The CUORE experiment: a search for neutrinoless double beta decay

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Abstract. Neutrinoless Double Beta Decay is searched by physicists since tens of years. Fighting to reach higher and higher sensitivities, novel techniques have been suggested and large mass experiments have been proposed or are under construction. Within this picture, cryogenic particle detectors play a primary role. CUORICINO, a 40.7 kg array of low temperature TeO$_2$ calorimeters, provided one of the best limits on the effective neutrino Majorana mass. The final result of this - now closed - experiment is here presented. The heir of CUORICINO is CUORE: an array of 988 TeO$_2$ calorimeters with a total mass of 750 kg. The current status of CUORE - presently under construction at Laboratori Nazionali del Gran Sasso - is illustrated, the perspectives for the Neutrinoless Double Beta Decay search are discussed.

1. Introduction

The Double Beta Decay is a transition in which an (A, Z) nucleus decays into its (A, Z+2) isobar. This is the only decay channel for a group of isotopes whose single beta decay is forbidden. The interest in its detection stands in the possibility that the transition goes through a channel in which no neutrinos are emitted. The Neutrinoless Double Beta Decay (ββ(0ν)) is possible only if the neutrino is a massive Majorana particle [1] and it happens to be (at least today) the only way to prove this property. If the ββ(2ν) exists, its half-life is inversely proportional to the square of the Majorana mass of neutrino, defined as $m_{ee} = |\sum m_i U^2_{ei}|$ (where $U_{ei}$ are elements of the PNMS matrix and $m_i$ are the three neutrino mass eigenstates). The ββ(2ν) half-life ($T_{1/2}^{0\nu}$) can be written as:

$$\frac{1}{T_{1/2}^{0\nu}} = m_{ee}^2 F_N = m_{ee}^2 G^{0\nu} |M^{0\nu}|^2$$

Here $G^{0\nu}$ is the two-body phase-space factor and $M^{0\nu}$ is the Nuclear Matrix Element (NME), their product $F_N$ is called the Nuclear Factor of Merit. Present experimental upper bounds on $\langle m_{ee} \rangle$ are of the order of ~0.5 eV [2, 3, 4, 5], with only one positive value reported by part of the Heidelberg-Moscow collaboration [6].

The decay is detected on the basis of the two electron signal: given the negligible energy of the recoiling nucleus the sum kinetic energy of the two electrons is equal to the Q-value of the ββ(0ν)transition. This almost monochromatic signal is the main signature used by

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1 On behalf of the CUORE Collaboration
In order to convert this expression to quantify the $\langle \nu \rangle$ above a background at a given C.L., which can be expressed in terms of the detection efficiency ($\epsilon$), the live-time ($T$), the energy resolution ($\Delta E$) and the background counting rate ($B$) as:

$$S^{0w} = \ln 2 \frac{N_A \cdot a \cdot \eta \cdot \epsilon}{W} \sqrt{\frac{M \times T}{\Delta E \times B}}$$

where $N_A$ is the Avogadro number, $\eta$ is the stoichiometric coefficient of the candidate and $a$ the isotopic abundance. $W$ is the molecular weight of the absorber and $M$ is the mass of the detector.

In order to convert this expression to quantify the $(m_{ee})$ sensitivity we can use equation 1 by taking into account the spread between the different nuclear matrix elements.

The Q-value, the predicted $F_N$ values, the natural isotopic abundance and the available detection techniques bias the choice of the $\beta\beta$ emitters used in experiments. High abundances (or isotopes with a viable enrichment) imply high $N_{\beta\beta}$. High Q-values imply low background ($B$) coming from environmental radioactive emissions. Finally the detection technique defines $\epsilon$ and $\Delta E$ and, in most cases, also restricts the number of isotopes that can be investigated.

$\beta\beta(2\nu)$ experiments can be divided into two major classes, conventionally referred to as $source=detector$ experiments (the particle detector used to search the decay contains - in its active material - the $\beta\beta(2\nu)$ candidate isotopes) and $source\neq detector$ (the source is a passive material inserted into a suitable particle detector). The former technique bases its power on the use of high resolution detectors (low $\Delta E$) with a rather simple set-up, having as a disadvantage the generally poor background rejection capability. In the latter technique only poor resolution detectors have been employed up to now, but the high value of $\Delta E$ is compensated by the presence of some supplementary information - like particle tracking - that allows to establish a powerful background rejection system.

