

RESULTS FROM CUORICINO EXPERIMENT AND PROSPECTS FOR CUORE

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Cuoricino is a taking data bolometric experiment searching for neutrinoless double beta decay ($0\nu\text{DBD}$) of ^{130}Te . The detector consists of an array of large cubic TeO_2 crystal bolometers. Cuoricino works at about 10 mK in the Gran Sasso Underground Laboratory. Good energy resolutions were obtained (2.1 keV at 911 keV and 3.9 keV at 2615 keV at best). The counting rate in the region of $0\nu\text{DBD}$ is 0.18 ± 0.02 c/keV/kg/y. The limit for the $0\nu\text{DBD}$ half lifetime is 2.0×10^{24} years at the 90% of C.L. This results correspond to a limit for the effective neutrino mass between 0.2 and 1.0 eV, depending on the nuclear matrix elements used. A large international collaboration is working on CUORE project, a future experiment with a mass of 741 kg of TeO_2 crystal bolometers. The experiment aims to probe the neutrino absolute mass down to 50 meV and to understand if the inverted hierarchy holds in the neutrino mass pattern.

1. Introduction

The recent positive results coming from neutrino oscillation experiments have increased the attention on neutrino physics. Indeed these experiments indicate that the neutrino flavor and the neutrino mass eigenstates are different and that neutrinos have non zero masses. These results are important in view of new theoretical models beyond Standard Model. However many questions regarding the properties of this particle are still open. In particular, which is the neutrino mass hierarchy? Up to now three mass scenarios are possible: the normal hierarchy, where $m_1 \ll m_2 \ll m_3$, the inverted hierarchy with $m_3 \ll m_1 < m_2$ and the quasi-degenerate one with $m_1 \sim m_2 \sim m_3$. Moreover the neutrino oscillations experiments indicate only the differences among the neutrino mass eigenvalues but not their absolute values, so what are the masses, M_i , of the neutrino mass eigenstates ν_i ? Another open question regards the neutrino nature: are the neutrino and the antineutrino the same particle? Possible answers could come from Neutrinoless Double Beta Decay ($0\nu\text{DBD}$) experiments.

1.1. *The Double Beta Decay*

The Double Beta Decay (DBD) is a rare spontaneous nuclear transition ^{1,2} where a nucleus (A, Z) becomes a $(A, Z \pm 2)$ nucleus. This type of decay is

not favored with respect to the single beta decay and so it is possible to observe it only for those nuclei whose single β decay is either energetically forbidden or suppressed by a large change of the nuclear spin–parity state.

Mainly two different channels of DBD are discussed: the first one, the 2ν DBD, is described by the following reaction

$$2\nu\text{DBD} : \quad (A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e, \quad (1)$$

where two neutrinos are emitted and the lepton number is conserved. This type of decay is allowed by the SM and presently it has been observed for ~ 10 nuclei³. The second possible DBD channel is the Neutrinoless Double Beta Decay described by the reaction

$$0\nu\text{DBD} : \quad (A, Z) \rightarrow (A, Z + 2) + 2e^- \quad (2)$$

Here the emission and the re–absorption of a virtual neutrino mediates the decay. This last channel requires that neutrino and antineutrino are the same particle or, as said, a Majorana particle. Moreover the decay is allowed only if the neutrino has a non–zero mass.

In 0ν DBD, the two electrons retain all the available kinetic energy. For this reason, the expected spectrum is just a spike at the transition energy. On the contrary, the 2ν DBD is a four body decay and so it is expected a continuum spectra with a maximum value around one third of the Q value. The total expected energy spectrum is shown in fig. 1 (left).

The DBD is characterized by a very long lifetime, for example those for the 2ν DBD is in the range of $\sim 10^{18} - 10^{22}$ years. The 0ν DBD probability is connected to the effective neutrino mass, $\langle m_\nu \rangle$, by Fermi’s golden rule:

$$\left[T_{1/2}^{0\nu} \right]^{-1} = G^{0\nu} |M^{0\nu}|^2 \langle m_\nu \rangle^2 \quad (3)$$

where $G^{0\nu}$ is the phase space integral that can be estimated exactly and $|M^{0\nu}|^2$ is the decay matrix element. The effective neutrino mass is a linear combination of the neutrino mass eigenvalues:

$$\langle m_\nu \rangle = \sum_i \phi_i M_i |U_{ei}|^2 \quad (i = 1, 2, 3) \quad (4)$$

with $|U_{ei}|$ the neutrino mass matrix elements. The ϕ_k phases that appear in last equation are the intrinsic neutrino CP parities. Their presence implies that cancellations are possible.

