RECENT RESULTS FROM CUORE(-0)

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Neutrinoless Double Beta Decay is a hot topic in the nowadays physics research, due to its potentiality to prove the Majorana nature of neutrinos. CUORE is an experiment designed to look for this rare event exploiting the decay of ^{130}Te with a $\sim$1 ton compact array of TeO_2 bolometers. The first CUORE tower (CUORE-0), constituting a self-consistent experiment by itself, was commissioned during spring 2012 and is now taking data. The full-mass experiment is actually under construction and is expected to run into operation by end 2014. The results obtained by now with CUORE-0 and the progress in the construction of CUORE will be presented in this article, together with an estimation of the sensitivity to the Neutrinoless Double Beta Decay.

1 Introduction

In the Standard Model of Particle Physics (SM) the Double Beta Decay ($\beta\beta$) is an allowed weak process of the second order which can occur in some even-even nuclei for which the single beta decay is energetically forbidden or suppressed by large change of angular momentum. It was observed for many nuclei [1] with half-lives as high as 10^{18}-10^{24} y. If neutrinos are Majorana particles the $\beta\beta$ could also proceed without the emission of any neutrino, giving rise to the so called Neutrinoless Double Beta Decay ($\beta\beta0\nu$). Such process violates the lepton number L by two units, and its observation would therefore provide a strong indication of new physics beyond the SM. Many mechanisms could theoretically drive this decay, the most popular being the exchange of a light Majorana neutrino. In this case the decay width can be expressed asan interplay of atomic, nuclear and particle physics:

$$\Gamma_{0\nu} \propto G_{0\nu}(Q,Z)|M_{0\nu}|^2\langle m_{ee}\rangle^2 \tag{1}$$

where $G_{0\nu}$ is the phase space integral, which is exactly calculable [2], $M_{0\nu}$ are the nuclear matrix elements for the isotope under dacay, and $\langle m_{ee}\rangle$ is the effective neutrino Majorana mass. The last term is a combination of the neutrino mixing matrix parameters, the neutrino mass eigenvalues and the CP Majorana phases. The observation of the $\beta\beta0\nu$ would therefore give an important piece of information for the knowledge about the neutrino absolute mass scale, its mass hierarchy and the CP Majorana phases.

The main signature exploited by experiments looking for the $\beta\beta0\nu$ is the monochromatic peak at the Q-value of the transition, due to the simultaneous detection of the two emitted electrons. This peak falls on the tail of the SM allowed $\beta\beta$ and is enlarged only by the detector resolution.

The most common techniques used nowadays to search the $\beta\beta0\nu$ exploits "homogeneus" detectors, i.e. devices acting simultaneously both as the source and the detector for the searched event. Their capability to detect the $\beta\beta0\nu$ peak over the background scales with the detector mass and can be expressed as [a]:

$$S^{0\nu} \propto \frac{\varepsilon\ a.i.}{A}\left(\frac{M\ T}{b\ \Delta E}\right)^{1/2} \tag{2}$$

where $S^{0\nu}$ corresponds to the minimum detectable number of events over backgroud at a given Conficence Level (C.L.). This expression gives at a glance an insight into the important parameters influencing the sensitivity: i) the detecting efficiency ε for the $\beta\beta0\nu$ events; ii) the isotopic abundance $a.i.$ of the decaying isotope and its mass number A; iii) the exposure M×T; iv) the background rate b per unit detector mass; and v) the energy resolution ΔE in the Region of Interest (ROI) (i.e. an energy region 100 keV around the Q-value). In order to reach a sensitivity on $\langle m_{ee}\rangle$ between 15 and 50 meV, corresponding to the Inverted Hierarchy Region (IHR) of the neutrino mass spectrum [3], M must be of the order of 1 ton with b of few counts per year and $\Delta E \approx 0.1\%$ in the ROI. These pose a big challenge for experimental technologies, analysis methodologies and materials radio-purity.