2. CUORICINO

Experiments using low temperature calorimeters (bolometers) belong to the $source=detector$ class. Here the isotope is contained in the molecule of the bolometer absorber which is a single crystal, generally with dielectric and diamagnetic properties. The working principle of a bolometer is quite simple: the energy deposited by a particle traversing or stopping in a crystal absorber produces a thermal signal that - when the temperature is low enough - can be detected with a proper sensor [7]. When compared with traditional solid state devices based on ionization (e.g. semiconductor devices or scintillators), bolometers offer a quite larger choice of materials. Size and energy resolution can be similar to those achieved with Ge diodes. The application of this technique to $\beta\beta(2\nu)$ searches was pioneered by the Milano group [8, 9, 10] with the study of $^{130}$Te $\beta\beta(2\nu)$ by means of TeO$_2$ bolometers. Indeed, $^{130}$Te is considered a golden candidate for $\beta\beta(2\nu)$ investigation because of the favorable $F_N$, the high transition energy 2527.5±0.01 keV [11] and the high natural isotopic abundance (33.8%). This was a good reason to start with $^{130}$Te, when the idea of applying the bolometric technique to $\beta\beta(2\nu)$ searches was proposed, about 20 years ago. The good performances of TeO$_2$ bolometers, their extremely good radiopurity, the reasonable cost of the crystals lead to a story of successes ending up with the result of the CUORICINO experiment that yields the most stringent bound on $m_{ee}$ based on $^{130}$Te studies, and one of the best in general [12].

CUORICINO was an array of 62 detectors (40.7 kg of total mass) of TeO$_2$ natural crystals operated as bolometers in a low temperature refrigerator. Two types of detectors were used for the construction of the array: 44 TeO$_2$ crystals of size 5x5x5 cm$^3$ and mass 790 g (big crystals).
and 18 TeO$_2$ crystals of size 3x3x6 cm$^3$ and mass 330 g (small crystals). All the crystals were made of natural tellurium but 4 of the small size ones. These were made with enriched materials: two of them were enriched to 75% in $^{130}$Te (130 Te-enriched crystals) and two were enriched to 82.3% in $^{128}$Te. The experiment was located underground, in Laboratori Nazionali del Gran Sasso (INFN - Italy), that provides an average coverage of 1400 m of rock (i.e. a depth of 3650 m.w.e.). The array and the experimental set-up are shown in figure 1.

CUORICINO operated between 2003 and 2008 in two slightly different configurations (run I and run II). The total $^{130}$Te exposure was 19.75 kg·y. For the $\beta\beta(0\nu)$ analysis the two $^{128}$Te enriched crystals were not used and their data will not be discussed here. The statistics collected in the two runs is detailed in table 1: big crystals, small-natural crystals and $^{130}$Te-enriched crystals are kept separate in this table as they have been treated separately for the $\beta\beta(2\nu)$ analysis. This is because they are characterized by different masses and consequently different efficiencies with respect both to the background sources and $\beta\beta(0\nu)$. Similarly run I and run II differ in the number of active detectors and in their energy resolutions, therefore they have been treated as two independent experiments whose likelihoods - for $\beta\beta(2\nu)$ analysis - have been combined.

In CUORICINO each detector was provided with its own read-out and DAQ channel and trigger, so that each was a completely independent device. Coincidences among the detectors could be invoked to reject background events (as discussed later) or for dedicated studies such as those aiming at the identification of the background sources. The energy calibration, i.e. the conversion of the thermal pulse amplitude into energy, was provided by a periodic exposure of the entire array to a $^{232}$Th source. The main full energy gamma lines emitted by the beta decaying isotopes of the $^{232}$Th chain (ranging from 511 keV to 2615 keV) were used for this...
Figure 2. Anticoincidence total energy spectrum of all CUORICINO detectors (black). The most prominent peaks are labeled and come from known radioactive sources such as: $e^+e^-$ annihilation (1), $^{214}$Bi (2), $^{40}$K (3), $^{208}$Tl (4), $^{60}$Co (5) and $^{228}$Ac (6). The total energy spectrum of all CUORICINO detectors during calibration measurements is also shown (green). For convenience it is normalized to have the same intensity of the 2615 keV line of $^{208}$Tl as measured in the background spectrum.