From eq (4) it is clear that 0ν DBD could help to solve questions on the absolute value of neutrino masses and to probe the hierarchy scheme as shown in fig. 1 (right) where the neutrino oscillation results have been considered.

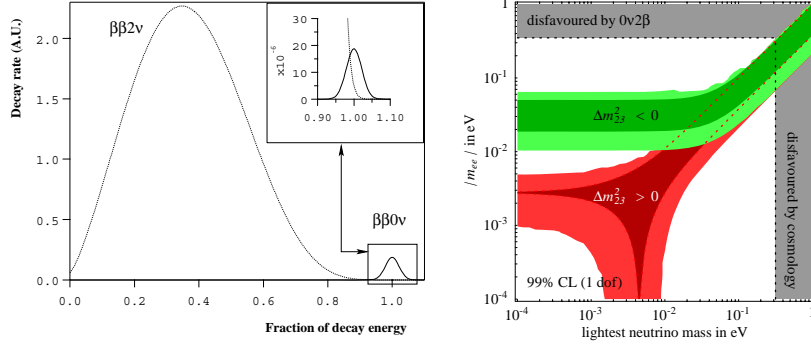


Figure 1. (Left) Expected spectrum of the sum of the energy of the electrons for $DDB2\nu$ (dashed line) and $DDB0\nu$ (solid line). In the inset the contribution of the 2ν decay to the $0\nu DDB$ background is underlined. (Right) Plot of the effective mass $\langle m_\nu \rangle$ as a function of the lightest neutrino mass (on a log-log scale). The dark regions are the possible neutrino mass range. Here neutrino oscillation experiment results have been considered with negligible errors.

From eq. (3), it is also clear that the evaluation of $\langle m_\nu \rangle$ from an experimental measure of $T_{1/2}^{0\nu}$ will require the exact knowledge of the nuclear matrix elements. This could be the main limitation when using $0\nu DDB$ results for implications on neutrino physics.

1.2. Experimental approaches

Most of the recent experiments use direct measurement approaches to study the $0\nu DDB$ that allow to determine the electron energy and its distribution, and sometimes permit also event reconstruction.

In order to perform a sensitive experiment searching for $0\nu DDB$ it is necessary to take into account the difficulties due to the very long half time of the DBD . Indeed, even if the signature of the $0\nu DDB$ is in principle very clear, to experimentally recognize a peak over the continuum background could be very hard. In order to increase the sensitivity of the experiment usually it is necessary:

- to work with very large source masses, of order of one ton or larger in next generation experiments.
- to use good energy resolution and high efficiency detectors; good energy resolution is mandatory to improve the signal to background in the peak search; moreover poor resolution means that the $2\nu DDB$ spectra would be a source of dangerous background for the $0\nu DDB$

peak.

- to perform the experiment in very radiopure conditions; this implies that detectors must be shielded from the environment and its associated radioactivity. Cosmic rays contributions are suppressed by performing experiments in underground laboratories.
- to have long data taking periods.

2. The bolometric technique

Large mass thermal detectors have been suggested since 1984 for search on rare decays ⁴. Over the last few years, low temperature detectors have provided better performance as regard energy resolution, low energy thresholds and wide material choice than conventional detectors. A complete overview on these detectors and the bolometric technique is offered by proceedings of specific low temperature detectors conferences ⁵.