In this paper we will focus on experiments based on bolometers, i.e. low temperature calorimenters in which the energy E of the impinging particle is measured by means of its conversion into lattice vibrations (i.e. phonons) of the crystal absorber. At the end of the phonon thermalization process the temperature of the absorber is approximately given by E/C, where C is the heat capacity of the absorber itself. For dielectric and diamagnetic crystals $C \propto T^3$, it is therefore possible to obtain measurable temperature signals coupling such crystals to a heat bath kept at very low temperatures (at 10 mK E=1 MeV corresponds to ΔT~300 mK). Biased temperature sensors are then thermally coupled to the absorbers to convert the temperature variation into an electrical signal.

2 The $\beta\beta0\nu$ research with TeO_2 arrays

Since 1997 TeO_2 has been used to operate big arrays of bolometers for the $\beta\beta0\nu$ research at the Underground National Laboratory of Gran Sasso (LNGS). This compound has good thermal and mechanical properties and contains ^{130}Te , which is a $\beta\beta0\nu$ candidate particularly appealing due to its high natural isotopic abundance (34.2%) and high Q-value (~2528 keV [4,5,6]). In all the operated arrays Neutron Transmutation Doped (NTD) germanium thermistors are glued on the crystal surface in order to read the temperature variations induced by any energy depositions in the crystals bulk and/or surface. The signal is then transmitted to the electronic chain by means gold wires. Small pieces of teflon anchor the TeO_2 crystals to a copper skeleton, which is thermally linked to the cold finger of a ^{3}He/^{4}He dilution refrigerator at ~10 mK. The array is kept in vacuum inside a structure of nested copper and lead shields, used to reduce the background induced by the environmental and the setup radioactivity. The Gran Sasso mountain provides a ~3650 m.w.e. [7] rock shielding from cosmic rays, with a measured μ flux [8] of $(2.58\pm\ 0.3)\times10^{-8}$ μ/s/cm^2 and a flux of neutrons with energy lower that 10 MeV [9,10] of 4×10^{-6} n/s/cm^2.

The overall detector mass has been strongly stepped up through years, increasing the global content of ^{130}Te atoms and thus enchancing the sensitivity to the $\beta\beta0\nu$. The first experiment, MiDBD, was a 1.8 kg ^{130}Te array [11], where 3×3×6 cm^3 crystals of 340 g each were deployed. It was followed by Cuoricino [12], a tower of 44 cubic 5×5×5 cm^3 crystals plus 18 crystals from MiDBD, totalling 11.3 kg of ^{130}Te. It run between 2003 and 2009 and reported a final lower limit on ^{130}Te half-life of 2.8×10^{24} y (90% C.L.), corresponding to a sensitivity for $\langle m_{ee}\rangle$ in the Degenerate Region (DR) of the neutrino mass spectrum. The next and final step, CUORE (see

[a] This expression is based on a gaussian approximation of the background and is therefore not fully accurate for very low background indexes. It is inteded to give a qualitative representation of the main parameters influencing the sensitivity.

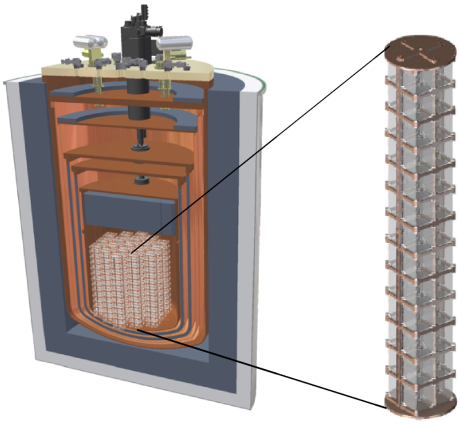

Figure 1: Set-up of the CUORE experiment and detail of 1 CUORE tower.