In CUORICINO the detector responses were quite uniform within the 3 groups of crystals (big, small and $^{130}$Te-enriched) with respect both to energy resolutions and to background counting rates. In run I we measured a FWHM resolution on the 2615 keV $^{208}$Tl line of $7.8 \pm 2.8$ keV for the big crystals, $9.1 \pm 3.1$ keV for small natural crystals and about 20 keV for the two $^{130}$Te enriched ones. In run II FWHM values were $6.3 \pm 2.5$ keV for the big crystals, $9.9 \pm 4.2$ keV for small crystals and about 13 keV on the two $^{130}$Te enriched ones. Here the error is the spread over the values measured for the different detectors in the 5 calibration measurements done in run I and in the 32 done during run II. The 2615 keV line is used as a reference because it is the high intensity gamma line nearest to the $\beta\beta$ $(2\nu)$ region.

The spectrum obtained by summing all the CUORICINO collected data is shown - below 2.7 MeV - in figure 2. The background recorded by the detectors is clearly dominated, in this region, by the gamma emissions due to radioactive contaminants of the detector and of the surrounding apparatus. The most intense gamma lines are listed in reference [12]. In figure 2, the spectrum corresponding to the sum of all calibration data is also shown. For convenience the calibration spectrum is normalized to have the same intensity of the 2615 keV line of $^{208}$Tl as measured in the background spectrum. The $\beta\beta$ $(2\nu)$ signal was searched for looking to the monochromatic peak that would be produced by the $\beta\beta$ $(0\nu)$ decays fully contained within the source crystal. These are a quite large fraction of the total number of decays (~87% for the big crystals and ~84% for the smaller ones) and would produce a line at the transition energy. When looking to this particular signature, an efficient background suppression technique is that obtained operating the array in anticoincidence. This provides in CUORICINO a suppression of the background in the Region Of Interest (ROI) of about 20%.

In the CUORICINO spectrum no peak was observed in correspondence of the $^{130}$Te $\beta\beta$ transition energy. The $\beta\beta$ $(2\nu)$ half-life limit was evaluated as follows. The peaks and continuum in the region of the spectrum centered on the $\beta\beta$ $(2\nu)$ energy were fit using a maximum likelihood analysis where free parameters were the $\beta\beta$ $(2\nu)$ rate, the $^{60}$Co rate and line position.

2 Here we refer to the 2505 keV line visible in the ROI, which is due to the coincident detection - in a crystal - of the two gamma rays emitted by $^{60}$Co.
Table 1. Cuoricino Run I and Run II crystal masses and exposures.

| Crystal Type       | Crystal Mass [g] | $^{130}$Te Mass [g] | Exposure Run II [kg($^{130}$Te)·y] | Exposure Run I [kg($^{130}$Te)·y] |
|--------------------|------------------|---------------------|------------------------------------|-----------------------------------|
| big                | 790              | 217                 | 15.80                              | 0.94                              |
| small              | 330              | 91                  | 2.02                               | 0.094                             |
| $^{130}$Te-enriched| 330              | 199                 | 0.75                               | 0.145                             |

and the flat background rate. A Bayesian approach has been then used to evaluate the $T_{1/2}^{0ν}$ lower bound for $^{130}$Te decay that results to be $2.8\times10^{24}$ y at 90% C.L.[13]. In this value the systematic errors have been included. This limit was used to extract an upper limit on $m_{ee}$ using the theoretical NME evaluations for the $^{130}$Te nucleus that - depending on the nuclear model- range from 300 meV to 710 meV. Indeed:

- 300-570 meV is the range obtained using the Quasiparticle Random Phase Approximation (QRPA) evaluations of reference [14].
- 360-580 meV is the range obtained using the QRPA evaluations of reference [15].
- 570-710 meV is the range obtained using the Shell Model (SM) evaluations of reference [16].
- 350-370 meV is the range obtained using the Interacting Boson Model (IBM) evaluations of reference [17].

Note that, for each reference, a range (and not a single value) for $m_{ee}$ is presented because of the different results on the NME obtained by the authors when e.g. varying the treatment of the short range correlations or the value of $g_A$ (the axial-vector coupling).

