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Search for neutrinoless double beta decay with CUORICINO and prospects for CUORE

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Abstract: CUORICINO is a cryogenic detector running in Gran Sasso National Laboratory, Italy, since 2003. With its 40.7 kg mass of TeO_2 mass, in the form of an array of 62 crystals, it has proven the feasibility of the CUORE experiment, whose aim is to be sensitive to the effective neutrino mass as low as a few tens of meV. It has moreover set the current lower limit on the lifetime of ^{130}Te for neutrinoless double beta decay: we report on the up-to-date CUORICINO results and discuss the prospects for CUORE.

Introduction

The recent observations of neutrino oscillations by atmospheric [1], solar[2], and reactor [3] neutrino experiments estabilished that neutrinos are massive particles; the oscillation exeriments have measured or constrained the elements of the neutrino mixing matrix and 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] for a list) involved in the determination of m_{ee} from the lifetime measurement. The feasibility of CUORE has been proved by its prototype, CUORICINO, which is the most massive $0\nu\beta\beta$ experiment currently running and whose performance will be discussed below.

Principles of operation

The search for $0\nu\beta\beta$ is pursued by the 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 [5]. Among the few even-even nuclei candidates for $0\nu\beta\beta$ decay, ^{130}Te has been chosen for its high transition energy (2530 ± 1.9 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.

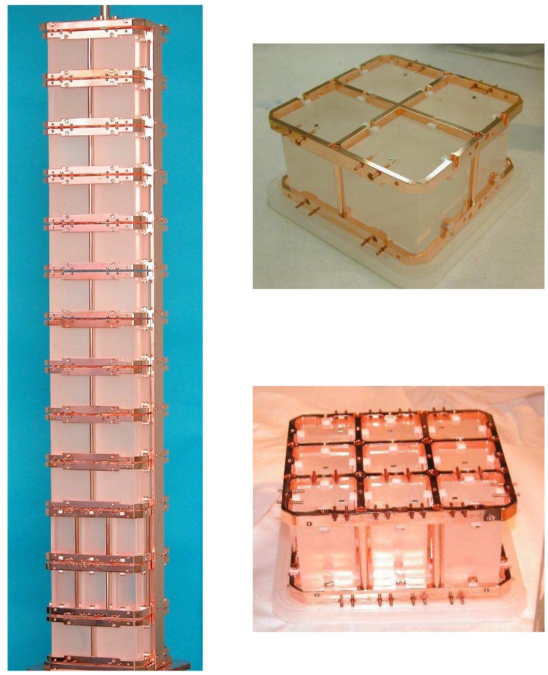

Figure 1: CUORICINO array (left) and details of the planes hosting the $5 \times 5 \times 5$ cm^3 crystals (top right) and $3 \times 3 \times 6$ cm^3 crystals (bottom right)

CUORICINO setup

The CUORICINO detector [6] is an array of 62 $^{130}TeO_2$ bolometers operated in Hall A of Laboratori Nazionali del Gran Sasso, Italy. The total sensitive mass is 40.7 kg and the mass of ^{130}Te is $\sim$ 11 kg. The crystals are arranged in 13 planes: 11 of them consist of four $5 \times 5 \times 5$ cm^3 crystals with a mass of 790 g each, 2 of them are made of nine $3 \times 3 \times 6$ cm^3 crystals whose mass is 330 g. All crystals are 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 has been 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 is 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 is framed around the array to reduce the backgrounds induced by contaminants on the thermal shields of the cryostat. The refrigerator itself is externally shielded by two layers of lead of 10 cm minimal thickness each. The background due to environmental neutrons is 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 is framed around the whole setup to reduce electromagnetic interferences. The detector is calibrated every month by inserting two thoriated tungsten wires between the refrigerator and the external lead shield.

