CUORE: An Experiment to Investigate for Neutrinoless Double Beta Decay by Cooling 750 kg of TeO_2 Crystals at 10mK

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Abstract. CUORE (Cryogenic Underground Observatory for Rare Events) is an experiment proposed to infer the effective Majorana mass of the electron neutrino from measurements on neutrinoless double beta decay (0νDBD). The goal of CUORE is to achieve a background rate in the range 0.001 to 0.01 counts/keV/kg/y at the 0νDBD transition energy of ^{130}Te (2528 keV). The proposed experiment, to be mounted in the underground Gran Sasso INFN National Laboratory, Italy, is realized by cooling about 1000 TeO_2 bolometers, of 750 g each, at a temperature of 10mK. We will describe the experiment, to be cooled by an extremely powerful dilution refrigerator, operating with no liquid helium, and the main experimental features designed to assure the predicted sensitivity. We present moreover the last results of a small scale (40.7 kg) 0νDBD experiment carried on in the Gran Sasso Laboratory (CUORICINO).

Keywords: Double Beta Decay, Neutrino mass, Low temperature equipment.
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INTRODUCTION

In recent years the observation of oscillations of neutrino flavors in atmospheric, solar, reactors and accelerator experiments [1-4] led to new proposals for experiments aiming to investigate the Majorana/Dirac behavior of neutrinos as well as to measure the electron neutrino mass $\left|\left\langle m_{\upsilon}\right\rangle\right|$, providing a scale for all the neutrino masses. All the recently published constraints on the mixing angles of the neutrino-mixing matrix suggest that, if the neutrinos are Majorana particles, experiments on double-beta decay (DBD) should be able to measure the above mentioned properties of the electron neutrino. In particular the neutrinoless DBD (0νDBD) should provide a stringent constraint or a positive value for the effective neutrino mass. In the neutrinoless DBD, a rare spontaneous nuclear transition [5], a nucleus (A,Z) decays into (A,Z+2) with the emission of two electrons and no neutrino. This process leads to a peak in the sum energy of the two electrons, that in our case (^{130}Te) is Q=2528.8 ± 1.3 keV [6]. One should stress that the appearance of a peak at this energy would be a necessary but not sufficient condition to claim for an evidence of 0νDBD, being the peak of possible different origin. Only a positive test at different energies in different nuclei would definitely prove the existence of this process. CUORE (Cryogenic Underground Observatory for Rare Events) is an experiment proposed to INFN and approved, aiming to search for 0νDBD in a large mass of TeO_2 crystals cooled at a temperature of 10 mK. As a figure of merit for the detector, to be compared with other detectors, we can use the neutrinoless sensitivity at 1σ level as a measure of the inferred lifetime when no evidence of decays is found:

$$\Sigma(\tau_{1/2}^{0\nu}) \cong 4.2 \cdot 10^{26}\ \varepsilon\ \frac{a.i.}{A}\sqrt{\frac{M \cdot t_m}{\Delta E \cdot Bkg}} \quad [\mathrm{y}]$$

where ε represents the detector efficiency in the vicinity of the energy Q, *a.i.* and *A* the isotopic abundance and the mass number, *M* the mass of the ββ emitter in kg, t_m the measurement time in years, ΔE the energy resolution in keV, and *Bkg* the background rate in counts/(keV· kg · y). It is clear from the above formula that the key points necessary to obtain a good sensitivity are: working with large masses, good energy resolution and with a very "clean" system to reach a very low background rate.

CUORE: EXPERIMENTAL DETAILS

The CUORE detector is a system of 988 bolometers, each being a cube of 5x5x5 cm^3; the array is composed of 19 vertical towers. Each tower consists of 13 layers of 4 cubes each. The single cube will be a single crystal of TeO2; this material is optimized for 0νDBD search, due to its high natural abundance (33.8%, more than three times the natural abundance of other element candidates for 0νDBD), and to the high energy of the process, falling in a "good" window of low natural radioactivity. Each crystal is weighing 750g, so the total mass of the detector will be 741 kg of granular calorimeter, corresponding to 600 kg of Te, and to 203 kg of ^{130}Te. The detecting procedure is based on the cryogenic technique proposed for the first time to study nuclear phenomena by Simon [7] and suggested more than twenty years ago for searching rare events by E. Fiorini and T. Niinikoski [8]. The proposed site for the experiment will be the underground Gran Sasso INFN National Laboratory, Italy, at a depth of 3400 m.w.e.

