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The search for neutrinoless double beta decay with Cuoricino and Cuore

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Abstract. Cuoricino was a cryogenic bolometric detector operating in Gran Sasso Underground Laboratory, Italy, from March 2003 to June 2008. With its 40.7 kg of ^{130}TeO$_2$ in the form of an array of 62 crystals it has set the currently best lower limit on the halflife of 130Te neutrinoless double beta decay, $T_{1/2} > 2.94 \cdot 10^{24}$ y at 90 % CL. It has moreover proven the feasibility of the CUORE experiment, whose aim is to be sensitive to values of the effective neutrino mass as low as few tens of meV. We will report on the latest results from Cuoricino and on the status of the CUORE project.

1. Introduction

The recent observations of neutrino oscillations by atmospheric[1], solar[2], and reactor[3] neutrino experiments established that neutrinos are massive particles.

The oscillation experiments have measured or constrained the elements of the neutrino mixing matrix and the values of the differences between the squared mass eigenvalues participating in the oscillations.

The question whether neutrinos are Dirac or Majorana fermions is however still open and neutrinoless double beta decay ($0\nu\beta\beta$) is currently the only experimentally viable way to answer it.

Besides this, the same process can probe the absolute neutrino mass scale by measuring the effective Majorana mass of the electron neutrino m_{ee}.

The goal of the CUORE experiment is to measure m_{ee} with a sensitivity in the 10-100 meV range, where the spread is due to the uncertainty on the nuclear matrix element (see [4], [5] and the references listed) involved in the determination of m_{ee} from the $^{130}Te_{0\nu\beta\beta}$ lifetime measurement.

The feasibility of CUORE has been proved by its prototype, CUORICINO, which has been the most massive $0\nu\beta\beta$ experiment currently running and whose performance will be discussed below.

2. Principles of operation of CUORE and Cuoricino

The search for $0\nu\beta\beta$ is pursued by a bolometric technique: the detectors consist of TeO$_2$ crystals operated at a temperature of $\sim$8 mK inside a ^{3}He/^{4}He dilution refrigerator.

The heat capacity of dielectric materials at this temperature is very low according to the Debye law, so that even tiny energy deposits in the crystals cause an appreciable rise in their temperature.

Thermal pulses are recorded by neutron transmutated doped Ge thermistors glued on each crystals [6].

Among the few even-even nuclei candidates for $0\nu\beta\beta$ decay, ^{130}Te has been chosen for its high transition energy (2527.518 ± 0.013 keV) and natural isotopic abundance (33.87%).

Besides achieving high energy resolutions, close to those obtained by Ge detectors, the bolometric technique provides the possibility to choose among different nuclei as sources for $0\nu\beta\beta$ decay, thus allowing for a cross check in case of discovery.

3. Cuoricino experiment
3.1. CUORICINO setup
The CUORICINO detector[7] was an array of 62 ^{130}TeO$_2$ bolometers operated in the Hall A of Laboratori Nazionali del Gran Sasso, Italy.

The total sensitive mass was 40.7 kg and the mass of ^{130}Te was 11.3 kg. The crystals were arranged in 13 planes: 11 of them consisted of four $5 \times 5 \times 5$ cm^3 crystals with a mass of 790 g each, 2 of them were made of nine $3 \times 3 \times 6$ cm^3 crystals whose mass was 330 g.

All crystals were made of natural tellurium except for four $3 \times 3 \times 6$ cm^3 cm^3 ones: two of these are enriched in ^{128}Te with an isotopic abundance of 82.3% and two in ^{130}Te with an isotopic abundance of 75%.

Great care was taken to reduce radioactive contaminations and background sources at all stages of the detector construction and assembly: the crystals were grown from low radioactive materials at the Shangai Institute of Ceramics and shipped to Italy by sea to minimize cosmic activation.

Once in Italy their surface was lapped with radiopure abrasives.

To avoid external vibrations reaching the detectors, the tower was mechanically decoupled from the cryostat through a steel spring.

A 1.2 cm shield of Roman lead with ^{210}Pb activity of 4 mBq/kg was framed around the array to reduce the backgrounds induced by contaminants on the thermal shields of the cryostat.

The refrigerator itself was externally shielded by two layers of lead of 10 cm minimal thickness each.

The background due to environmental neutrons was reduced by a layer of borated polyethylene of 10 cm minimum thickness.

The refrigerator sits inside a Plexiglass anti-radon box flushed with clean N$_2$ and a Faraday cage was framed around the whole setup to reduce electromagnetic interferences.

The detector was calibrated every month by inserting two thoriated tungsten wires between the refrigerator and the external lead shield.

