# STATUS OF THE CUORE EXPERIMENT AND RESULTS OF CUORICINO: SEARCHING FOR 0νDBD OF $^{130}$Te WITH LOW TEMPERATURE DETECTORS

**L. M. Ejzak (on behalf of the CUORE collaboration)**

[1] *Department of Physics, University of Wisconsin-Madison, Madison, USA*

The Cryogenic Underground Observatory for Rare Events (CUORE) is an experiment under construction at Gran Sasso National Laboratories in Italy to search for neutrinoless double beta decay (0νDBD) in $^{130}$Te and other rare processes. The observation of 0νDBD would indicate that neutrinos are Majorana particles and would provide information about the absolute neutrino mass scale. CUORE is a bolometric detector composed of 988 $TeO_2$ crystals, with a total mass of about 750 kg of natural tellurium. Cuoricino, the predecessor experiment operated at LNGS until 2008, employed an array of large cubic $TeO_2$ crystals with a total mass of 40 kg. We will discuss the status of the CUORE experiment, including a discussion of critical points, the recent R&D efforts, and the anticipated sensitivity. We will also discuss the performance of the Cuoricino detector, and present the physics results.

## 1. Introduction

Nuclear beta decay is the familiar process in which a nucleon decays, releasing a positron (electron) and an electron (anti)neutrino. For some even-even nuclei, this single beta decay is forbidden, since the resulting nucleus would be less bound than the initial nucleus; however, it is possible to instead observe two-neutrino double beta decay (2νDBD), in which two nucleons decay coherently, if the nucleus resulting from this process would be more bound than the initial nucleus. The half-lives for 2νDBD are long – typically of order $10^{18}$ - $10^{21}$ years, or longer – since it is a second-order weak process, but this decay has been observed in a number of isotopes [1].

If neutrinos are Majorana particles, some small fraction of the time these isotopes could undergo neutrinoless double beta decay (0νDBD) instead, in which a virtual particle exchange would take the place of the production of two physical (anti)neutrinos. The signal for this process is a sharp peak in the beta energy spectrum at the Q-value of the decay, as the nucleus is so heavy that the recoil is negligible. At this time, the only feasible experimental approach to determining whether neutrinos are Majorana particles is to search for evidence of 0νDBD.

The observation of 0νDBD also has some potential to probe the absolute mass of the neutrino and the neutrino mass hierarchy. In the case that 0νDBD is mediated by the exchange of a virtual light Majorana neutrino, the 0νDBD decay rate $\Gamma_{0\nu}$ is related to the neutrino mass by

$$\Gamma_{0\nu} = G^{0\nu} \left|M_{nucl}\right|^2 \left\langle m_\nu \right\rangle^2 , \tag{1}$$

where the effective 0νDBD neutrino mass is

$$\left\langle m_\nu \right\rangle = \left|\sum_j \left|U_{ej}\right|^2 e^{i\phi_j} m_j\right|. \tag{2}$$

In the above equations, $G^{0\nu}$ is a phase space integral; $M_{nucl}$ represents nuclear matrix elements; the $U_{ej}$ are elements of the neutrino mixing matrix; the $\phi_j$ are (only two non-zero) possible complex Majorana phases, and the $m_j$ are the physical neutrino mass eigenvalues [2]. Experimental results are often expressed in terms of the half-life $T_{1/2}^{0\nu}$ $(\propto \Gamma_{0\nu}^{-1})$.

Unfortunately, the measured quantity, $\Gamma_{0\nu}$, can offer only limited information about the physical masses. While $G^{0\nu}$ can be accurately calculated, there is significant theoretical uncertainty in the calculation of the $M_{nucl}$, and the non-zero phases $\phi_j$ are completely unknown [3]. Nonetheless, it is possible to use the information about the $U_{ej}$ that has been gained from oscillation experiments to determine the allowed phase space for $\left\langle m_\nu \right\rangle$ with respect to the sum of the physical masses; an observation of 0νDBD would then reduce the size of this allowed region.

It is important to note that the above discussion applies *only* in the simple case that 0νDBD is mediated by the exchange of a virtual light Majorana neutrino (assumed for the rest of this paper). If some other lepton-number-violating physics is responsible, it becomes much more difficult if not impossible to extract $\left\langle m_\nu \right\rangle$ [2]. However, no matter what mechanism is responsible, if 0νDBD is observed then neutrinos are Majorana particles [4].