3. CUORE

CUORE is the natural extension of the CUORICINO experiment toward higher $ββ(2ν)$ sensitivities. The CUORE Project [18] foresees the realization of a $ββ(2ν)$ experiment with an active mass of the order of 1 ton. CUORE will employ 988 natural TeO$_2$ bolometers each made of a cubic $5\times5\times5$ cm$^3$ TeO$_2$ crystal with a mass of about 750 g. The goal of the CUORE collaboration is to reach, in the energy region of interest, a background level lower than $10^{-2}$ counts/keV/kg/y obtaining hence a sensitivity on the effective Majorana mass of the order of 50 meV. The background counting rate in the ROI has to be reduced by a factor $\sim$16 with respect to CUORICINO (in the ROI the $5\times5\times5$ cm$^3$ crystals in CUORICINO had a counting rate of 0.161±0.006 counts/keV/kg/y). The CUORE array 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 interposed. The 988 bolometers of the array are arranged in a cylindrical matrix organized into 19 towers, each made of 13 planes. Every plane contains four crystals supported inside a Copper frame. 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 (see figure 3). 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 activity. A borated polyethylene shield and an air-tight cage will surround externally the cryostat. The experiment will be installed underground in the same experimental hall of LNGS where CUORICINO was operated.

While operating a 1000 bolometer array at 10 mK could look rather challenging, the technical feasibility of CUORE has been extensively proved by the good performances of the CUORICINO
experiment, and the possibility of cooling large masses in dilution refrigerators have been proved, for example, by the gravitational antenna experiments. With respect to CUORICINO, the CUORE array will benefit from an improved mechanical decoupling of the array from the cryogenic set-up, from the elimination of the LHe bath and from a holder for the crystal that has been specifically studied to reduce vibrational noise contribution to the energy resolution. All this should lead to a better reproducibility of the detectors from the point of view of their energy resolution and threshold, as well as to a better duty cycle in the data taking.

The true challenge in CUORE - as in all the next generation $\beta\beta(2\nu)$ experiments - will be in achieving the background target. The set-up of the experiment is designed in order to ensure a negligible contribution coming from external background sources such as cosmic rays (i.e. the residual underground muon flux), neutrons (muon-induced or radioactivity-induced) and gammas (from radioactive contamination or from neutron/muon-induced reactions) [19]. The severe selection of all the construction materials used in CUORE will allow to control the gamma contribution to the $\beta\beta(0\nu)$-decay background. This contribution is expected to be mainly due to the $^{208}\text{Tl}$ gamma line at 2615 keV. Indeed, this is the only gamma line due to environmental long-living contaminations ($^{208}\text{Tl}$ belongs to the $^{232}\text{Th}$ chain) having an energy high enough to contribute to the ROI with a sizable branching ratio. In CUORICINO the contribution of this line is evaluated to be of about 30\% of the total counting rate in the ROI, while the residual 70\% of counts (i.e. $\sim 0.11$ counts/keV/kg/y) is ascribed mainly to degraded alpha particles. Indeed, $^{238}\text{U}$ and $^{232}\text{Th}$ contaminations in the $\text{TeO}_2$ crystal surfaces or in the materials directly facing the crystals produce - in their decay - alpha particles with energies larger than 4 MeV. When the alpha deposits only a fraction of its energy in the crystal - either because the decay

\footnote{Note that the array is held in vacuum, fixed in a Copper skeleton by means of PTFE stands, and bolometers are fully active i.e. they do not have any dead layer.}
originated in a facing inert material or in a nearby crystal - it contributes to the background below 4 MeV [20]. Such contributions can extend down to the lowest energies and certainly in the ROI. This kind of sources are responsible of the rather flat continuum - extending from 4 MeV down to the 2.615 keV line - which is measured by the CUORICINO experiment. The alpha background due to crystal surface contaminations is reduced by operating the detectors in anticoincidence, in CUORICINO a fraction of the mentioned 20% reduction obtained by the anticoincidence cut has to be ascribed to the rejection of this kind of events. In CUORE the same technique will be much more efficient, since a larger fraction of the crystal surface will be facing a nearby crystal. However anticoincidences have no effect on alpha events where a crystal and an inert material (as the Copper holder) are involved. For this reason huge efforts have been devoted by the CUORE collaboration in the study of procedures capable of control and reduce \(^{238}\text{U}\) and \(^{232}\text{Th}\) surface contaminations in all the parts used for the array construction, and mainly in TeO\(_2\) crystals and Copper. For both of these materials important achievements have been obtained [21, 22] proving that a background of \(10^{-2}\) counts/keV/kg/yr is feasible. These techniques will be used to assemble the first CUORE tower that will be tested, as a stand alone experiment, in the CUORICINO cryostat within year 2011. Besides being a very important step in CUORE construction this first tower (CUORE-0) will be able to produce a meaningful improvement in the \(^{130}\text{Te}\) \(\beta\beta(2\nu)\) results of CUORICINO.

