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Preliminary results on the search for the neutrinoless double beta decay of ^{130}Te with the Cuoricino experiment

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Abstract. The search for neutrinoless double beta decay (DBD-0ν) is a powerful tool to establish the correct neutrino mass hierarchy and whether the neutrino is a Majorana or Dirac particle. The Milano group has run several experiments using thermal detectors to search for the ^{130}Te DBD-0ν. The Cuoricino experiment consists of an array of 62 TeO_2 thermal detectors for a total mass of about 40 kg, by far the largest cryogenic experiment in the world. The detector installation in the Gran Sasso Underground Laboratory has been recently completed. After a test phase the experiment is now taking data and we report here the preliminary results. Cuoricino is the first step toward the CUORE experiment, which will consists of 1000 TeO_2 thermal detectors for a total mass of about 760 kg: in this paper we discuss also the physics potential of both stages for what concerns the DBD-0ν search.

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1 Introduction

The evidence for neutrino flavor oscillations proves that neutrinos are massive particles. However oscillation experiments measure only the differences between squared neutrino masses and therefore the absolute scale of the neutrino masses is still missing.

Neutrinoless double beta decay (DBD-0ν) can occur only if the neutrino is a massive Majorana particle (i.e. $\nu \equiv \bar{\nu}$): therefore the search for DBD-0ν provides a powerful tool to identify the correct neutrino mass hierarchy and to establish whether the neutrino is a Majorana or Dirac particle. DBD-0ν searches actually measure the process half-life $\tau^{0\nu}_{1/2}$, which is related to neutrino masses through $[\tau^{0\nu}_{1/2}]^{-1} \propto [\langle m_\nu \rangle / m_e]^2 |M^{0\nu}|^2 G^{0\nu}$, where $M^{0\nu}$ is the matrix element, $G^{0\nu}$ is the phase space factor and $\langle m_\nu \rangle$ is the effective electron neutrino mass defined as $\langle m_\nu \rangle = \sum_k m_{\nu_k} \eta_k |U_{ek}|^2$. Therefore DBD-0$\nu$ does not measure the neutrino mass directly, but can eventually set the absolute scale for the masses m_k of the neutrino mass eigenstates ν_k, using the neutrino mass matrix element U_{ek} determined by the oscillation experiments and with some hypothesis on the Majorana CP phases η_k (see for example [1]). An additional difficulty stems from the large uncertainties in the matrix element $M^{0\nu}$ which is needed to obtain the effective neutrino mass from the measured half-life.

The Milano group has run several experiments in the Gran Sasso Underground Laboratory using thermal detectors to search for the ^{130}Te DBD-0ν. This isotope was chosen because of its many advantages: 1) it is present naturally with an abundance of about 34%, 2) it has a large transition energy $Q_{\beta\beta}$ of about 2539 keV, 3) it has a favorable matrix element $M^{0\nu}$. Thermal detectors are made of an absorber and an attached thermometer which measures the temperature change induced by energy depositions in the absorber: the sensitivity required for single particle detection is achieved by keeping the detectors at temperatures well below 0.1 K. Making the absorbers out of TeO_2 crystals it is possible to perform a calorimetric search of the DBD-0ν of ^{130}Te. A calorimeter acts both as source and detector: all the energy released in the decay and shared by the two electrons is measured with high efficiency giving as a signal a peak at $Q_{\beta\beta}$ in the energy spectrum.

At the end of Phase II of the MIBETA experiment – about 6.3 kg of TeO_2 – a lower limit of 2.1×10^{23} years at

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90 % C.L. for the $\tau_{1/2}^{0\nu}$ of ^{130}Te was reached with a total statistics of 4.3 kg×year [2]: this result translates in an upper limit of about $1.1 \div 2.6$ eV for $\langle m_\nu \rangle$ at 90 % C.L. (the systematic uncertainties on $\langle m_\nu \rangle$ reflect the uncertainties in the theoretical estimates of $M^{0\nu}$).

The experimental sensitivity on $\langle m_\nu \rangle$ scales as $[(\Delta E \cdot b)/(M \cdot t_M)]^{1/4}$, where ΔE is the energy resolution, b is the background level per units of mass, energy and time, M is the detector mass, and t_M is the measuring time: therefore the present limit on $\langle m_\nu \rangle$ can be further improved by increasing the detector mass M and reducing the background level b.