Fig. 1), was designed in order enter in the IHR, aiming to a sensitivity about 35 times higher than Cuoricino. In order to achieve this goal the detector mass was increased to 741 kg of TeO_2, corresponding to 206 kg of ^{130}Te, meaning a factor 20 with respect to Cuoricino. Additional improvements are expected on the measuring live-time (a factor 2 thanks to the use of a cryogen-free dilution refrigerator) and on the energy resolution (resolutions a factor $\sim$1.5 better than the Cuoricino ones have been measured with sample detectors from the CUORE production batches).

The most challenging issue is background reduction. The base goal is set to a background index (BI) in the ROI of 0.01 cts/keV/kg/y, i.e. a factor 20 better than Cuoricino. In TeO_2 bolometers the phonon signal shows very little dependence on either the identity of the impinging particle or on the position of the event in the detector. This fact and the absence of a surface dead-layer on the crystals mean that α's as well as β's and γ's form a background if they deposit an amount of energy in the bolometer equivalent to the $\beta\beta0\nu$ Q-value . Studies performed on data acquired with Cuoricino [13,14] indicated that $\sim$30% of the background originated from the cryogenic apparatus and $\sim$70% from detector surface contamination, i.e. the TeO_2 crystals and the inert materials facing them (most likely copper). To meet the ROI-background goal of CUORE both these sources must be addressed.

3 The background challenge

While testing different active methods for the reduction of the background, many passive shrewdnesses have been implemented. In order to ensure a negligible contribution from the environmental radioactive component the CUORE detector is provided with 6 nested copper vessels, with an internal and an external lead shield ($\sim$35 cm of minimum thickness in total) and with a 2 layer shield for neutrons (20 cm in total). These ensure an overall contribution from this source lower than 10^{-4} cts/keV/kg/y [15]. The materials for the cryostat and the for shields have been selected with a radiopurity level sufficient to ensure a ROI-background contribution far below the target level of 10^{-2} cts/keV/kg/y.

For the TeO_2 crystals and the copper holder the acceptable ^{232}Th and ^{238}U contamination levels are as low as 10(^{232}Th)-100(^{238}U) μBq/kg for the bulk and 1-10 nBq/cm^2 for the surface. While copper bulk contamination can be adequately validated with HPGe spectroscopy and Neutron Activation Analysis (NAA), these techniques do not have sufficient sensitivity to validate the radiopurity of the copper surface, the TeO_2 surface, and the TeO_2 bulk.

To meet this validation challenge a series of test arrays containing a few bolometers arranged in the style of one or a few floors of CUORE were operated in dedicated runs at LNGS [16]. The results of the TeO_2 crystal surface validation runs (CCVR) were reported in [17]. 90% C.L. upper limits on ^{238}U and ^{232}Th surface concentration corresponding to 3.8 nBq/cm^2 and 2.0 nBq/cm^2 respectively were demonstrated, thus ensuring a 90% C.L. upper limit contribution to the ROI-background of 10^{-4} cts/keV/kg/y.

Reguarding copper we strove to both minimize the amount of this material facing the bolometers and to identify the better surface treatment to mitigate the background from the remaining surfaces. Three techniques were compared in the so called Three Towers Test (TTT) [18]: (i) wrapping of surfaces with polyethylene, (ii) simple surface cleaning with ultra-clean acids, and (iii) a procedure based on Tumbling, Electropolishing, Chemical etching and Magnetron plasma etching (TECM). The data from the TTT apparatus demonstrated that surface contamination levels lower than 7×10^{-8} Bq/cm^2 for ^{232}Th and ^{238}U and below 9×10^{-7}Bq/cm^2 for ^{210}Po can be achieved using both the TECM procedure and polyethylene wrapping. The extrapolation of the TTT results to CUORE gives a 90% C.L. upper limit for the contribution to the ROI-background of ~0.02 - 0.03 counts/keV/kg/y, depending on a reasonable range of unknown parameters in the extrapolation model. Since the surface contamination of inert materials facing the detectors constitutes, based on our current knowledge, the dominant contribution to the $\beta\beta0\nu$-background, this also represents the upper limit for the ROI-background expected for CUORE. This means that the BI goal of the experiment is almost achieved.