Since 0νDBD, assuming it happens at all, is such a rare process – even more so than 2νDBD – the attempt to observe it experimentally poses a challenge. The sensitivity of an experiment can be written

$$\text{half-life sensitivity at } n_\sigma = \frac{\ln(2)}{n_\sigma} \frac{N_A \alpha \varepsilon}{W} \sqrt{\frac{Mt}{b\Delta E}}, \tag{3}$$

where $n_\sigma$ is the desired confidence level in terms of the number of Gaussian standard deviations, $N_A$ is Avogadro's number, $\alpha$ is the isotopic abundance of the candidate nuclide, $\varepsilon$ is the detector efficiency, $W$ is the molecular weight of the detector material, $M$ is the total detector mass, $t$ is the detector live time, $b$ is the constant background rate per unit detector mass per energy interval, and $\Delta E$ is the energy resolution of the detector. Thus a successful 0νDBD experiment will need to be a long-running, low-background experiment with good resolution and a large-mass detector.

## 2. Moving from Cuoricino to CUORE

The CUORE experiment will be a search for evidence of neutrinoless double beta decay. It will use the bolometric technique established with its predecessor, Cuoricino, and should be able to achieve an improvement of approximately two orders of magnitude in sensitivity to the 0νDBD half-life $T_{1/2}^{0\nu}$ over Cuoricino's current limit (see Section 3).

### 2.1. The Cuoricino and CUORE Detectors

The design of the CUORE detector is based on the bolometric principle, as tested in the pilot experiment, Cuoricino. The detector is an array of (dielectric and diamagnetic) $TeO_2$ crystals, so the detector itself contains the source ($^{130}Te$) under investigation. The crystals are operated as calorimeters; whenever an event occurs in a crystal, the energy it deposits is converted to phonons and manifests as a small temperature rise. The array is housed in a cryostat which keeps the crystals at 8 - 10 mK, reducing their heat capacity and thereby improving both the magnitude of the temperature response and the recovery time constant [5]. Each crystal is equipped with a thermistor – a resistor whose resistance changes rapidly with temperature. A bias current $I$ is applied across the thermistor, and the change in the resultant voltage $V$ across it as the thermistor's resistance changes with temperature is read out. The detector's exact response depends on the point on its $V-I$ load curve at which it is operating, known as the working point, which in turn depends on the base temperature of the bolometer.

Both Cuoricino and CUORE use $TeO_2$ crystals to study the decay of $^{130}Te$. Tellurium is an advantage in this instance because of the relatively high natural abundance (33.8%) of the 0νDBD candidate isotope, which means that enrichment is not necessary to achieve a reasonably large active mass. Also, the Q-value of the decay falls in a relatively clean window between the peak and the Compton edge of the 2615 keV gamma line of $^{208}Tl$, the highest-energy gamma from the natural decay chains [5]. Two recent measurements give the Q-value as 2527.01 ± 0.32 keV [6] and 2527.518 ± 0.013 keV [7], a marked improvement in precision over the previously-accepted value of 2530.3 ± 2.0 keV [8]. Cuoricino was comprised of a single tower of crystals, with a total detector mass of 40.7 kg and a $^{130}Te$ mass of 11.34 kg. By contrast, CUORE will consist of an array of 988 $5\times5\times5$ cm$^3$ $TeO_2$ bolometer crystals, arranged in 19 towers of $2\times2\times13$ crystals apiece; the total detector mass will be 741 kg, which corresponds to a $^{130}Te$ mass of ~204 kg.

The design and construction of the cryostat that will be used to maintain the detectors at the necessary cryogenic temperatures is a rather unique undertaking. It is based on the comparatively recently-developed technology of the cryogen-free dilution refrigerator, which utilizes pulse tube pre-cooling instead of a liquid helium bath; this should allow improved stability of the base temperature of the detector as compared to the traditional $^3He/^4He$ refrigerator (used for Cuoricino). It will be the first cryostat of its kind big enough to house and cool the large detector mass represented by the CUORE array (~1 ton).

In addition to the increase in scale from Cuoricino to CUORE, in order for CUORE to reach its anticipated sensitivity, improvement is foreseen in two crucial aspects of detector performance: resolution and background. The average FWHM resolution at 2615 keV of the Cuoricino bolometers was approximately 7 keV; the goal for CUORE is 5 keV. Tests of the first batches of crystals produced for CUORE have shown that this goal has already been met, by means of improvements in the crystal quality, detector mounting structure, and reproducibility of the thermistor-crystal couplings. The average flat background in the region of interest seen in Cuoricino was 0.18 counts/(keV kg yr); the CUORE goal is to reach 0.01 counts/(keV kg yr) [9].

