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The status of the CUORE experiment

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Abstract. The Cryogenic Underground Observatory for Rare Events (CUORE) is an experiment to search for neutrinoless double beta decay ($0\nu\beta\beta$) in ^{130}Te and other rare processes. The observation of $0\nu\beta\beta$ would indicate that neutrinos are Majorana particles and would provide information about the absolute neutrino mass scale. CUORE is a bolometric detector composed of 988 TeO_2 crystals, with the total mass of about 750 kg of Tellurium. We will discuss the status of the CUORE experiment, including recent R&D efforts, anticipated sensitivity, and present the most recent results from CUORICINO, the predecessor experiment operated in Gran Sasso National Laboratories in Italy.

1. Introduction

The nature of neutrino mass is one of the frontier problems of fundamental physics. Neutrinoless Double Beta Decay ($0\nu\beta\beta$) is a powerful tool to investigate the mass hierarchy and possible extensions of the Standard Model. The $0\nu\beta\beta$ is a rare spontaneous nuclear transition, never observed, involving a change of the nuclear charge Z by two units ($A, Z \pm 2$) with the emission of two electrons and no neutrinos, resulting in a peak at the summed energy spectrum of the electrons. The decay is possible only if the neutrino is a Majorana massive particle. Its transition width is proportional to the square of the effective Majorana mass, $|\langle m_{ee} \rangle|$ [1]. In case of neutrino mixing the Majorana mass experiments measure a specific mixture of neutrino mass eigenvalues, $|\langle m_{ee} \rangle|^2 = |\sum_i U_{ei}^2 m_i|^2$, i summed over all mass eigenstates. From the $0\nu\beta\beta$ half-life it is therefore possible to infer important information concerning the mass hierarchy and the absolute mass scale of neutrinos.

In the $0\nu\beta\beta$ all the energy is shared between the two electrons and the nucleus is so heavy that the recoil is negligible. For these reasons the experimental signature is a monochromatic line at the Q -value of the decay. The experimental Sensitivity ($S^{0\nu}$), defined as the decay time corresponding to the minimum number of detectable events above background (B), is given by

$$S^{0\nu} = \ln 2 \cdot \epsilon \cdot \frac{\text{i.a.}}{A} \cdot \sqrt{\frac{M \cdot T}{B \cdot \Gamma}} \quad (1)$$

where i.a. is the isotopic abundance of the a chosen $\beta\beta$ -emitter isotope, M its mass, ϵ the efficiency of the detector, Γ the energy resolution (around the Q -value), B is the background, A the molecular mass, and finally, T the measurement time. According to eq. 1, it is straightforward that to obtain the best sensitivity a double beta decay experiment must have a very large mass, high efficiency, a good resolution, a long measurement time, a very low background and the chosen $\beta\beta$ -emitter isotope should have a high natural isotopic abundance (if enrichment is not necessary the result is a significant cost savings).

The bolometric technique, proposed for the first time in the 1986 [2], is a powerful tool to study neutrinoless double beta decay. A bolometer is composed by two main parts: the *Energy Absorber* and the *Phonon Sensor*. An impinging particle, which releases an amount of energy ΔE in the *Absorber*, is detected through a small temperature rise ΔT (eq. 2) that is converted by the *Sensor* to a voltage pulse signal ΔV (eq. 2).

$$\Delta T = \frac{\Delta E}{C} e^{-\frac{t}{\tau}} \quad , \quad \frac{\Delta V}{\Delta E} \simeq 0.1 \frac{\text{mV}}{\text{MeV}} \quad (2)$$

This temperature rising is directly proportional to the released energy ΔE and inversely proportional to the absorber thermal capacity C . To maximize the temperature rise a very small thermal capacity is needed. This is possible using dielectric and diamagnetic crystals, in which the thermal capacity, at very low temperature, is proportional to the cube of the temperature, following the Debye Law (eq. 3).

$$C(T) \propto \left(\frac{T}{T_D} \right)^3 \quad (3)$$

The main features of the bolometric technique are the very high efficiency ($\simeq 100\%$, a true calorimeter), a very large detection volume, and finally, a high intrinsic energy resolution (about 7 keV FWHM @ 2615 KeV).

