Cuoricino Results and Perspectives for CUORE

M.A. Carrettoni on the behalf of the CUORE collaboration [1]

Abstract CUORE will be one of the next generation experiments designed for the search of a rare nuclear events such as Neutrinoless Double Beta Decay. It will be a closely packed array of TeO_2 crystals operating at the cryogenic temperature of 10 mK. While presenting the main reasons and ideas behind CUORE, the results of its smaller scaled prototype, Cuoricino, will be shown. Cuoricino consists of an array of 62 bolometric detectors operating in anti-coincidence to reduce background events: it took datas for 4 years, being the largest bolometric experiment who operated until now in the search for rare events.

Keywords: Neutrinoless Double Beta Decay, radioactivity, bolometers, cryogenics, neutrinos, Majorana

1 Introduction

Since their discovery neutrinos have always puzzled the scientific world. Given the precious informations from oscillation experiments, there are still many open questions concerning their nature. Massive neutrinos can in fact be described either by a Dirac field or by a Majorana field and we can't still point out their mass hierarchy.

A probe which is very sensitive to the neutrino nature is Neutrinoless Double Beta Decay.

Double Beta Decay (DBD) is a rare transition, in which an even nucleus (A, Z) decays in its isobar (A, Z+2) with the emission of two electrons and two antineutrinos. The search for its neutrinoless variant (DBD0ν) is a powerful and sensitive way to investigate the neutrino nature and mass. The next generation experiments have the possibility to reach down to a few meV scale. The signature for DBD0ν

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is a sharp peak in the energy spectrum at the Q-value of the transition due to the energy released by the two electrons emitted in the decay with no energy carried away by neutrinos. The measurement of the rate of the DBD0ν decay is related to the effective Majorana neutrino mass by $\Gamma_{0\nu} = G_{0\nu}(Q,Z)|M_{nucl}|^2\langle m_{ee}\rangle^2$, where $G_{0\nu}(Q,Z)$ is the phase space factor, $|M_{nucl}|$ are the nuclear matrix elements, and $\langle m_{ee}\rangle = \Sigma_k|U_{ek}|^2 m_k e^{i\alpha_k}$, where U_{ek} are the mixing matrix elements for the mass eigenstates m_k and $e^{i\alpha_k}$ are the CP Majorana phases. A search for DBD0ν in several nuclei is imperative [3] due to the theoretical uncertainties in $|M_{nucl}|$.

One of the promising nuclei is ^{130}Te. Its high natural isotopic abundance of 34% alleviates the requirement for isotopic enrichment, and its high Q-value of 2530.3 keV results in a large phase space for the decay and lies in a relatively background free region between the Compton edge and the full peak of the ^{208}Tl 2615 keV line. The large phase space contributes to a decay rate that is four or five times higher for ^{130}Te than for ^{76}Ge.

Two main approaches are used to search for DBD0ν: homogeneous and non-homogeneous. In the non-homogeneous approach, an external source of the chosen DBD candidate is placed in the form of thin foils inside the detector. In the homogeneous approach, the detector material is chosen to be a compound containing the DBD candidate, providing a high efficiency and in many cases, high resolution technique.

2 Cuoricino

Cuoricino has a total TeO_2 mass of 40.2 kg consisting of an array of 62 TeO_2 crystals, arranged in a tower of 13 planes. Eleven of the planes are made of four crystals of 5 cm cube, while two of the remaining planes have nine crystals of $3 \times 3 \times 6$ cm^3. Cuoricino uses a bolometric technique to search for DBD0ν of ^{130}Te, in which an energy deposition in the crystals induces temperature increase. A measurable temperature increase can be achieved in dielectric and diamagnetic materials such as TeO_2 when operated at very low temperatures. The operating temperature of Cuoricino is 10 mK. The temperature change of each crystal is detected using neutron transmutation doped Ge thermistors, thermally coupled to each crystal with glue spots.

The detector has a series of shields designed to reduce the background radioactivity. The inner-most lead shield is made of roman lead with ^{210}Pb content of less than 4 mBq/kg (90% confidence level), 1.5 cm around the side and 10 cm on the top and the bottom of the tower. The background from the cryostat contamination is reduced by the copper shields, and 20 cm of commercial lead shielding and 10 cm of borated PET shielding surround the cryostat to reduce environmental gammas and neutrons in the detector volume.