### 2.2. Backgrounds

0νDBD experiments must be low-background experiments, and CUORE is no exception. The CUORE detector, like Cuoricino before it, will be located underground in the Laboratori Nazionali del Gran Sasso (LNGS) in Italy in order to reduce the rate of cosmic ray events; the cryostat will also contain shielding constructed from ancient low-radioactivity lead (Fig. 1) and be surrounded by additional lead to block environmental radioactivity from reaching the detector, and the detector structure itself will be composed of low-background materials and handled entirely in clean room conditions.

In Cuoricino, the main sources of the 0.18 ± 0.01 counts/(keV kg yr) background were the natural uranium and thorium decay chains from contamination of the detector materials. There were two main components: surface contamination of the detector components, and bulk contamination of the cryostat materials. The surface contamination produced a flat α background in the region of interest; the main contributors were the surfaces of the copper support structures facing the bolometers (50 ± 20 % of the total background in the 0νDBD region) and of the crystals themselves (10 ± 5 %). The principal background contribution due to bulk contamination was the tail of the 2614.5 keV

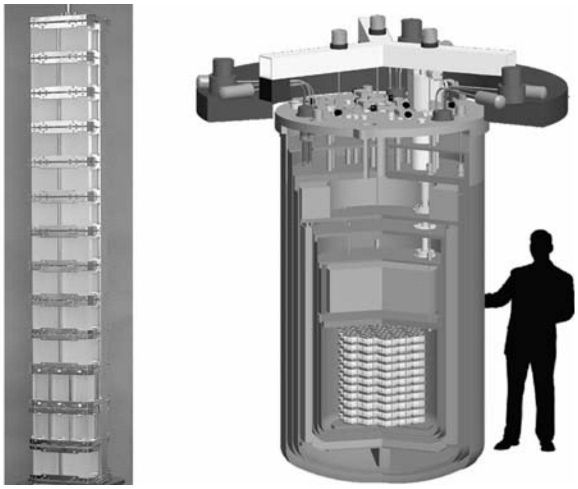

Fig. 1. *Left*: a photo of the Cuoricino detector tower. *Right*: a 3-D scale model of the CUORE detector and cryostat.

gamma produced by the decay chain of $^{232}$Th in the cryostat materials (30 ± 10 %). These values have been verified by extensive Monte Carlo studies [9].

The goal that CUORE is striving to reach is 0.01 counts/(keV kg yr). To this end, stringent new material selection, production, cleaning, handling, and storage procedures have been established for all detector components. The cleaning of the copper support structures in particular has been the subject of an intense R&D program. Test runs have demonstrated background levels within a factor of 2-4 of the goal when extrapolated to CUORE.

To some extent, the array can self-veto against penetrating background particles like muons, and spurious events due to detector noise can be filtered out through pulse-shape analysis; however, in the end, the only real data, and therefore the only real handle on event identification, that bolometers provide is energy information. This is quite suitable for a 0νDBD experiment, since an energy signal is precisely what is sought, but it does mean that reliable, precise energy calibration is absolutely essential to the experiment's ability to provide meaningful data.

### 2.3. The CUORE Detector Calibration System

Energy calibration must be performed in order to determine the relationship between the energy deposited in a crystal and the voltage signal subsequently obtained from the thermistor. In order to do this, a gamma source with a known spectrum is used to illuminate the crystals. Although the most critical energy region that must be calibrated is the region of interest around the 0νDBD Q-value, the whole spectrum should be calibrated as well as possible for reliable identification of backgrounds. For this purpose, Cuoricino used $^{232}$Th as its calibration source, since its decay chain produces a number of gamma lines up to 2615 keV that are strong enough to be used for calibration; the 2615 keV peak is particularly strong, and can be used to ensure good calibration in the region of interest. The calibration uncertainty in the region of interest is a systematic error in the determination of $T_{1/2}^{0\nu}$. In Cuoricino, this uncertainty was negligible; however, with the improved precision in recent Q-value measurements, the performance of the CUORE calibration system is of greater importance.

The thermistors' response will change with small variations in the working point of the detector. Between calibrations, the response of the bolometers is stabilized by means of periodic heater pulses of known energy, and the base temperature of the detector is stabilized with a DC feedback loop; however, it is still necessary to perform a calibration every month or two. 'Minimal disruption' means that the calibration system must not compromise the low-background environment of the detector, nor place excessive thermal load on the cryostat such that the detector warms up, changing the working points of the bolometers.