Cryogenic thermal detectors are realized by using dielectric crystals cooled to very low temperature. The signal due to an event releasing energy ΔE is in fact proportional to the heat capacity of the crystals, following, according to the Debye law, a $(T/T_D)^3$ dependence at low temperatures. The crystals used in our experiment have a heat capacity $C \cong 2 \cdot 10^{-9}$ J/K, evaluated at a temperature of 10mK. The energy predicted for the DBD gives, therefore, a $\Delta T = \Delta E/C =$ 0.2 mK. At this temperature the limits due to the statistical fluctuations of the crystal internal energy are:

$$\left\langle \Delta U^2 \right\rangle = k_B C T^2 \Rightarrow \Delta U^{\min} \cong 1{,}7 \cdot 10^{-18} J = 11\ \mathrm{eV}$$

and

$$\left\langle \Delta T^2 \right\rangle^{1/2} = T(k_B / C)^{1/2} \Rightarrow \Delta T^{\min} \cong 7\ \mathrm{nK}$$

ΔU^{min} and ΔT^{min} being the lower energy and temperature resolution evaluated at the thermodynamic temperature *T=10mK*, and k_B the Boltzmann constant. These limits are well below the energy and the temperature resolution of the readout system. All the crystals will be produced and cut to the required dimensions by the Shanghai Quinhua Material Company (SQM) in Shanghai, China. The thermal sensors converting the thermal signal into a voltage signal will be Neutron Transmutation Doped (NTD) germanium thermistors developed and produced at the Lawrence Berkeley National Laboratory (LBNL) and UC Berkeley Department of Material Science.

These thermistors have a strong dependence of the resistance with temperature, according to the relation: $R(T;R_0,T_0) = R_0 \exp(T_0/T)^{1/2}$, where R_0 and T_0 are the single thermistor parameters fixed by the neutron doping procedure. Each bolometer consists of a crystal, an NTD thermistor and a heater (Si doped with As) glued with Araldit Rapid (Novartis) epoxy onto the crystal surface. The connections between the thermistor and the heat sink on the Cu holder are realized by Au wires of 25-50 μm in diameter. Every layer of each CUORE tower will be composed of four crystals, kept in place by a structure of OFHC Cu and PTFE. No other material is allowed to be used due to the surface and bulk radioactivity. The Cu and PTFE used will be subjected to a cleaning procedure to remove any surface contamination at the lowest possible level. This contamination is in fact the main contribution to the background measured by the detector and particular attention must be paid to the surface treatment of all the surfaces that could raise the background of the detector.

The dilution refrigerator will be a very particular one. It must possess the following characterisitics: 1) No liquid helium must be used in normal operation, so that the main cooling down to liquid helium temperature will be given by n pulse tubes thermally anchored to the 100K, 40K and 4.2K shields. 2) No, or very few super-insulation must be used to prevent unwanted radioactive signals. 3) The total mass to be cooled by the mixing chamber at a temperature of 8mK will be of approximately 1.5 ton (crystals mass + lead). 4) The total mass to be cooled at the level of the 50mK shield will be approximately 6 tons due to the lead shields. 5) All the system must have a very good mechanical attenuation in the 1Hz-1 kHz region, not to degrade the noise baseline of the detectors, usually operating in this range of frequency.

CUORICINO: A SMALL SCALE TEST SYSTEM

To test all the apparatus and the techniques proposed to realize the CUORE project, a small scale experiment (CUORICINO) has been realized and it is in operation in the same Gran Sasso Underground Laboratory (Italy) where the CUORE experiment is planned to be mounted. The CUORICINO array is similar to one tower of CUORE array, and consists of 44 cubic crystals of TeO_2 of 5 cm side and by 18 crystals of 3x3x6 cm^3. The total mass of TeO_2 is 40.7kg. The system is presently in operation at a temperature of 8mK. The statistic on the first two runs, corresponding to an effective exposure of 10.85 kg×year, give the following results: energy resolution $\Delta E=7.8\pm2.8$ keV(on 5x5x5 cm^3 crystals, measured at 2615 keV, ^{208}Tl line), mean background in the region 2470÷2560 keV: Bkg=0.18±0.02 c/(keV·kg·y), no evidence is found on a peak at 2529 keV; lower limit on 0νDBD half time at 90% CL [9] is $\tau_{1/2} > 1.8\cdot10^{24}$y.