2. The CUORE Experiment

CUORE [3, 4] (Cryogenic Underground Observatory for Rare Events) aims at searching for $0\nu\beta\beta$ of ^{130}Te using the bolometric technique. The CUORE detector is an array of 988 cryogenic bolometers arranged in 19 towers of 52 crystals. The bolometer is a TeO_2 cubic crystal (*absorber*), $5 \times 5 \times 5 \text{ cm}^3$ in size, with an NTD-Ge thermistor (*sensor*) glued onto the crystal surface. Tellurium is an advantage in this instance because of the relatively high natural abundance (34.2% [5]) of the $0\nu\beta\beta$ candidate isotope, which means that enrichment is not necessary to achieve a reasonably large active mass. Also, the Q-value (2528 keV [6, 7]) of the decay falls between the peak and the Compton edge of the 2615 keV gamma line of ^{208}Tl , the highest-energy gamma from the natural decay chains; this leaves a relatively clean window in which to look for the signal. Moreover TeO_2 crystals are easy to be grown big with low radioactive contaminations [8], they have good mechanical properties and low heat capacity at low temperature (dielectric and diamagnetic). The entire detector will be maintained at the temperature of about 10 mK through a Pulse Tube Assisted Cryostat.

The CUORE program, started in the 2003 with the pilot experiment CUORICINO, includes an intensive R&D and three experimental main steps: CUORICINO [9–11], CUORE-0 (also known as CUORE One Tower), that will take data for three years starting at the end of 2011, and, the final step, CUORE. The R&D program is aimed at selecting and validating all the needed materials and procedures from a radioactive point of view in order to obtain the lowest possible background.

3. The first step: CUORICINO

CUORICINO [9–11] was a tower array of 62 TeO_2 crystals, the largest bolometric experiment ever realized. It took data from April 2003 to June 2008. The array was operated underground, in a dilution refrigerator located at the Laboratori Nazionali del Gran Sasso (LNGS, Italy), which provides an average coverage of 1400 m of rock (3650 m.w.e. [12–14]). CUORICINO was composed by 11 modules of 4 TeO_2 crystals $5 \times 5 \times 5 \text{ cm}^3$ (790 g) and by 2 modules of 9 TeO_2 crystals $3 \times 3 \times 6 \text{ cm}^3$ (330 g). These 2 modules, in turn, were composed by 14 crystals of natural

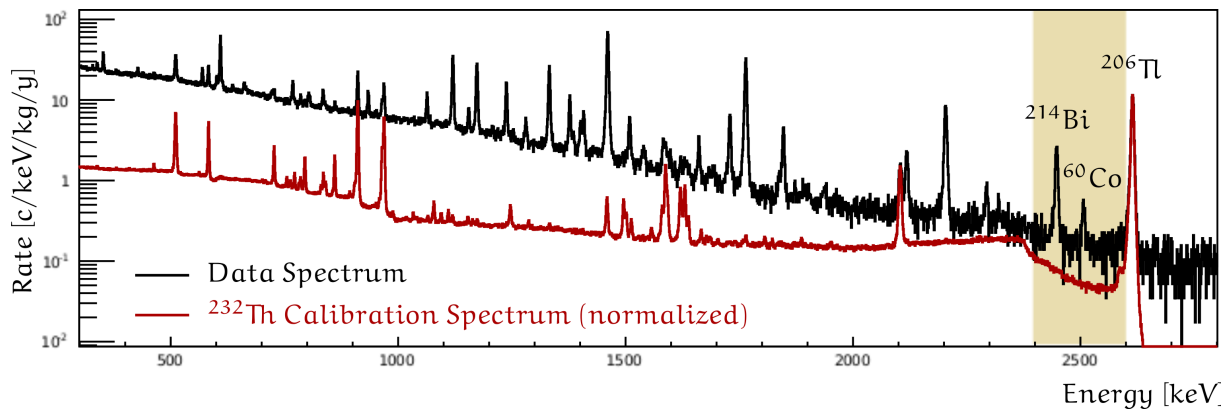


Figure 1. Anticoincidence total energy spectrum of all CUORICINO detectors (black) and the total energy spectrum of all CUORICINO detectors during calibration measurements (red). For convenience, it is normalized to have the same intensity of the 2615 keV line of ^{208}Tl as measured in the non-calibration spectrum.