Bolometers are low temperature detectors sensitive to single particle interactions. The basic idea of bolometers is to measure the energy lost in particle interactions as a temperature variation of the detector. The two main components of a bolometric detector are an energy absorber, where particles lose all or part of their energy and produce elementary excitations, and a sensor which collects these excitations generating an electrical signal. As a first approximation, the height of the thermal pulse is given by the ratio of the deposited energy to the heat capacity C of the bolometer, whereas the pulse time constant is equal to the ratio between C and the thermal conductance of the detector to the heat sink. Consequently, in order to achieve big and fast signals, it is important to make bolometers with small heat capacity. This is obtained by using dielectric diamagnetic materials kept at very low temperatures (~ 10 mK in our case). Their heat capacity in fact scales as the cube of the ratio between the operating temperature T and the Debye temperature Θ_D (Debye law). The mechanism that limits the energy resolution in these conditions is due to thermodynamic fluctuations. It can be shown that the intrinsic energy uncertainty is in this case ⁶

$$\Delta E_{rms} \sim (kT^2C)^{1/2} \tag{5}$$

where k is the Boltzmann constant.

The Milano group started some years ago a program to develop both large mass bolometers to search for $0\nu\text{DBD}$ of various isotopes and microcalorimeters for X-ray and β -spectroscopy. A series of bolometric experiments have been carried out by the Milano group since 1989 in the

Gran Sasso Laboratory, searching for the double beta decay of ^{130}Te . From the experience of this group and with an international collaboration, the Cuoricino experiment started at the beginning of 2003. In October 2003, an enlarged collaboration has proposed a new generation large mass experiment named CUORE (Cryogenic Underground Observatory for Rare Events) that has the search for $0\nu\text{DBD}$ of ^{130}Te with the bolometric technique as a main goal.

3. The Cuoricino experiment: detector and results

Cuoricino is the biggest running $0\nu\text{DBD}$ experiment. The source of $0\nu\text{DBD}$ is ^{130}Te that, thanks to its high natural abundance, permits to work with large active masses also without isotopic enrichment. Moreover the transition energy value of the $0\nu\text{DBD}$ of ^{130}Te is in a favorable position of the energy spectrum with respect to the natural radioactive background, indeed it is outside the ^{238}U background and in a window of low natural radioactivity: between the full energy and the Compton edge of ^{208}Tl gamma peak (2615 keV).

As absorbers of the bolometer, Cuoricino uses Tellurium Oxide (TeO_2) crystals, that of course contain ^{130}Te . In fact it is possible to grow large single TeO_2 crystals with excellent properties. Furthermore, the Debye temperature of TeO_2 is higher than pure Te and so lower heat capacity and higher pulses are obtainable. In addition, Te dominates in mass the compound and these crystals have a high radiopurity ($< 1\text{pg/g}$ in ^{232}Th and ^{238}U).

As sensors, Cuoricino uses germanium Neutron Transmutation Doped (NTD) thermistors, whose resistivity at low temperature depends steeply on temperature. More details on these devices could be found in ⁷.

Cuoricino detector is a tower-like structure that uses 40 kg of TeO_2 . The array is composed by 44 crystals of $5\times 5\times 5\text{ cm}^3$ size and a 760 g weight and 18 crystals of $3\times 3\times 6\text{ cm}^3$ size and a 340 g weight placed in 13 elementary modules. A picture of Cuoricino detector is shown in fig. 2 (left).

Cuoricino detector has reached good energy resolution in the DBD energy region (3.9 keV at the best, and 7 keV as average at 2615 keV with the big size crystals) and is characterized by good efficiency (86%). An example of energy spectrum obtained during a calibration measurement is shown in fig. 2 (right).

The current background in $0\nu\text{DBD}$ region is $0.18\pm 0.02\text{ c/keV/kg/y}$. The present best interpretation of this continuum background, coming from

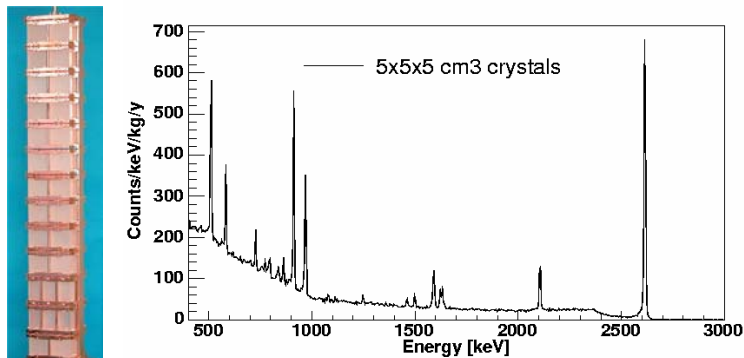


Figure 2. (Left) Picture of Cuoricino detector. It contains 62 TeO_2 crystals arranged in 13 planes. (Right) Example of an energy spectrum obtained during a calibration measurement. This spectrum is the sum of all the spectra obtained by the 44 $5 \times 5 \times 5 \text{ cm}^3$ detectors.

