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ScienceDirect
Nuclear Physics B (Proc. Suppl.) 168 (2007) 60–62
NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS
www.elsevierphysics.com

CUORE/CUORICINO: Double Beta Decay with low temperature detectors.

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CUORICINO is an array of 62 TeO_2 bolometers designed to search for the $\beta\beta(0\nu)$ of ^{130}Te. With a total mass of 40.7 kg of TeO_2 ,corresponding to about 11 kg of ^{130}Te, CUORICINO has collected up to now a total statistics of 8.38 kg(^{130}Te) y. No evidence for the 2530 keV peak that should be produced by $\beta\beta(0\nu)$ events is found. The upper limit on the half life 2.4×10^{24} years at 90% C.L. is converted into a lower bound on the neutrino effective Majorana mass of 0.18-0.9 eV.

CUORE, a one ton scale experiment based on the CUORICINO technology and intended to push Majorana mass sensitivity for ^{130}Te $\beta\beta(0\nu)$ toward the inverted hierarchy region, is here discussed.

1. Introduction

Although the existence of neutrino oscillations (and consequently of massive neutrinos) seems now to be well proved, several properties of the neutrino family have still to be fixed. Measuring the masses, the mixing angles (and phases) as well as assessing the Dirac/Majorana character of neutrinos will be the goal of the next generation experiments. In this scenario a unique role is played by Neutrinoless Double Beta Decay ($\beta\beta(0\nu)$) searches: these are the only experiments that can prove the Majorana character of neutrinos (as foreseen by the majority of theories) allowing in the meantime to obtain information on the neutrino mass hierarchy and scale.

The lepton number violating process of $\beta\beta(0\nu)$ decay has a transition rate given by: $\lambda^{0\nu}_{\beta\beta(0\nu)} = F_{N\beta\beta(0\nu)}\ |\langle m_\nu\rangle|\ ^2$ where F_N is the Nuclear Factor of Merit (product of the $\beta\beta(0\nu)$ phase space and the square of the $\beta\beta(0\nu)$ nuclear matrix element) while $|\langle m_\nu\rangle|$ is the effective Majorana electron neutrino mass. From the lower limits experimentally obtained for $\beta\beta(0\nu)$ half-lives of various isotopes [1] upper bounds of the order of 0.3 - 1 eV on $|\langle m_\nu\rangle|$ have been obtained. Theoretical considerations combined with the present results coming from atmospheric and solar neutrino experiments seem to indicate that $|\langle m_\nu\rangle|$ should lie in the range between 100 meV and 1 meV [2]. This reinforces the will of projecting and realizing experiments that could explore that mass range. Indeed in the last few years several experiments (among these are CUORE, EXO, GERDA, MAJORANA and MOON) [1] have been proposed to search for the $\beta\beta(0\nu)$ decay of various nuclei. The challenge of these experiments is the realization of a large mass (of the order of tons) counting facility with extremely low background.

2. Double Beta Decay with TeO_2 bolometers

Natural tellurium contains about 33.8% of the isotope ^{130}Te that, given its high Q-value ($\sim$2530 keV) and its favorable nuclear factor of merit, is one of the more interesting candidates for $\beta\beta(0\nu)$ study. To scale $|\langle m_\nu\rangle|$ sensitivity toward the next generation experiment frontier (i.e. to tens of meV) a favorable candidate is not enough: a technique that guarantees large operating masses is indeed mandatory. The so called "source=detector" configuration, where the candidate nuclei are contained within the active mass of the detector, makes mass scaling toward high

doi:10.1016/j.nuclphysbps.2007.02.007

values easy and natural. In this configuration the $\beta\beta(0\nu)$ decay signal would appear in the background spectrum of the detector as a peak at the Q-value of the decay and sensitivities are determined on one side by detector mass and energy resolution and on the other by the background level. Up to now only two kind of particle detectors have been realized using Te compounds: CdTe semiconducting diodes and TeO_2 bolometers. But only the latter devices have actually achieved masses and performances that are extraordinarily similar to Ge diodes. Not surprisingly TeO_2 bolometers share with Ge diodes the "pole-position" in the next generation experiments. CUORE (TeO_2) and GERDA (Ge) are indeed the two large scale experiments already in the preparation phase: approved, space allocated and partially funded. Both exploit an already demonstrated technology. For CUORE the know-how is based on the experience gained in almost 15 years by the Milano group in bolometers technology and culminated in CUORICINO experiment [3].

3. CUORICINO

CUORICINO is a 13-plane tower array made of 62 low temperature bolometers. Eleven planes are 4-detector modules hosting $5\times5\times5$ cm^3 crystals (790 g), the other two are 9-detector modules hosting $3\times3\times6$ cm^3 crystals (330 g). The total mass of TeO_2 in CUORICINO is of about 41 kg. All the crystals are made of natural tellurium but 4 of the small size ones. These are made with enriched materials: two of them are enriched to 75% in ^{130}Te and two are enriched to 82.3% in ^{128}Te. The mechanical structure of the array, the set-up and the shielding configuration are discussed in [3].