3.2. Cuoricino results
CUORICINO took data from February 2003 to June 2008. The background spectrum collected up to June 2008, corresponding to an exposure of 19.75 kg ^{130}Te·y, is shown in figure 2.

The background level in the $0\nu\beta\beta$ region is 0.153 ± 0.006 counts/(keV·kg·y) and the average energy resolution (FWHM), calculated on the ^{208}Tl gamma line at 2615 keV is (6.3 ± 2.5) keV for the large crystals and (9.9 ± 4.2) keV for the small crystals.

Apart from the sum of the ^{60}Co gamma lines and the aforementioned ^{208}Tl line (not visible in figure 2), no peak is found near the 2527 keV ^{130}Te $0\nu\beta\beta$ Q value.

This allowed us to set a lower limit on the $0\nu\beta\beta$ ^{130}Te hal-flife of 2.8×10^{24} y at 90 % CL.

Depending on the nuclear matrix element calculation adopted ([8][9][10][11]), this can be translated into an upper limit on m_{ee} in the range $m_{ee} < (0.3 - 0.70)$ eV.

This constraint is currently the most restrictive for ^{130}Te and is comparable with the values obtained with Ge diodes.
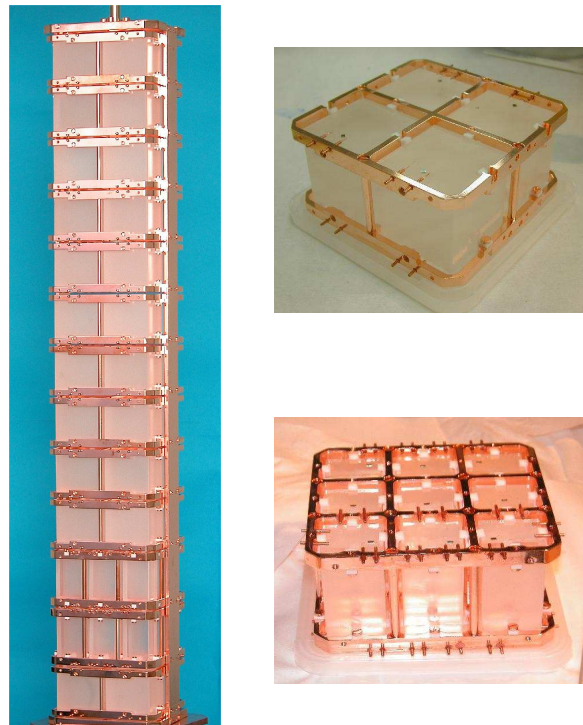
Figure 1. CUORICINO array (left) and details of the planes hosting the $5 \times 5 \times 5$ cm^3 crystals (top right) and $3 \times 3 \times 6$ cm^3 crystals (bottom right)

The current limit is less stringent than the previously published one [7] due to the recent filling of the dip which was present in the spectrum around the ^{130}Te Q value.

4.   From CUORICINO to CUORE

The CUORE detector[12] will consist of a cylindrical array of 988 TeO$_2$ bolometers arranged in 19 towers of 52 crystals each (figure 3), for a total mass of $\sim$ 741 kg, 203 kg of which will be ^{130}Te.

The detector and its inner 6 cm of lead will be cooled to $T \simeq 8$ K inside a dilution refrigerator in Hall A of Laboratori Nazionali del Gran Sasso, next to CUORICINO.

A further layer of 30 cm of low activity lead will shield the array from the dilution unit of the refrigerator and from environmental activity.

A borated polyethylene shield and an air-tight cage will enclose the cryostat.

The detector structure will be more compact than in Cuoricino: the ^{130}TeO$_2$ crystals will be closely packed and this will increase the effectiveness of the anticoincidence techniques used in the data analysis.

The detector will furthermore benefit from the improved mechanical decoupling between the experimental and the cryogenic set-ups and from a better crystal holding structure specifically designed to reduce vibrational noise responsible of worsening the energy resolution.

In 5 years of running CUORE sensitivity to the $0\nu\beta\beta$ half-life of ^{130}Te will be $S_{0\nu} \simeq 2.1 \times 10^{26}$ years: this will provide an upper limit on m_{ee} in the range $0.035 - 0.082$ eV.