2.1 Results

Cuoricino took datas form April 2003 to June 2008 at the underground laboratory at LNGS (Gran Sasso National Laboratory). The data used for this analysis are from two separate runs, taken from April 2003 to September 2003 and from May 2004 to the end of the experiment. The total statistics consists of 15.83 kg year of ^{130}Te. The average FWHM resolution at the ^{208}Tl gamma line is 8 keV for the $5 \times 5 \times 5$ cm^3 crystals, and 11 keV for the $3 \times 3 \times 6$ cm^3 crystals.

The detected events are run through pulse-shape analysis for noise rejection, then through software filtering to optimize energy resolution (Optimum filter) and to reject pile-ups (Wiener filter). Coincident events were used to reduce and study the background. The detection efficiency for fully contained DBD0ν events is 86% as evaluated by Monte Carlo simulations. Rejecting coincident events reduces the background by roughly 20%. The total measured background in the DBD0ν region is 0.18 +/– 0.01 cnts/keV/kg/year.

In evaluating the limit for the ^{130}TeDBD0ν half-life ($T^{0\nu}_{1/2}$) the background spectra collected in the two runs are kept separate, due to the different measured FWHM and background. A maximum likelihood procedure is applied in the 2475–2550 keV energy interval to evaluate the maximum number of DBD0ν events possible with a flat continuum plus the 2505 keV ^{60}Co gamma line. The Q-value for the DBD0ν peak is set at 2530.30 keV and a peak shape obtained by summing up N gaussians is considered, in order to account for the different detectors energy resolutions. The obtained limit is of 3.1×10^{24}year at 90% C.L. (Fig. 1), corresponding to a limit for $\langle m_{ee} \rangle$ between 0.2 and 0.68 eV (with nuclear matrix elements from [4]). Limit variations on the order of 10% were observed when the expected peak was shifted by ± 3 keV around the Q-value and for different models for the background fitting function and for the peak shape of the ^{60}Co.

DBD0ν evidence for ^{76}Ge have been claimed [2] with a best value for $\langle m_{ee} \rangle$ of 0.44 eV, in the degenerate region of the neutrino mass spectrum.

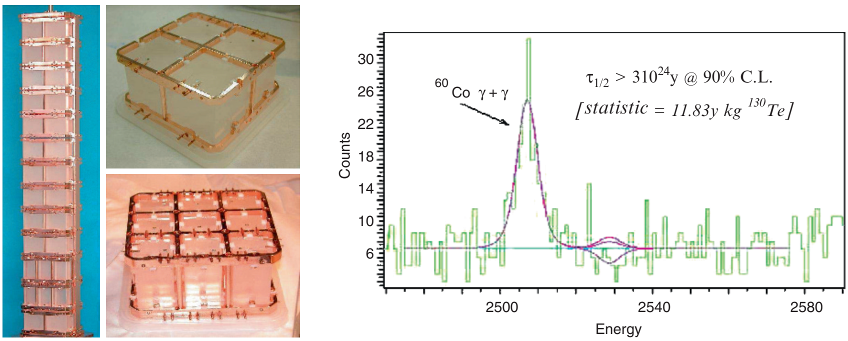

Fig. 1 Cuoricino set-up and DBD0ν limit evaluation

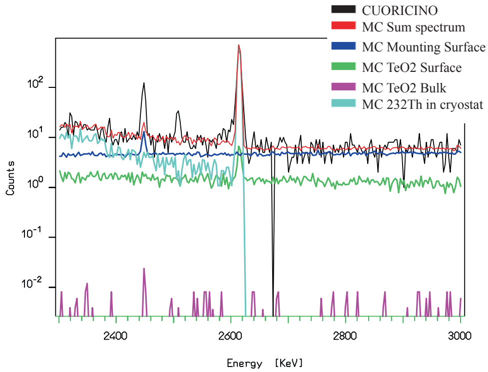

Fig. 2 CUORICINO DBD0ν background contributions

Given the present sensitivity, it is not possible for CUORICINO to confirm the claimed evidence however, in fact a null result will not rule it out due to the uncertainty in the nuclear matrix element calculations.

Next generation experiments, with $\sim$1 t of detector mass, and with a background in the DBD0ν region down to 0.01–0.001 c/keV/kg/year, are necessary to increase the sensitivity enough to reach the inverted hierarchy region of the neutrino mass spectrum.