Data taking started in April 2003. Unfortunately during the cooling procedure some of the signal wires disconnected so that only 32 of the large size crystals and 16 of the small ones could be read. This made necessary an interruption of the experimental run: the cryostat was warmed to room temperature, the wires repaired and in middle 2004 the second run started.

The performances recorded for the detectors in the two runs are excellent: the average FWHM resolution measured during the periodic (once a month) exposition to a ^{232}Th source of the detectors is $\sim$ 7 keV for the 5x5x5 cm^3 crystals and $\sim$ 9 keV for the 3x3x6 cm^3 crystals. Both these values are measured on the ^{208}Tl gamma line at 2615 keV. Similar values are measured on the ^{208}Tl line visible in the sum background spectra of $5\times5\times5$ cm^3 and $3\times3\times6$ cm^3 crystals: no deterioration of the FWHM is observed when summing long measurements and all the detectors together. The statistics collected up to May 2006 for the $\beta\beta(0\nu)$ measurement corresponds to 8.38 kg(^{130}Te) y. No evidence of a 2530 keV peak is found in these data. A Maximum Likelihood procedure is used to establish the maximum number of $\beta\beta(0\nu)$ events compatible with the measured background. The Likelihood relative to the spectra collected in the two runs three kind of detectors (big, small natural and enriched crystals) are combined together allowing for different background levels in the two runs for the 3 detector types. The FWHM is fixed to the measured values and the efficiencies to the MonteCarlo evaluated ones. A lower bound for the ^{130}Te $\beta\beta(0\nu)$ half-life of 2.4$\times$ 10^{24} years at 90% C.L. results, with a weak dependence on the used background function (linear or flat), and on the assumed $\beta\beta(0\nu)$ peak position (allowing it to span over the 1 sigma error quoted for the Q-value) and peak shape (symmetric or asymmetric gaussian). The corresponding upper bound on the Majorana effective mass ranges from 0.18 and 0.9 eV (using the NME from [3]). CUORICINO will run until the completion of CUORE, foreseen for 2010. Assuming a 60% live time efficiency in May 2010 Cuoricino would have added 2.4 years of statistics reaching therefore 28 kg(^{130}Te) y and resulting in a sensitivity of about 6 10^{24} years on the $\beta\beta(0\nu)$ half-life.

4. The CUORE Project

The CUORE Project [4] foresees the realization of a $\beta\beta(0\nu)$ experiment with an active mass of the order of 1 ton. CUORE will employ 988 natural TeO_2 bolometers each made of a cubic $5\times5\times5$ cm^3 TeO_2 crystal with a mass of about

750 g. The goal of the CUORE collaboration is to reach, in the energy region of interest, a background level lower than 10^{-2} counts/keV/kg/y obtaining hence a sensitivity on the effective Majorana mass of neutrino of the order of 50 meV.

The CUORE array is designed in order to have the most compact structure reducing to a minimum the distance between the crystals and the amount of inert material interposed between them. The 988 bolometers of the array are arranged in a cylindrical matrix organized into 19 "towers", each made of 13 planes. Every plane contains four crystals supported inside a copper frame. The entire array, surrounded by a 6 cm thick lead shield, will be operated at about 10 mK in a He^3/He^4 dilution refrigerator. A further thickness of 30 cm of low activity lead will be used to shield the array from the dilution unit of the refrigerator and from the environmental activity. A borated polyethylene shield and an air-tight cage will surround externally the cryostat. The experiment will be installed underground in the Laboratori Nazionali del Gran Sasso(LNGS) at a depth of 3400 m.w.e.

Despite operating a 1000 bolometer array at 10 mK could look rather challenging, the technical feasibility of CUORE has been extensively proved by the good performances of the CUORICINO experiment while the possibility of cooling large masses in dilution refrigerators have been proved, for example, by the gravitational antenna experiment. The true challenge in CUORE - as in all the next generation $\beta\beta(0\nu)$ experiments - will be the background achievement. Up to now - thanks to the background knowledge acquired through CUORICINO and dedicated radioactive measurements of various type (NAA, ICMPS, HPGe ...) - the limiting factor appears to be the background coming from contamination of the detector surfaces (TeO_2 crystals and Cu mounting structure surfaces). With the present know-how the background in CUORE would be between 2 and 4 10^{-2} counts/keV/kg/y. New techniques are however under development and will be applied to a test array consisting in a CUORE-like small tower (two or three planes instead of 13) that is used to evaluate background achievements in view of CUORE.

5. Conclusions

Although being a sensitive experiment itself, CUORICINO finds its place in the CUORE Project as a test facility intended to verify the technical feasibility of CUORE. Indeed the good results obtained as far as the detector performances are concerned prove that the realization of CUORE could be more straightforward than expected: CUORICINO proves that the increase in the number of bolometers and in the total mass of the array do not affect substantially the quality of the experiment. There is still some study that is required from the point of view of radioactivity to reach the goal of 10^{-2} counts/keV/kg/y.

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