2 The CUORE experiment

The CUORE (Cryogenic Underground Observatory for Rare Events) experiment is the natural evolution of our experiments to search for DBD-0ν with thermal detectors: it consists of an array of 1000 TeO_2 crystals with a total mass of about 760 kg. CUORE, proposed by a large international collaboration, is one of the few next generation experiments to search for DBD-0ν, but it will be also a powerful observatory for Cold Dark Matter and solar axions [3].

The main issue of the CUORE experiment will be a strong reduction of the background level: the detector is therefore designed to be compact, highly segmented, well shielded and with the use of a minimum amount of passive material – mostly copper and PTFE. Simulations based on our present understanding and knowledge of material contaminations indicate that a reduction of the background to a level of about 1 count/ton/year/keV is feasible. Under this favorable hypothesis, running the experiment for 5 years with an energy resolution of about 5 keV, the sensitivity of CUORE on $\tau_{1/2}^{0\nu}$ would be 6.6×10^{26} years at $1\,\sigma$. The CUORE experiment would therefore have a $1\,\sigma$ sensitivity on $\langle m_\nu \rangle$ of about $19 \div 46$ meV and should be able to shed some light on the neutrino mass hierarchy issue [4].

3 The Cuoricino experiment

The CUORE detector is made of one thousand of 760 g TeO_2 crystals arranged in 25 *towers* of 40 crystals each. As a test bench of the CUORE *tower* structure we have built the Cuoricino experiment: it consists of an array of 62 TeO_2 thermal detectors for a total mass of about 40 kg, by far the largest cryogenic experiment in the world. 44 detectors are made of $5 \times 5 \times 5\,cm^3$ crystals with a mass of about 790 g, the other 18 are $3 \times 3 \times 6\,cm^3$ crystals with a mass of about 330 g. The detectors are arranged in a pile of 13 modules – the Cuoricino *tower*: 11 modules are made of 4 of the 790 g detectors in a 2×2 square arrangement, the other 2 modules consist of 9 of the smaller detectors in a 3×3 arrangement. The central crystals of these latter modules have an active shielding on 4π given by other detectors: the application of anticoincidence cuts on these crystals will give interesting informations about the background reduction potential of a highly segmented detector like CUORE. Four of the 330 g crystals are made of enriched Te: two are enriched in ^{130}Te and two in ^{128}Te. With these detectors we will perform a better measurement of the ^{130}Te DBD-2ν half-life [2].

The surfaces of the TeO_2 crystals and of the copper pieces facing the detectors have been treated to remove radioactive impurities. The detectors have then been assembled in a clean room with special care to avoid the introduction of radioactive contaminations: in particular, whenever possible, nitrogen flushed boxes have been used to prevent exposure to radon.

The Cuoricino *tower* has been installed in our low background dilution refrigerator in the Gran Sasso Underground Laboratory. The refrigerator is surrounded by a shield made of 10 cm of regular lead plus 10 cm of low ^{210}Pb content lead; just around the detectors – inside the vacuum chamber of the refrigerator – a further shielding is provided by a 1 cm thick roman lead layer [5]. The whole set-up is enclosed in a plexiglass box flushed with nitrogen to remove the radon gas, and in a Faraday cage.

The Cuoricino installation has been completed at the beginning of 2003. During the first cool-down to about 0.01 K the electrical connections to few detectors opened: therefore only 32 of the 790 g crystals and 16 of the 330 g crystals are actually operative. After the detector optimization phase, the experiment started data taking on April, 19^{th}. The data reported in this paper were collected until June, 23^{rd}, when all experiments in the Laboratory were temporarily shut down because of environmental problems. We present here only the preliminary analysis for the data of the 790 g crystals – about 25.3 kg of TeO_2: the analysis of the complete data set is still in progress.

3.1 Preliminary results

Figure 1 shows the calibration spectrum obtained by summing the spectra from all 32 operating 790 g detectors, which corresponds to about 227.73 hours of exposure to