2.2 Background analysis

An accurate knowledge of the radioactive sources, responsible of the background measured in CUORICINO in the DBD0ν region, is fundamental, in order to be able to reduce it to the wanted level in CUORE. The study of the coincidence and anticoincidence spectra, together with a comparison with Monte Carlo simulations of different radioactive contaminations in the bulk and surfaces of the various detector components, allowed us to identify the main sources of background in the DBD0ν region. They are β and α decays from ^{238}U ,^{232}Th and ^{210}Pb contaminations on the crystal surface (20% $\pm$ 5%), α decays from the same contaminats on the surface of the mounting structure (50% $\pm$ 10%) and ^{208}Tl multi-Compton events due to ^{232}Th contaminations of the cryostat shields, far away from the detectors (30% $\pm$ 5%) (Fig. 2).

3 CUORE

The next generation experiment CUORE will be made of 19 Cuoricino-like towers, 52 $5 \times 5 \times 5$ cm^3 crystals each, arranged in a tight cylindrical structure (Fig. 3), for a total TeO_2 mass of $\sim$741 kg. CUORE is expected to start at the beginning of 2011

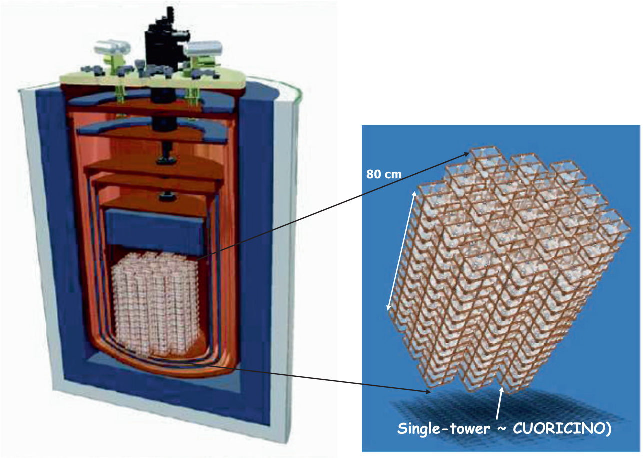

Fig. 3 CUORE set-up: Internal Pb and Cu shields and external Pb and borated PET shields are present

with a sensitivity goal for $\langle m_{ee} \rangle$ down to the inverted hierarchy region of the neutrino mass spectrum. CUORE is expected to probe the range between 29 and 150 $\times t^{1/4}$ meV for a background level in the DBD0ν region of 0.01 c/keV/kg/year and between 16 and 85 $\times t^{1/4}$ meV for a background level of 0.001 c/keV/kg/year. The high granularity of the detector will provide an effective reduction of the background by employing anticoincidence cuts. The detector shieldings have been designed in order to completely eliminate the contribution from environmental gamma radioactivity and from cryostat contaminations.

3.1 R&D for background reduction

The technical feasibility of CUORE has been proven by the good performances of Cuoricino. The true challenge, as in all the next generation DBD0ν experiments, will be the background achievement. The background knowledge acquired with Cuoricino was a helpful starting point for the background reduction R&D towards CUORE, aimed to reduce the background in the DBD0ν region to a level between 0.01 and 0.001 c/keV/kg/year.

The shielding is designed to reduce the contribution from ^{208}Tl multi-Compton events, due to ^{232}Th sources in the cryostat shields, to a negligible level. The dominant background appears to be the surface contamination both of the crystals and the copper parts facing them. A "Radioactivity study Array Detector" (RAD), was built at the end of summer 2004. The detector consists of two planes of $5 \times 5 \times 5$ cm^3 TeO_2 crystals, with a structure almost identical to that of Cuoricino.

The tests were performed in a second cryostat, housed in the Hall C of LNGS, provided with 5 cm thick internal copper shields and a 10 cm thick external lead shield. Due to the limited space in the cryostat, there is less shielding against the multi-Compton events from ^{208}Tl in the DBD0ν region than in Cuoricino. This results in higher background in the DBD0ν region in the RAD runs and direct comparison between RAD run and Cuoricino is only possible above 3 MeV where no gamma lines from the U or Th are present. We were able to isolate the alpha decays occurring in the crystals bulk (peaks at the transition energy) and surfaces (broader and asymmetric peaks at the transition energy and at the alpha energy), and on the surfaces facing the crystals, whose largest one is due to copper (flat continuum from alpha energy down to low energies).