This sensitivity will result from reducing the background in the $0\nu\beta\beta$ region to $B \simeq 0.01$ counts/(keV·kg·y) and by improving the energy resolution to the level of $\Gamma(2.5$ MeV$) = 5$ keV: both goals will be accomplished thanks to the improvements described above and to the recent development of new, better material cleaning techniques.
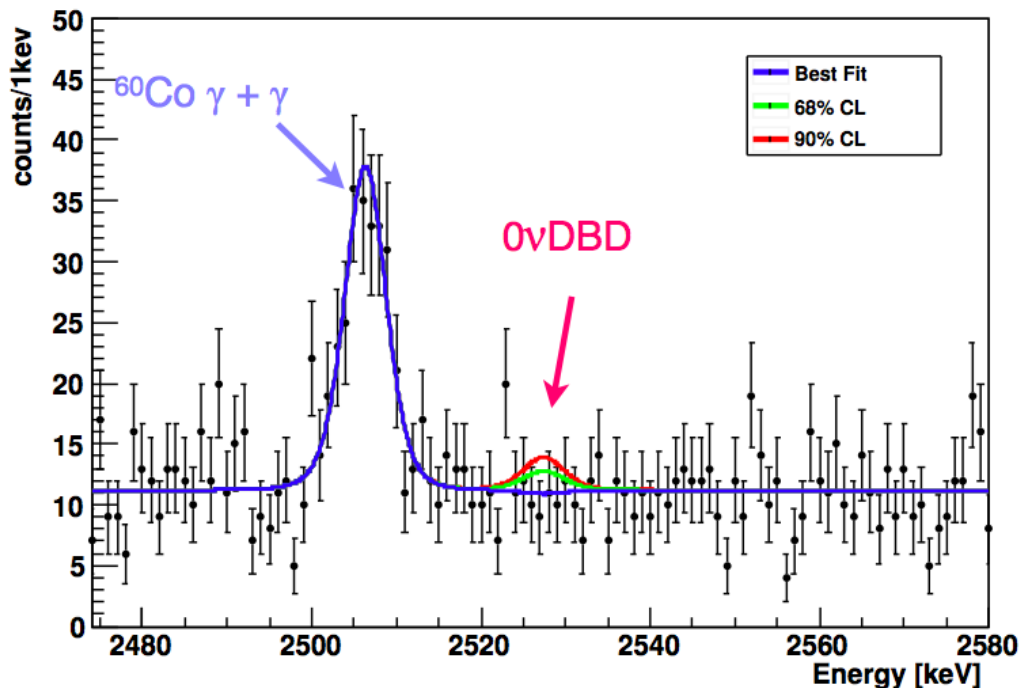
Figure 2. CUORICINO spectrum in the $0\nu\beta\beta$ region

5. CUORE prospects and current status

Cuore construction is now proceeding in the Hall A of Laboratori Nazionali del Gran Sasso: the hut where the detector will be placed has been built as well as the clean room for the detector assembly.

In parallel, the collaboration is also preparing Cuore 0, a prototype of Cuore consisting a single tower made of 52 already available Cuore crystals, prepared and assembled according to the Cuore standards and operated within Cuoricino cryostat.

This detector will be the ultimate test of Cuore concept before Cuore start, and it is scheduled to take data in 2011-2012.

As mentioned in the previous section, the ultimate goal of CUORE is to measure or constrain m_{ee} in the $\sim 0.035 - 0.082$ eV range.

This will allow to probe part of the inverse and degenerate neutrino mass hierarchy pattern scenarios envisioned by neutrino oscillations experiments[13].

6. Acknowledgements

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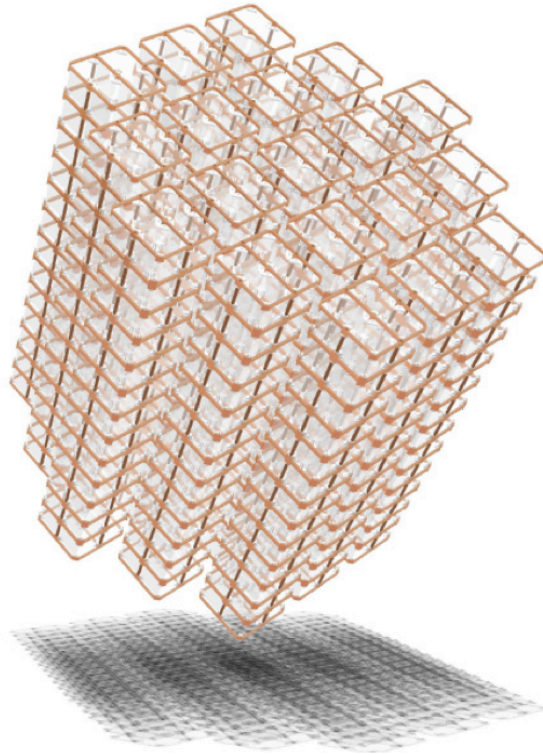[5] Rodin V 2009 (*Preprint* `0910.5866`)

Figure 3. CUORE detector: the bolometers array is made of 19 CUORICINO like towers

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