4. Conclusions
The result of the CUORICINO experiment has been presented: with an average background of 0.161±0.006 in the ROI, it was possible to set an upper limit for the effective neutrino Majorana mass from 300 to 710 meV, depending on the nuclear model used for NME calculations. The next generation bolometric experiment CUORE, which has CUORICINO as a fundamental prototype, has also been presented. CUORE, with a forseen aim of \(10^{-2}\) counts/keV/kg/yr of background contributions in the region of interest and with an active mass of nearly 206 kg of \(^{130}\text{Te}\), will be able to probe the inverted hierarchy of neutrino mass in 5 years of live time.
References

[1] Examples of reviews are:
  V. I. Tretyak and Yu. G. Zdesenko, Atomic Data and Nuclear Data Tables, 80 (2002) 83.
  S. Elliott and P. Vogel, Ann. Rev. Nucl. Part. Sci. 52 (2002) 115.
  A. Morales and J. Morales, Nucl. Phys. B (Proc. Suppl.) 114 (2003) 141.
  F. T. Avignone III, S. R. Elliott and J. Engel (2006), Rev. Mod. Phys. 80 (2008) 481.

[2] H. V. Klapdor-Kleingrothaus et al., Eur. Phys. J. A 12 (2001) 147.

[3] C. E. Aalseth et al., Phys. Rev. D 65 (2002) 092007.
  C. E. Aalseth et al., Phys. Rev. D 70 (2004) 078302.

[4] R. Arnold et al., Phys. Rev. Lett. 95 (2005) 182302. A. S. Barabash (NEMO Collaboration), Presentation at XXXIII International Conference on High Energy Physics (Moscow, July 26 - August 02, 2006), [arXiv:hepex/0610025].

[5] C. E. Aalseth et al., Phys. Rev. D 65 (2002) 092007.
  C. E. Aalseth et al., Phys. Rev. D 70 (2004) 078302.

[6] R. Bernabei et al., Phys. Lett. B 546 (2002) 23.
  H. V. Klapdor-Kleingrothaus et al., Mod. Phys. Lett. A, 16 (2001) 2409.
  H. V. Klapdor-Kleingrothaus et al., Nucl. Instr. Meth. A, 522 (2004) 371.

[7] H. V. Klapdor-Kleingrothaus et al., Nucl. Instr. Meth. A, 522 (2004) 371.
  N. Booth, B. Cabrera and E. Fiorini, Ann. Rev. Nucl. Part. Sci. 46(1996) 471.
  A. Alessandrello, Czech. J. Phys. 48 (1998) 133.
  C. Enss and D. McCammon, J. of Low Temp. Phys. 151(2008) 5;

[8] A. Alessandrello et al., Phys. Lett. B 285 (1992) 176;
  A. Alessandrello et al., Phys. Lett. B 335 (1994) 519-525.

[9] A. Alessandrello et al., Nucl. Instr. Meth. A 360 (1995) 363.
  A. Alessandrello et al., Nucl. Instr. Meth. A 370 (1996) 241.

[10] A. Alessandrello et al., Phys. Lett. B 433 (1998) 156.

[11] M. Redshaw, B. J. Mount, E. G. Myers, and F. T. Avignone III, Phys. Rev. Lett. 102 (2009) 212502.

[12] C. Arnaboldi et al., Phys. Rev. Lett. 95 (2005) 14501.
  C. Arnaboldi et al., Phys. Rev. C 78 (2008) 035502.
  C. Arnaboldi et al., submitted to AstroparticlePhysics (2010).

[13] Andreotti et al., Astropart. Phys. 34 (2011) 822831.

[14] F. Simkovic et al., Phys.Rev. C 77 (2008) 045503.

[15] O. Civitarese et al., JoP Conference series 173 (2009) 012012.

[16] J. Menendez et al., Nucl. Phys. A 818 (2009) 139.

[17] J. Barea and F. Iachello, Phys.Rev. C 79 (2009) 044301.

[18] C. Arnaboldi et al., Astropart. Phys. 20 (2003) 91.
  C. Arnaboldi et al., Nucl. Instr. Meth. A 518(2004) 775.

[19] F. Bellini et al., Astropart. Phys. 33 (2010) 169.

[20] M. Pavan et al., Eur. Phys. J A 36 (2008) 159.
  C. Bucci et al., Eur. Phys. J A 41 (2009) 155.

[21] C. Arnaboldi et al., J. Cryst. Growth 312 (2010) 2999.

[22] C. Arnaboldi et al., LNGS Annual Report year 2009.