A series of RAD runs were performed. In the first run, the crystals were etched with nitric acid, removing about 10 μm of the surfaces, then polished with SiO_2 powder. The copper mounting structure was also etched and successively treated through electroerosion, removing from 10 to 20 μm of the surfaces. All the operations were performed in a clean environment. In the second run, all copper parts facing the crystals were fully covered with polyethylene film. The result was quite successful from the point of view of crystal cleaning: the TeO_2 surface contamination in ^{238}U and ^{232}Th was drastically reduced (a factor ∼5), as proven by the reduction of the correspondent alpha peaks (Fig. 4). The extremely low background reached allowed us for the first time to disentangle the bulk vs. surface contamination of the crystals. Once the broader peaks due to surface contamination had disappeared, the Gaussian and sharp peaks due to crystals bulk contamination became visible.

From the observed peaks and assuming secular equilibrium, TeO_2 bulk impurities have been evaluated: ^{232}Th and ^{238}U are present at a level of $\sim\times 10^{-13}$ g/g, ^{210}Pb concentration is of $\sim 10^{-5}$ g/g. The background due to surface contamination of the copper was reduced by a factor 1.8 in the 3–4 MeV region by improved surface treatment and covering its surfaces with polyethylene film (Fig. 4).

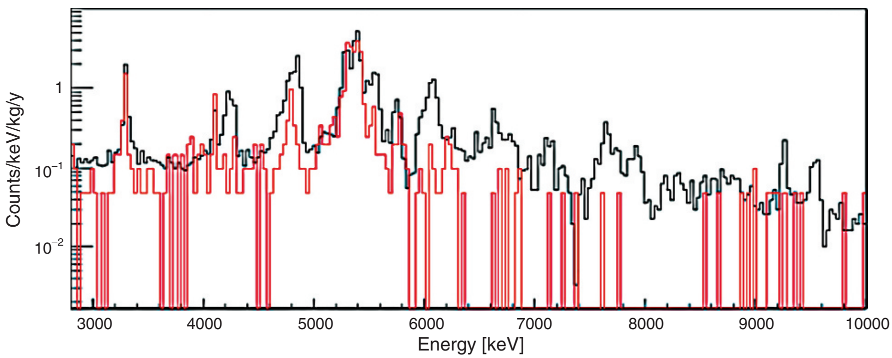

Fig. 4 Comparison between CUORICINO (black) and RAD (red) alpha background

With the surface treatment techniques, material reduction and shielding developed in the R&D program towards CUORE, the dominant sources of background are expected to be crystal surfaces (7×10^{-3} c/keV/kg/year) and copper surfaces (2.5×10^{-2} c/keV/kg/year). A small contribution is expected from crystal bulk impurities (10^{-4} c/keV/kg/year).

Additional R&D is underway to further reduce the background. One novel approach is the use "surface sensitive bolometers" (SSB) [5] where the main bolometer crystal is completely surrounded by and thermally coupled to six thin bolometers. Surface events either from the crystal or the surrounding, would deposit energy on both the main crystal and a surrounding bolometer, and these events can be excluded via anticoincidence analysis. Unfortunately several wires were lost during our test run however, we were able to reduce the background by a factor of 2 between 3 and 4 MeV with respect to the first RAD. This technique has the possibility to serve as a valuable R&D tool that allows us to unambiguously identify the origins of the background observed in Cuoricino.

4 Conclusions

CUORICINO set a limit on the half-life of ^{130}Teof 3.1×10^{24}year at 90% C.L. and $\langle m_{ee} \rangle$ between 0.2 and 0.68 eV. It demonstrated the technical feasibility of CUORE, the next generation experiment on the 1-t scale, and has given us important insight into the sources of background. An R&D program is underway to achieve a background of below 0.01 counts/keV/kg/year.

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References

1. The complete list of authors can be found at http://crio.mib.infn.it/wig/Cuorepage/CUORE.php
2. Klapdor Kleingrothaus HV. et al., *Phys. Lett.* B**586** (2004) 198–212
3. S.M. Bilenky and S.T. Petcov (hep-ph/0405237)
4. C. Arnaboldi et al., *Phys. Rev. Lett.* **95** (2005) 142501
5. M. Pedretti et al. (the CUORE Collaboration) AIP conference proceedings vol. 897, p. 59–64, "Topical workshop on low radioativity techniques" LRT (2006) Aussois, France