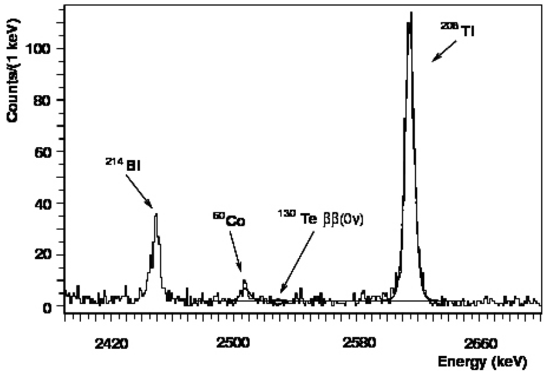

FIGURE 1. Experimental background spectrum of all the CUORICINO detectors in the DBD region.

TECHNIQUES TO REDUCE THE BACKGROUND RATE: SSD

As we have seen from Eq. 1 the major challenge in obtaining the desired sensitivity is the reduction of the background rate. This task can be accomplished in three main ways: 1) By reducing the amount of material (Cu in our case) surrounding the crystals. 2) By a proper cleaning procedure of all the materials that will be in contact or will "see" the crystals. 3) By finding a veto procedure to eliminate unwanted signals coming from outside the bolometer. In view of exploiting this last possibility we have designed and tested Surface Sensitive Bolometers (SSB) to be coupled to the crystals. The idea is to cover all (or a great part) of all the crystals with 6 layers of a thin Ge slab, equipped with a thermistor similar to those glued onto the crystal. If an α particle, coming from the outside the bolometer, interacts with the Ge shield it will release all its energy there. As a consequence we will have a raise of the temperature both on the Ge slab and on the TeO_2 crystal. These two signals will be however very different: due to the small heat capacity of the slab the signal in the Ge thermistor will be higher and easily saturated, moreover the rise time of the Ge signal will be much faster than that in the TeO_2.

These characteristics should lead to an easy identification of the spurious signals coming from the outside, creating a veto procedure to reduce the background rate. In Fig.2 the scatter plot of the SSD pulse amplitudes vs. crystal signal amplitudes are shown, for a test performed on a small sample at the Insubria University in Como, i.e. not in the Gran Sasso underground site.

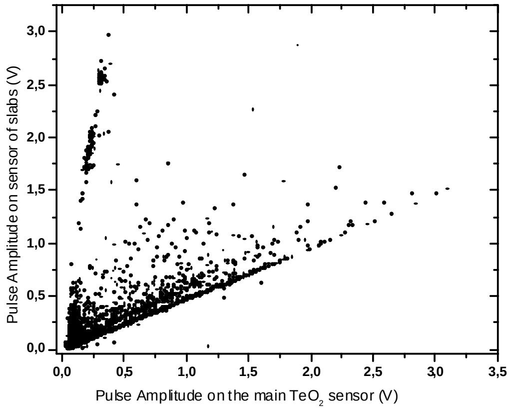

FIGURE 2. Scatter plot of the SSD pulse amplitudes vs. the TeO$_2$ pulse amplitudes.

It is evident from the above figure that a clear difference exists between the amplitudes coming from the SSD with respect to the TeO$_2$ bolometer amplitudes. Work is in progress to repeat the test in the Gran Sasso underground facility, with more crystals and in a more clean and controlled environment. Moreover a series of measurements will be performed to test the new design of the copper holder for the crystals, that should reduce the amount of copper seen by the crystals, and to test new cleaning procedures for the copper and the crystals. All these efforts should lead to the desired decrease in the background necessary to reach the design sensitivity on $|<m_\nu>|$ expected to be of the order of 30mV.

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REFERENCES

1. Q.R. Ahmad, et al., *Phys. Rev. Lett.,* **89**, 1302-1306 (2002).
2. S. Fukuda, et al., *Phys. Rev. Lett,.* **86**, 5656-5660 (2001).
3. T. Kajita, Y. Totsuka, *Review of Modern Physics.* **73**, 85 (2001).
4. K. Educhi, et al., *Phys. Rev. Lett.,***90**, 21802-21806 (2003).
5. S.R. Elliott and P. Vogel, *Ann. Rev. Nucl. Part. Sci.,***52**, 115 (2002).
6. G.R. Dyck, et al., *Phys. Lett. B,* **245**, 343 (1990).
7. S. Simon, *Nature,* **135**, 763 (1935).
8. E. Fiorini and T. Niinikoski, *Nuclear Instruments and Methods,* **224**, 83 (1984).
9. R.M. Barnett et al., *Phys. Rev. D,* **54** , 1 (1996).