In scaling up from the single tower of Cuoricino to the 19 towers of CUORE, the calibration system must grow in complexity. In Cuoricino, a single tower of crystals, two radioactive source wires were inserted inside the external shielding on either side of the cryostat. In CUORE, the outer towers will shield the inner towers, so some calibration sources must be routed inside the cryostat itself and between the towers in order to achieve sufficient event rates on the inner crystals without causing excessively high rates on the outer ones. Since bolometers are inherently slow (each pulse lasts several seconds), a high rate causes pileup and raises the baseline temperature of the detectors, leading to increased dead time and degradation of the energy resolution.

The CUORE detector calibration system addresses these requirements in the following way: the system consists of 12 flexible source carriers, routed through the levels of the cryostat by means of guide tubes, and stored and deployed by four motion boxes containing three spools each which sit on top of the 300 K flange of the cryostat. This approach allows the sources to be stored entirely outside the cryostat during normal data-taking, and to traverse the complicated routes through the interior of the cryostat necessary to reach the detector area. Motion in cryogenic and vacuum conditions is challenging, because of the mechanical and thermal effects of friction and vibration; additional complication arises from the fact that the calibration sources must travel through regions of differing temperatures, from 300 K to 8 - 10 mK, without failing under thermal cycling or thermally overloading the cryostat. Similarly, the low-background environment of the cryostat must not be compromised. The system has been carefully designed to meet these challenges; a detailed discussion can be found in [10].

## 3. Cuoricino results and expected future reach

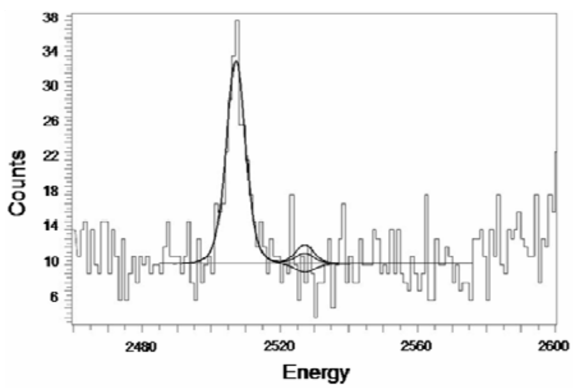


Fig. 2. The most recent evaluation of the Cuoricino limit (preliminary). The left-hand peak comes from gammas caused by $^{60}$Co contamination of the copper support structures. The three 0νDBD contours shown are, from bottom to top: best fit, 1σ, and 90 % C.L.

At the moment, experimental limits on $T_{1/2}^{0\nu}$ lie in the so-called degenerate-hierarchy region of the $\langle m_\nu \rangle$ phase space, where the absolute neutrino mass scale is much larger than the mass difference. There is also a claim to have actually seen 0νDBD in $^{76}$Ge from a subset of the Heidelberg-Moscow collaboration, also in the degenerate-hierarchy region [11 - 13]. It is important to test this claim using a different DBD isotope, with different systematics and nuclear matrix element calculations. Thus the goal of CUORE, and of all next-generation 0νDBD experiments, is twofold: to test the $^{76}$Ge claim, and to extend sensitivity into the inverted-hierarchy region.

The last-published Cuoricino limit was $T_{1/2}^{0\nu} \geq 3.1\cdot10^{24}$ yr (90 % C.L.) [9]. However, the current Cuoricino limit (Fig. 2), a preliminary result including more statistics and using an updated Q-value measurement (see section 2.1) as compared to the last-published result, revises this number to $T_{1/2}^{0\nu} \geq 2.94\cdot10^{24}$ yr (90 % C.L.) [14]; this corresponds to $\langle m_\nu \rangle \leq$ (300 - - 690) meV, where the range arises from the different calculations of the nuclear matrix elements in Refs. [15 - 18]. CUORE's predicted limit after about five years of running is $T_{1/2}^{0\nu} \geq 2.1\cdot10^{26}$ yr (90 % C.L.), corresponding to $\langle m_\nu \rangle \leq$ (35 - 82) meV, assuming the 0.01 counts/(keV kg yr) goal for the background rate is met (see Section 2.2).

## 4. Conclusions and status of the experiment

CUORE is in the construction phase. The facilities at LNGS are under construction, and crystal production has been ongoing since 2008. By the end of 2010, the first CUORE tower will be assembled and installed in the Cuoricino cryostat; this tower will take data independently as CUORE-0, providing an 'engineering run' to verify CUORE assembly procedures as well as allowing statistics compatible with those of Cuoricino to continue to accrue until the full CUORE array is operational. CUORE detector construction will continue through 2012; data taking with the full CUORE array will begin in 2013.