^{130}Te (34.2% [5]), by 2 crystals enriched in ^{130}Te (75% [15]) and by 2 crystals enriched in ^{128}Te (82.3%). The total mass of TeO_2 was 40.7 kg for a total mass of ^{130}Te equal to 11.3 kg.

After a total exposure of 19.75 kg-y of ^{130}Te the CUORICINO final results, for the half life and for the majorana mass, are summarized with the following limits [16]:

$$\begin{aligned} \text{Lower Limit, Half-life: } \tau_{1/2}^{0\nu}(^{130}\text{Te}) &> 2.8 \cdot 10^{24} \text{ y (90\% C. L.)} \\ \text{Upper Limit, Majorana Mass: } m_{\nu_e} &< (300 \div 710) \text{ meV} \end{aligned} \quad (4)$$

These limits were obtained using the Nuclear Matrix Elements computed in [17–20]. The background in the Region Of Interest (ROI: 2474÷2580 keV) resulted [16]:

$$B = (0.153 \pm 0.006) \text{ c/keV/kg/y} \quad (5)$$

The main sources for this background were the natural uranium (^{235}U) and thorium (^{232}Th) decay chains from contamination of the detector materials. There were two main components to this background: surface contamination of the detector components, and bulk contamination of the cryostat materials. The surface contamination (70%) produced a flat α background; the main contributors were the surfaces of the copper support structures facing the bolometers and of the crystals themselves. The principal background contribution due to bulk contamination was the tail of the 2614.5 keV gamma produced by the decay of ^{232}Th in the cryostat materials (30%).

These values, verified by extensive Monte Carlo studies, were obtained with a anti-coincidence analysis. In fact, the granularity of the CUORICINO detector allows to perform a coincidence analysis which lets to discriminate the location of the contamination, identifying single hits events (only one detector at time) and multi hits events (two or more events at the same time). The anti-coincidence technique leads a background reduction of about 15% in the ROI. In the case of CUORE, in order to reduce this background, more stringent material selection, production, cleaning, handling, and storage procedures have been established for all detector components to be used.

4. The near Future: CUORE-0

CUORE-0 will be a single CUORE-like tower realized with the same procedures defined for CUORE and, in particular, crystals from the same production line, the same copper and the

same teflon, the same copper surface cleaning technique and the same assembly line. The tower will be installed in the Hall A cryostat at LNGS, the same as CUORICINO. CUORE-Zero will be not only an engineering run, useful to verify the CUORE assembly procedure, but also a new double beta decay experiment with a total mass of tellurium ^{130}Te of about 11 kg and a resolution around $\Delta E \simeq (5 \div 6)$ keV. Considering an aimed background of $B \simeq 0.12$ c/keV/kg/y, in one year of live time CUORE-0 will double the CUORICINO limit in sensitivity. The array will be assembled starting on May 2011 at the LNGS and will start to take data before the end of 2011.

5. Conclusion

Bolometers are a powerful tool for the search of Double Beta Decay and CUORICINO has demonstrated the feasibility of CUORE. Main concepts are to have about 20 times the active mass of CUORICINO, stringent controls on radioactivity of materials and assembly and to have a high efficiency in background rejection [21]. The goal is to reach a background of 0.01 count/keV/kg/year that, for a live time of five years, means a lower limit for the half life $\tau_{1/2}^{0\nu} = 1.5 \cdot 10^{26}$ y, which gives an upper limit for the effective majorana mass in the range $41 \div 82$ meV. In this scenario CUORE will have the capability to explore the inverse hierarchy mass region. The experiment is under construction at the LNGS and the data taking is foreseen in 2015.

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