTD Ge thermistors.

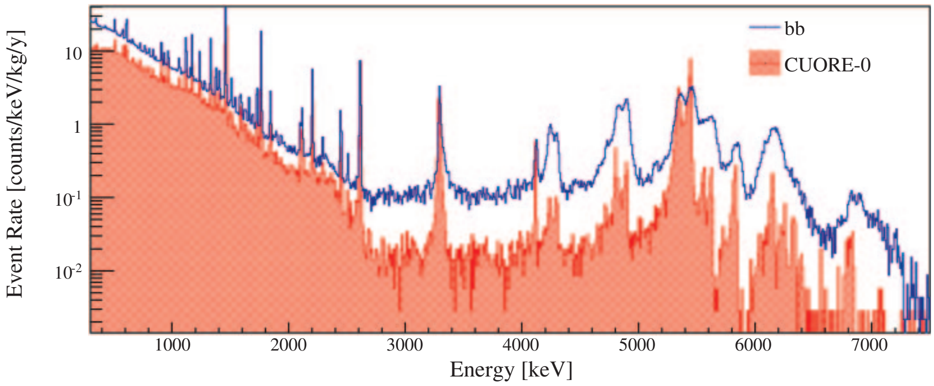

Fig. 1. – Comparison between the CUORE-0 (red) and Cuoricino (blue) energy spectra.

The data used for the detector characterization were collected in two campaigns, from March 2013 to August 2013 and from November 2013 to March 2015. With an exposure of 9.8 kg · yr, a total efficiency of 81.3 ± 0.6%, a detector FWHM energy resolution of 5.1 ± 0.3 keV and a background of 0.058 ± 0.004(stat.) ± 0.002(syst.) counts/(keV·kg·yr) in the energy region of the 0νDBD, CUORE-0 achieved a median 90% CL lower-limit sensitivity of 2.9×10^{24} yr. Since no evidence for the decay was found, CUORE-0 set a Bayesian lower bound on the ^{130}Te half-life of $T^{0\nu}_{1/2}(^{130}Te) > 2.7 \times 10^{24}$ yr at 90% CL, that combined with Cuoricino resulted in $T^{0\nu}_{1/2}(^{130}Te) > 4.0 \times 10^{24}$ yr [5].

Besides placing the most stringent limit to date on the half-life of ^{130}Te, CUORE-0 proved that the resolution, efficiency and background targets for CUORE are within reach. The comparison between the CUORE-0 and Cuoricino energy spectra (fig. 1) shows the effectiveness of the new assembly-line designed for CUORE. As expected, there is not a significant improvement below the 2615 keV line of ^{208}Tl, because this region is dominated by the γ radioactivity of the cryogenic system, which is the same for CUORE-0 and Cuoricino. On the contrary, the flat continuum above 3 MeV, ascribed to α interactions, was reduced of about a factor ~ 6 with respect to Cuoricino.

It is reasonable to assume that with this low-background assembly line, the self-shielding of the 19 towers, as well as the more radio-pure cryogenic environment, CUORE will achieve the target background of 10^{-2} counts/(keV · kg · yr) in the energy region of the 0νDBD. With such a low background CUORE will reach a sensitivity of 9.5×10^{25} yr at 90% CL in 5 yr, corresponding to an upper limit on the $m_{\beta\beta}$ of 50–130 meV.

3. – The future of bolometers: CUPID

Next-generation experiments aim at observing 0νDBD with high confidence (at least 3σ) even if the neutrino Majorana mass were in the inverted hierarchy region. The CUPID [6] (CUORE Upgrade with Particle IDentification) interest group is investigating the possibility of achieving the required sensitivity on $T^{0\nu}_{1/2}(> 10^{27}$ yr) using a bolometric detector. The many technological solutions that have been proposed for the CUORE upgrade can be divided in two main groups, one exploiting the well-known TeO_2 crystals, one investigating other possible bolometric compounds. The isotopic enrichment, as well as the achievement of excellent efficiency and energy resolution will be necessary

TABLE I. – 90% *CL sensitivity of a bolometric detector based on ZnSe, $ZnMoO_4$ and TeO_2 crystals* 90% *enriched in the isotope of interest, assuming* 5 *keV FWHM energy resolution and* 10^{-4} *counts/(keV·kg·yr) background in the region of interest. The upper limit on* $m_{\beta\beta}$ *is reported in the last column using the most/least favorable nuclear matrix elements.*