Montecarlo simulation of the whole detector, is that it is mainly due to degraded alphas coming from passive materials that face the crystal absorbers, as the copper structures holding the detectors. This shows that Cuoricino experiment is not only a powerful experiment that is giving important results on DBD but it is also a good instrument to obtain information in view of CUORE Project. Cuoricino is presently giving a limit of 2.0×10^{24} years at the 90 % of C.L. on $T_{1/2}^{0\nu}$, corresponding to a bound on $\langle m_\nu \rangle$ between 0.2 and 1.0 eV. The double decay region of the energy spectrum is shown in fig. 3.

Cuoricino can reach a sensitivity on neutrino mass between 0.13 and 0.31 eV in a few years⁸. Unfortunately, due to the uncertainties on nuclear matrix elements, it will not be able to exclude totally the range indicated by part of the H-M collaboration for effective neutrino mass¹⁰, but has the potential to verify this claim.

4. The CUORE experiment

CUORE (Cryogenic Underground Observatory for Rare Events), that has been proposed and partially funded⁹, will be placed in hall A of the Gran Sasso Underground Laboratory. The CUORE detector will be constituted by 19 Cuoricino-like towers packed in a cylindrical structure for a total of 988 TeO_2 detectors and a total mass of ~ 741 kg and corresponding to ~ 200 kg of ^{130}Te . Like Cuoricino detector, CUORE will work at about 10 mK in a new big dilution refrigerator built with low radioactive materials. CUORE

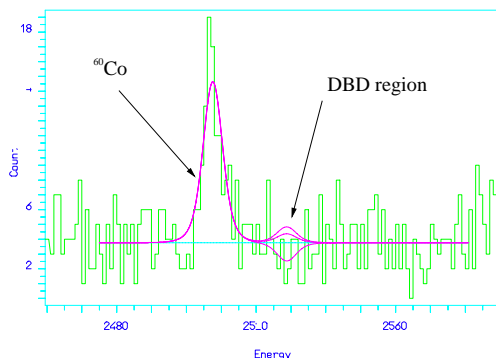


Figure 3. Energy spectrum in the Neutrinoless Double Beta Decay region.

is planned to start in 2010. In a conservative hypothesis about background (0.01 c/keV/kg/y) and with 10 keV of energy resolution CUORE should obtain in 10 years of data taking a sensitivity on half life of $0\nu\text{DBD}$ of $2.1 \cdot 10^{26}$ years corresponding to a neutrino mass limit ranging between 19 and 167 meV. In a optimistic, but realistic, hypothesis regarding the background (0.001 c/keV/kg/y), with 5 keV of energy resolution and 5 years of data taking, CUORE is foreseen to have a sensitivity on half life of $0\nu\text{DBD}$ of $6.5 \cdot 10^{26}$ years and a neutrino mass limit of 11-57 meV.

5. CUORE R&D and the Surface Sensitive Bolometers

Big efforts on CUORE R&D are performed in order to obtain a significant reduction of radioactive background in the $0\nu\text{DBD}$ region. Tests on a second dilution refrigerator in hall C of LNGS are in progress and the CUORE collaboration is working on both passive and active background reduction techniques. Last tests on the use of very radiopure powders to lap the crystals and on the use of chemical etching to polish their surfaces showed a reduction of about a factor 4 in the peaks of ^{238}U and ^{232}Th alpha decays. This reduction could be attributed to contaminations in the crystal surface. Study of cleaning procedures for the copper surface that surrounds the detector are in progress, in particular the collaboration is working on a plasma cleaning technique that is giving positive preliminary results.

The CUORE collaboration is working on new detectors to make a discrimination of background events. These devices are called Surface Sensitive Bolometers (SSB) and are able to actively discriminate events orig-

inated near the crystals surface ¹¹. They are composite bolometers able to identify degraded alphas and beta particles coming from outside and reaching the crystal absorber. For this purpose thin bolometers (secondary bolometers) are glued around the main large TeO₂ bolometers and used as active shields. Tests with secondary bolometers of different materials were performed.