4 CUORE status

CUORE is expected to start operating by end 2014. It's construction is approaching the final stages. At LNGS the Hut and the clean room are fully equipped. The radon abatement system is installed, the commissioning of the cryostat vessels and of the cryostat dilution unit have started. Meanwhile in the US the calibration system construction has begun, the thermistors production is finished and their characterization is on-going. Copper parts are being machined and cleaned at Laboratori Nazionali di Legnaro, where the TECM procedure was implemented, and the final delivering should be by end 2013. Crystal production at the Chinese crystal factory is coming to the end. Almost 95% of the TeO_2 detectors are already stored underground at LNGS to avoid exposure to cosmic rays. In order to reduce recontamination of crystals surfaces, they are kept in nitrogen overpressure inside stainless-steel cabinets until their extraction for the construction of CUORE.

In March 2013 the CUORE towers assembly has started and the first two towers are amost ready. All the operations are performed in clean room and must follow very strict prescriptions in order to avoid any possible contamination of the detectors. The construction of every single CUORE tower consists of 5 main steps, for each of which a specific glove boxe was realized in order to handle the detectors in nitrogen overpressure and without any direct contact with the external environment. The first step is the gluing of the thermistor to the crystal, performed using a semi-authomatic machine developed in order to make this operation fast, more uniform and reproducible among detectors. Once all the 52 detectors of one tower are equipped the assembly is performed in the "Tower Assembly Line". It consists of a sealed and nitrogen fluxed stainless steel chamber provided with an elevator platform and supporting a working plane where 4 different glove boxes can switch for: 1) mounting the detectors inside the copper skeleton; 2) installing the wires strips used to connect the detector to the electronics; 3) bonding 25 microns gold wires from the thermistor gold pads to the copper pads of the wire strips; 4) storing the assembled tower.

5 CUORE-0

While the full mass experiment is being constructed a smaller scale TeO_2 array, CUORE-0, was put into operation inside the dilution refrigerator previously hosting Cuoricino. It consists of exactly one CUORE-like tower and is intended to be at the same time a proof of concept fo

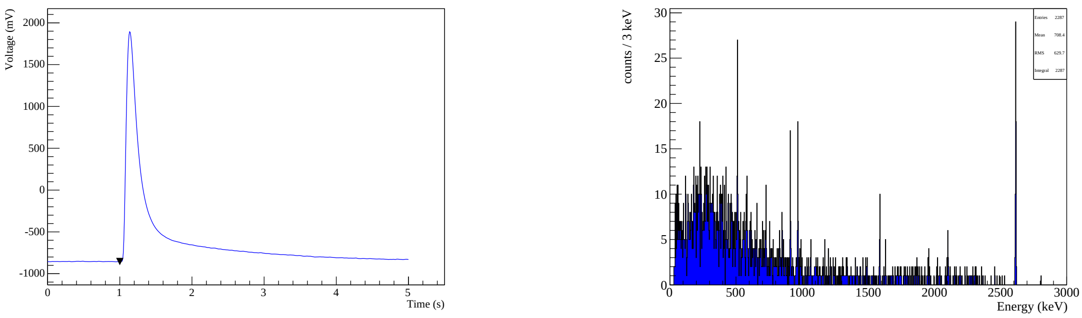

Figure 2: Left: 2615 keV γ sample event. Right: ^{232}Th calibration spectrum of one detector.

CUORE in all stages and a self-consistent experiment, able to extend the physics reach beyond Cuoricino and to demonstrate the potentiality of big TeO_2 arrays for Dark Matter and Axion detection.

The crystals of CUORE-0 come from the same production of CUORE; all the detector components have been manifactured, cleaned and stored following the same protocols. The 52-crystals tower was assembled using the infrastructures and with the procedures developed for CUORE. The Data Acquisition System (DAQ) and the analysis software of CUORE are here being tested and optimized, aiming to an easier and more authomatic handling of the data in view of the 988 detectors.