CUORICINO results

CUORICINO has been running since the spring of 2003. The duty cycle of the experiment is $\sim$ 73%, mainly limited by the time required to refill the cryostat preiodically with ^{4}He. Excluding the time spent for energy calibration, the total background live time is 63%. The background spectrum collected up to May 2006, corresponding to an exposure of 8.38 kg ^{130}Te·y, is shown in figure 2. The background level in the $0\nu\beta\beta$ region is 0.18 ± 0.01 counts/(keV·kg·y) and the average energy resolution (FWHM), calculated on the ^{208}Tl gamma line at 2615 keV is 7.8 keV for the large crystals and 9.1 keV for the small crystals. Apart from the ^{60}Co sum gamma line and the

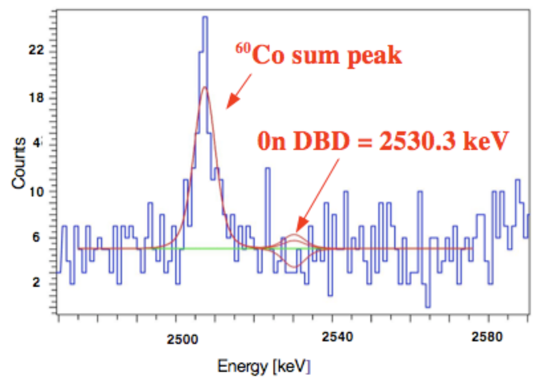

Figure 2: CUORICINO spectrum in the $0\nu\beta\beta$ region

aforementioned ^{208}Tl line, no peak is found near the 2530 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 2.4×10^{24} y at 90 % CL [7]. Depending on the nuclear matrix element calculation adopted, this can be translated into an upper limit on m_{ee} in the range $m_{ee} < (0.18 - 0.94)$ eV. This constraint is currently the most restrictive for ^{130}Te and is comparable with the values obtained with Ge diodes.

From CUORICINO to CUORE

The CUORE detector [8] will consist of a cylindrical array of 988 TeO_2 bolometers arranged in 19 towers containing 52 crystals each (figure 3), for a total mass of $\sim$ 741 kg. The detector will be operated at $T \simeq 10$ K inside a dilution refrigerator in Hall A of Laboratori Nazionali del Gran Sasso, next to CUORICINO. In 5 years of running the 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 $0.019 - 0.10$ eV. This sensitivity will be achieved by 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. This requires careful materials selection, a slight improvement in the currently available material cleaning techniques, and an optimization in the mechanical decoupling of the bolometers from

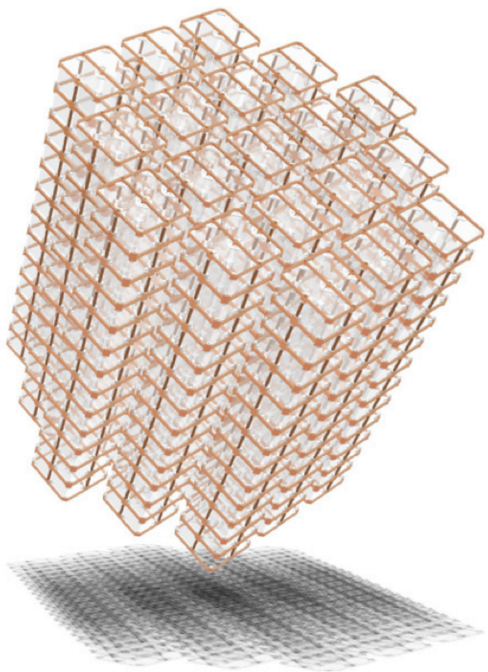

Figure 3: CUORE detector: the bolometers array is made of 19 CUORICINO like towers

the surrounding environment in the detector design and assembly phase.

CUORE prospects and current status

As mentioned in the previous section, the ultimate goal of CUORE is to measure or constrain m_ee in the $\sim 0.024 - 0.13$ eV range. This will allow to probe part of the inverse and degenerate neutrino mass hierarchy pattern scenarios envisioned by neutrino oscillations experiments [9]. An improvement of this result could be obtained by either further reducing the background level or using ^{130}Te enriched crystals. Enriched TeO_2 crystals have been already operated in CUORICINO making this latter option feasible. Assuming a 95% enrichment and a background level of $B \simeq 0.01$ counts/(keV·kg·y), the sensitivity of CUORE would be $S_{0\nu} \sim 6.04 \times 10^{26}$ years in 5 years of running, yelding an upper limit on m_{ee} in the range $11 \div 59$ meV. The inverse hierarchy region could therefore be completely covered and the normal hierarchy parameter space partially spanned. CUORE is a joint European and American project. The detector construction is underway and data taking is scheduled to start in 2011.

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