As secondary bolometers and the TeO₂ absorbers are thermally coupled, pulses with different shapes are obtained depending on the particle impact point. If particles interact into the TeO₂ crystal absorber, then both the sensors on shield absorbers and on the TeO₂ bolometer will develop pulses with the usual shape. Otherwise, in case that the interacting point of the particle is in a secondary bolometer, the sensor on this shield will read out fast and high pulses, whereas usual shape pulses will be read out by sensors on the other bolometers.

The comparison between the pulses from two sensors could be carried out by means of a *scatter plot*, i.e. plotting the secondary bolometer pulse amplitudes versus the corresponding main bolometer pulse amplitudes. Two clearly separated bands distinguish events generated in the shield from events generated in the main crystal. Another possibility is to distinguish the origin of events by means of pulse shape discrimination.

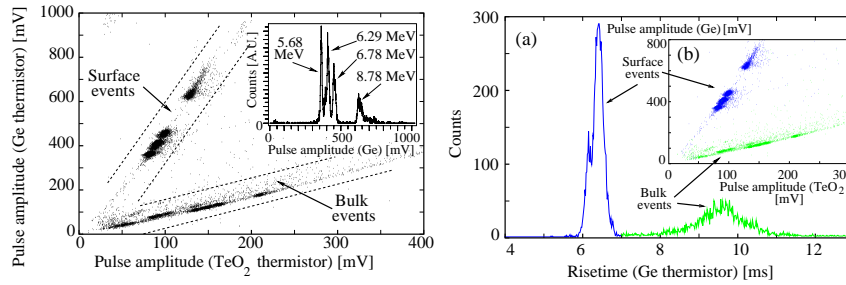


Figure 4. (Left) Scatter plot showing the relationship between the amplitudes of the pulses acquired in coincidence from the main absorber (X-axis) and from the active layer (Y-axis). In the inset, the energy spectrum obtained by selecting surface events is shown. (Right) (a) Rise Time distribution for pulses developed by sensor on the secondary bolometer. (b) Scatter plot where the different colors evidence the contribution due to fast and slow signal.

In fig. 4 (left) and 4 (right) it is possible to observe an experimental

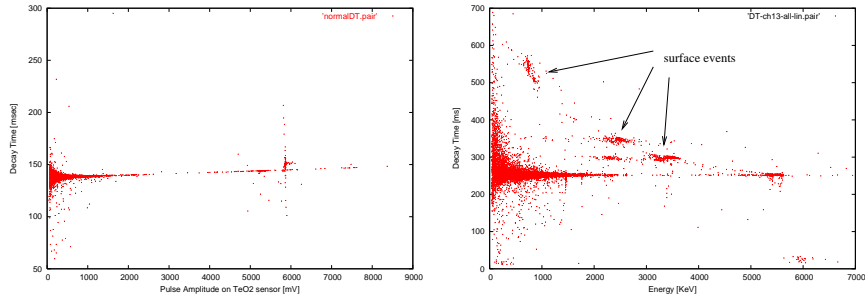


Figure 5. Differences between the decay time achieved with a normal CUORE-like detector (left) and a detector with SSB (right). In the second detector, events coming from outside interact with the secondary bolometer and cause in the sensor on the main TeO₂ crystal pulses with different decay times with respect to those to events that interact directly with the main absorber.

scatter plot obtained at Insubria University with a SSB composed by a $2 \times 2 \times 2$ cm³ TeO₂ bolometer and by a $1.5 \times 1.5 \times 0.05$ cm³ Ge secondary bolometer and working at about 20 mK.

Tests of this new technique are in progress at the Gran Sasso Underground Laboratory on a CUORE-like single module. Also, even if the results are really preliminary, they show a large discrimination capability and powerful rejection. Moreover they indicate the possibility to discriminate the event origin by using not only pulse amplitude and rise time of pulses on secondary bolometers, but also decay time of corresponding pulses on the main bolometer. In fig. 5 it is shown the decay time as seen from the main TeO₂ crystal of a normal detector and of a detector with SSB.

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