CUORE-0 was cooled down to a base temperature of $\sim$8 mK in August 2012 to start the pre-operation and optimization phase. Unfortunately this was disturbed by some cryogenic problem (vacuum leaks) due to the advanced age of the dilution refrigerator ($\sim$25 y old). This deteriorated the detector performances and imposed a stop to recover the system. The calibration performed before this stop was anyway enough to have a preliminary evaluation of detector performances. 51 detectors over 52 are alive and almost all of them showed reasonable performance. In the left panel of Fig. 2 the shape of one triggered pulse is shown as acquired by the DAQ for one sample detector. In the right panel the spectrum acquired by the same detector during the calibration with a ^{232}Th wire source is shown. The FWHM energy resolution at 2614.5 keV, the energy of the ^{208}Tl gamma line most close to the $\beta\beta0\nu$ Q-value, was of $\sim$5.3 keV.

The cryogenic problems were finally fixed in February 2013 and in mid March CUORE-0 restarted the pre-operation and optimization phase, mainly devoted to noise reduction. The official data-taking is now on-going.

6 CUORE-0 and CUORE sensitivity

In the current scientific scenario many 1-ton $\beta\beta0\nu$ experiments are in the construction phase, designed to probe a part or all of the IHR of the neutrino mass spectrum in the next 10 years. Some of them, like CUORE-0, are already operating in a smaller version, with detector masses of the order of tents of kg, with the purpose to peer into DR in order to confirm or refute the the claim for discovery made by part of the Heidelberg-Moscow collaboration [19].

The half-life sensitivity for the $\beta\beta0\nu$ of ^{130}Te of CUORE-0 and CUORE versus the live-time is shown in Fig. 3 [20]. It was evaluated assuming a detecting efficiency ε =87.4% (as obtained with Monte Carlo simulations), a FWHM energy resolution in the ROI ΔE =5 cts/keV/kg/y and BI of 0.05 cts/keV/kg/y and of 0.01 cts/keV/kg/y for CUORE-0 and CUORE respectively. The CUORE-0 ROI-background is evaluated by scaling the one measured in Cuoricino on the bases of the improvements achieved in the crystals/copper surface purity and therefore considering the contamination of the cryostat as the dominant source.

The CUORE cryostat was constructed with very low activity materials, in order to guarantee that the BI from this component is negligible. The ROI-background of CUORE is therefore

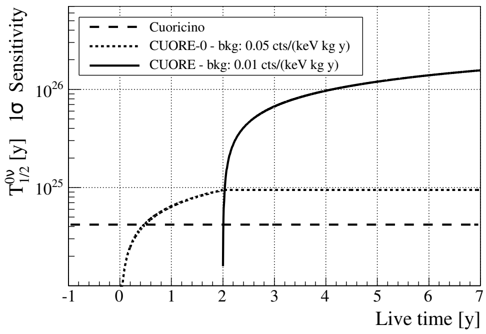

Figure 3: CUORE-0 and CUORE 1σ sensitivity on ^{130}Te $T^{0\nu}_{1/2}$ as a function of the live-time.

expected to be dominated by the surface activities of the inert materials facing the detectors. As shown in Sec. 3 a 90%C.L. $\beta\beta0\nu$-background of 0.02 cts/keV/kg/y is at reach for CUORE, corresponding to about 0.01 cts/keV/kg/y at 1σ. From Fig. 3 it can be seen that CUORE-0 will surpass CUORICINO (whose final result is reported for reference) in 6 months of live-time, and is expected to have a 1σ half-life sensitivity close to 10^{25} y in 2 years of live-time. CUORE will allow to improve the sensitivity by another order of magnitude, reaching in 5 years of live-time a 1σ half-life sensitivity of 1.6×10^{26} y. With such sensitivity CUORE will be able to start to explore $\langle m_{ee}\rangle$ values as low as 40÷100 meV (the range is due to the spread in the NME calculations), corresponding to the upper part of the IHR of the neutrino mass spectrum.

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