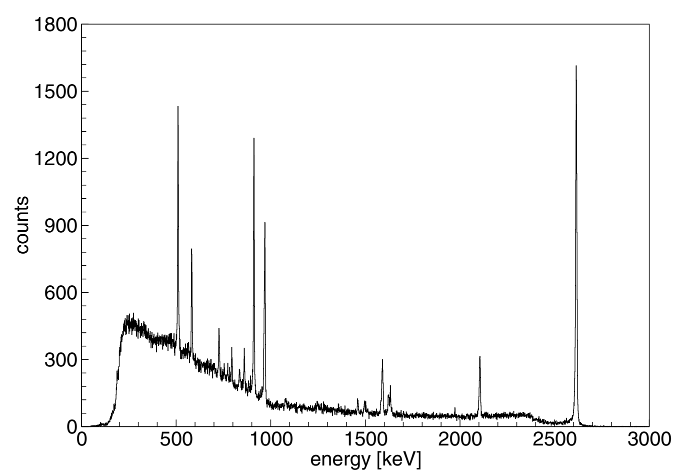

Fig. 1. Sum of the ^{232}Th calibration spectra of 32 detectors

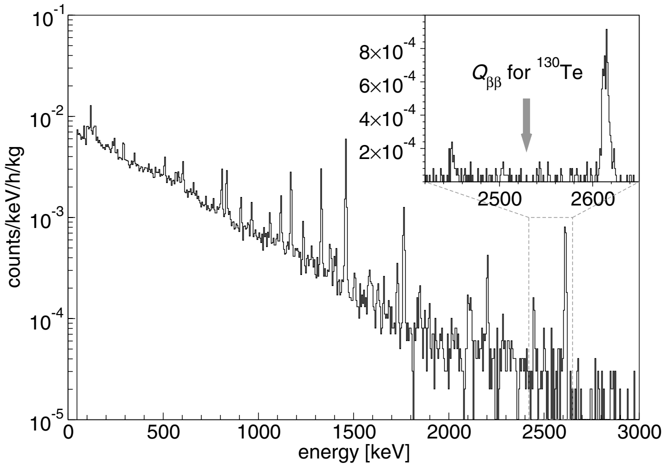

Fig. 2. Background measurement: 29 detectors in anticoincidence with a total statistics of 2.26 kg×year

a ^{232}Th source. The mean energy resolution FWHM for the ^{208}Tl γ-rays at 2615 keV is about 8 keV. The total background measurement is shown in Fig. 2: it is obtained by summing the spectra of 29 of the operating 790 g and by discarding every coincidence event between two or more detectors. The background measurement lasted 891.27 hours – yielding a live-time of about 57% – which correspond to a total statistics of 2.26 kg×year.

The inset in Fig. 2 shows the background in the energy region around $Q_{\beta\beta} = 2528.9$ keV, i.e. where the DBD-0ν peak is expected: the measured counting rate is 0.23 ± 0.04 counts/kg/year/keV. In this region one can distinguish peaks at 2447 and 2615 keV which are γ-rays from ^{214}Bi and ^{208}Tl respectively; a faint peak appears also at 2506 keV which can be attributed to the coincidence detection of the two ^{60}Co γ-rays with energies equal to 1173 and 1332 keV. The observed continuum can be attributed both to multiple Compton interactions of 2615 keV γ-rays and to the partial energy deposition of α particles from contaminations on the surfaces either of the detectors itself or the materials close to the detectors – mainly copper.

Performing a maximum likelihood analysis as described in [2] a lower limit of about 5×10^{23} years at 90% C.L. can be set on the ^{130}Te DBD-0ν half-life: this turns in an upper bound on the effective neutrino Majorana mass $\langle m_\nu \rangle$ of about $0.7 \div 1.7$ eV.

4 Conclusions

From these preliminary results it is apparent that Cuoricino is a self-standing experiment giving very important scientific results. We are planning to replace soon the faulty electrical links to recover all the detectors – about 40.7 kg of TeO_2. Running for 3 years live-time we will then increase the statistics to about 120 kg×year. Assuming to keep the present energy resolution and background level, we could expect a 90% C.L. limit on $\tau^{0\nu}_{1/2}$ of about 4×10^{24} years, estimated simply by scaling the present result according to the increased statistics. The corresponding upper limit on $\langle m_\nu \rangle$ would then be $0.25 \div 0.60$ eV.

It is also possible to draw useful conclusions for what concerns the upcoming CUORE experiment. The 790 g TeO_2 crystals arranged in a *tower*-like structure show very good and reproducible performances. The adopted surface cleaning techniques, an improvement of the ones used for the MIBETA experiment, appear to be quite reliable. Future R&D for CUORE will focus on the further reduction of the background level: we believe that a factor 200 can be accomplished with the improved design of the CUORE detector together with a more effective shielding of external γ radiation and with a better material selection and cleaning to reduce α emitting contaminations.

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