	Mass [kg]	Isotopes	$T^{0\nu}_{1/2}$ 90% CL Sensitivity [yr]	$m_{\beta\beta}$ 90% CL Sensitivity [meV]
ZnSe	664	2.4×10^{27}	2.2×10^{27}	11–32
$ZnMoO_4$	540	1.3×10^{27}	1.1×10^{27}	13–37
TeO_2	751	2.4×10^{27}	2.5×10^{27}	10–25

regardless of the chosen crystal. The main difference in the two scenarios consists in the technological approach that will guarantee an efficient background suppression.

3·1. TeO_2-*based detectors*. – Decades of studies on TeO_2 allowed to optimize the crystal growth procedures in order to produce excellent bolometers with high radio-purity levels. Working with (the more expensive) enriched Te will require some modifications to these procedures to suppress material loss or inclusions of contaminants, but preliminary tests show that energy resolution, as well as the radio-purity of the crystals, are not heavily affected by the use of the enriched material.

As shown by the CUORE background model, the main concern for TeO_2-based experiments is the α background suppression. A possible solution has been proposed by the ABSuRD collaboration, and consists in measuring the light emitted by α's impinging on a scintillating foil placed around the TeO_2 crystal to tag α interactions [7].

A viable alternative consists in measuring the Cherenkov light produced by electrons (possible 0νDBD signals) and not by α's. The amount of emitted light depends on the energy of the electrons and on the crystal size. For CUORE-like bolometers, it was estimated that electrons with energy of the ^{130}Te 0νDBD emit only ~ 100 eV of Cherenkov light [8], which sets stringent requirements on the light detector features: devices with noise resolution lower than 20 eV, wide active surface ($5 \times 5\,\mathrm{cm}^2$), reproducible behavior and low heat-load for the cryogenic system are needed. Measurements performed on single light detectors realized with Transition Edge Sensor (TES) read-out, proved that the necessary background rejection can be achieved [9]. Similar results were obtained exploiting the Neganov-Luke effect, both with TES [10] and NTD Ge thermistors. Nevertheless, since these technologies are difficult to scale up to a thousand of light detectors, other approaches are now being investigated. One of the most promising is the CALDER experiment [11, 12], that is exploiting the high sensitivity and the natural multiplexing in the frequency domain provided by Kinetic Inductance Detectors to realize a wide area light-detector that can be easily adapted to CUORE-like experiments.

3·2. *Scintillating bolometers*. – Another viable option for CUPID consists in the switch to scintillating crystals. Unlike TeO_2, many crystals of interest emit scintillation light at low temperature, thus even less sensitive light detectors enable background suppression via particle identification. In addition, isotopes other than ^{130}Te characterized by high Q-value are less affected by the background produced by the natural radioactivity.

Emitters like ^{82}Se (2997 keV) or ^{100}Mo (3034 keV) can be embedded in scintillating crystals like ZnSe to $ZnMoO_4$, which have been extensively studied by the LUCIFER [13] and LUMINEU [14] collaborations. In 2016, the first medium-scale experiment based on enriched ZnSe and $ZnMoO_4$ crystals will start operations in the cryostat used for CUORE-0, to demonstrate that this technique allows to reach a background as low as 10^{-3} counts/(keV · kg · yr).

3˙3. *Projected sensitivity.* – To prove the potential of bolometric detectors in exploring the inverted hierarchy mass region, a simulation of the expected sensitivity was performed. The detector size was set equal to CUORE so that, in principle, the same cryogenic facility could be used. The chosen crystals were TeO_2, ZnSe and $ZnMoO_4$ (enriched up to 90% in the isotope of interest), as these bolometers are now rather well-known, but similar performances are expected with other compounds. A FWHM energy resolution of 5 keV, already proved for TeO_2 and not too optimistic for the other options was chosen. Finally, the expected sensitivities were calculated assuming that the promising technologies presented in this document will allow to achieve a background of 10^{-4} counts/(keV · kg · yr). As shown in table I, despite the final choice of the crystal, that will be driven by the results of the R&D activities in the next few years, CUPID will be able to achieve the sensitivity required for the full exploration of the inverted hierarchy region.

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