CUORE is a next-generation 0νDBD experiment which will utilize the bolometric detection technique proven in its predecessor, Cuoricino. It is now in the construction phase, and will be one of the first 0νDBD experiments to probe the inverse hierarchy mass region.

REFERENCES

1. *Barabash A.S.* Average and recommended half-life values for two-neutrino double-beta decay: Upgrade '05 // Czech J. Phys. - 2006. - Vol. 56. - P. 437 - 452.
2. *Elliot S. R., Vogel P.* Double beta decay // Ann. Rev. Nucl. Part. Sci. - 2002. - Vol. 52. - P. 115 - 151.
3. *McKeown R. D., Vogel P.* Neutrino masses and oscillations: triumphs and challenges // Phys. Rept. - 2004. - Vol. 394. - P. 315 - 356.
4. *Schechter J., Valle J.* Neutrinoless double-β decay in SU(2)xU(1) theories // Phys. Rev. D - 1982. - Vol. 25. - P. 2951 - 2954.
5. *Ardito R. et al.* [CUORE collaboration] CUORE: A Cryogenic Underground Observatory for Rare Events // arXiv:hep-ex/0501010v1 - 2005.
6. *Scielzo N. D. et al.* Double-β-decay Q values of $^{130}$Te, $^{128}$Te, and $^{120}$Te // Phys. Rev. C. - 2009. - Vol. 80. - P. 025501.
7. *Redshaw M., Mount B. J., Myers E. G., Avignone F. T. III* Masses of $^{130}$Te and $^{130}$Xe and Double-β-decay Q value of $^{130}$Te // Phys. Rev. Lett. - 2009. - Vol. 102. - P. 212502.
8. *Audi G., Wapstra A. H., Thibault C.* The AME2003 atomic mass evaluation: (II). Tables, graphs and references // Nucl. Phys. A. - 2003. - Vol. 729. - P. 337 - 676.
9. *Arnaboldi C.* Results from a search for the 0νββ-decay of $^{130}$Te // Phys. Rev. C. - 2008. - Vol. 78. - P. 035502.
10. *Sangiorgio S. et al.* The low-temperature energy calibration system for the CUORE bolometer array // Proc. of the 13$^{th}$ Int. Workshop on Low Temperature Detectors (LTD) / Ed. by B. Cabrera, A. Miller, B. Young. - AIP Conf. Proc. 1185. - Melville, NY, 2009. - P. 677 - 680.
11. *Klapdor-Kleingrothaus H.V., Dietz A., Harney H.L., Krivosheina I.V.* Evidence for neutrinoless double beta decay // Mod. Phys. Lett. A. - 2001. - Vol. 16. - P. 2409 - 2420.

12. *Klapdor-Kleingrothaus H.V., Dietz A., Krivosheina I.V., Chkvorets O.* Data acquisition and analysis of the $^{76}$Ge double beta experiment in Gran Sasso 1990 - 2003 // Nucl. Inst. and Meth. A. - 2004. - Vol. 522. - P. 371 - 406.
13. *Klapdor-Kleingrothaus H.V., Krivosheina I.V.* The evidence for the observation of $0\nu\beta\beta$ decay: the identification of $0\nu\beta\beta$ events from the full spectra // Mod. Phys. Lett. A. - 2006. - Vol. 21. - P. 1547 - 1566.
14. *Ferroni F.* Results of Cuoricino and review of neutrinoless double beta searches // Proc. of Rencontres de Moriond EW 2009.
15. *Simkovic F., Faessler A., Rodin V. et al.* Anatomy of nuclear matrix elements for neutrinoless double-beta decay // Phys. Rev. C. - 2008. - Vol. 77. - P. 045503.
16. *Suhonen J., Kortelainen M.* Nuclear matrix elements for double beta decay // Int. J. Mod. Phys. E. - 2008. - Vol. 17. - P. 1 - 11.
17. *Menendez J., Poves A., Caurier E., Nowacki F.* Disassembling the nuclear matrix elements of the neutrinoless double beta decay // Nucl. Phys. A. - 2009. - Vol. 818. - P. 139 - 151.
18. *Barea J., Iachello F.* Neutrinoless double-β decay in the microscopic interacting boson model // Phys. Rev. C. - 2009. - Vol. 79. - P. 044301.