From Cuoricino to CUORE: investigating neutrino properties with double beta decay

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Abstract. CUORE is the only fully approved 1-ton size neutrinoless double beta decay experiment to date, with the goal of scrutinizing the inverted hierarchy region for the effective Majorana mass. CUORE, presently being built in Gran Sasso Underground Laboratory, is an array of 988 TeO$_2$ cryogenic detectors containing 200 kg of $^{130}$Te, the neutrinoless double beta decay candidate. CUORE is due to start data taking in 2012. The feasibility of the project has been proved by Cuoricino, the pilot experiment that took data until 2008, for about five years, with 62 TeO$_2$ cryogenic detectors. Cuoricino will be superseded in 2010 by CUORE-0, the first CUORE tower to be installed in Cuoricino cryogenic facility, which will take data until CUORE start. In this paper the final results of Cuoricino are reported, and CUORE-0 and CUORE potential and state of the art are discussed.

1. Introduction

Neutrinoless double beta decay ($\beta\beta0\nu$) is a key tool for investigating neutrino properties: if observed it would undoubtedly imply that neutrinos are massive Majorana particles. Expected sensitivities of future planned experiments should be able to probe the inverted hierarchy allowed region for the effective Majorana mass [1].

Experimental techniques based on the calorimetric approach with cryogenic detectors offer several advantages like high efficiency, high energy resolution, large masses, and a wide choice of the absorbing material (i.e. the $\beta\beta0\nu$ source). Cuoricino and CUORE, described in the following sections, are calorimetric experiments searching for the $\beta\beta0\nu$ of $^{130}$Te with cryogenic detectors.

2. Cuoricino

The Cuoricino experiment was running from February 2003 until June 2008 in Hall A of the Gran Sasso Underground Laboratory (AQ, Italy) at a depth of $\sim$ 3500 m.w.e. It was by far the largest cryogenic detector in the world, using an array of 62 TeO$_2$ crystals, for a total active mass of 40.7 kg. The array, in a tower like structure, was composed by 11 modules of 4 crystals $5\times5\times5$ cm$^3$ each, and 2 modules of 9 crystals $3\times3\times6$ cm$^3$ each. Every module is composed by two copper frames holding the TeO$_2$ crystals via teflon springs. All the TeO$_2$ crystals had natural $^{130}$Te isotopic abundance ($\sim$34%) except for 4 of the smaller type, two of which enriched to 82.3% in $^{128}$Te and the other two to 75% in $^{130}$Te, corresponding to a total $^{130}$Te mass of 11 kg. The array was operated at a temperature of about 10 mK inside a dilution refrigerator, shielded from environmental radioactivity and neutrons. Further details
about the experimental setup can be found in [2]. The performance of the detectors were very good: the average FWHM energy resolution of the entire array was about 8 keV at the $^{130}$Te transition energy (2527 keV). The total analyzed exposure adds up to 18 $y \times kg$ of $^{130}$Te and the final sum spectrum is obtained with the detectors operated in anticoincidence, in order to reduce background contributions from U and Th on the crystal surfaces and from external $\gamma$s presumably due to Th contamination of the refrigerator. The achieved background level in the $\beta\beta0\nu$ energy region is $\sim 0.18$ counts/keV/kg/$y$, which translates into a 90% C.L. lower limit on the half life of $^{130}$Te $\beta\beta0\nu$ of $\tau_{1/2}^{0\nu} > 2.94 \times 10^{24}$ y. The corresponding upper limit for the effective Majorana mass is $m_{\beta\beta} < 0.21 - 0.70$ eV, with the spread due to the uncertainties in nuclear matrix element calculations, as given by [3]. This result does not completely rule out the claim of evidence by H.V. Klapdor-Kleingrothaus and his co-workers [4].

A careful analysis of the background level above the highest natural $\gamma$ line of $^{208}$Tl shows a continuum up to about 4 MeV which clearly extends in the region of interest and accounts for most (~70%) of the count rate around $^{130}$Te $\beta\beta0\nu$ transition energy. On the basis of MonteCarlo simulations and of ad hoc measurements in the CUORE R&D facility - located in Hall C of Gran Sasso Laboratory - we could disentangle the different sources contributing to the background in the crucial energy region: $\sim 30\%$ of the count rate is due to multi-Compton events of $^{208}$Tl $\gamma$ transition, $\sim 20\%$ is ascribed to degraded alphas coming from U and Th surface contaminations of the TeO$_2$ crystals, and the remaining $\sim 50\%$ seems to originate from U and Th surface contaminations of the inert materials surrounding the detectors, most probably the copper of the detector holders.

3. From Cuoricino to CUORE
From statistical considerations, the sensitivity \( \Sigma(\tau_{1/2}^{0\nu}) \propto \epsilon i.a. (M_{t_{meas}}/(\Delta E bkg))^{1/2} \), where \( \epsilon \), i.a., \( M \), \( t_{meas} \), \( \Delta E \), and \( bkg \) are the detector efficiency, the active isotope abundance, the detector mass, the measuring time, the energy resolution, and the background level at the $\beta\beta0\nu$ transition energy, respectively. Therefore, to improve the sensitivity reached by Cuoricino one could in principle act on several parameters. Since i) the natural isotopic abundance of $^{130}$Te is already quite high and isotopic enrichment is expensive and needs R&D effort to maintain a high radiopurity level, and ii) the single crystal mass of TeO$_2$ is close to the size limit which allows to meet the required performance - especially in terms of the energy resolution $\Delta E$, key parameters to work on remain the number of detectors and the background level. Also an improvement of the experimental live time - the duty cycle of Cuoricino was only 30% - is extremely important.

In order to probe the inverted hierarchy region for the effective neutrino mass Cuoricino upper limit must be improved by a factor of 10, which in turn means to improve $\Sigma(\tau_{1/2}^{0\nu})$ by a factor of 100. By increasing the total mass $M$ by a factor $\sim 20$, and the measuring time by $\sim 5$, the challenging step to meet the goal will be a background reduction factor of $\sim 100$. This could be achieved by a heavier shielding, to reduce the environmental $\gamma$ contribution, by a better surface cleaning, to reduce the degraded $\alpha$ continuum, and by an improvement of the design, to reduce the amount of material facing the detectors.

4. CUORE
CUORE (Cryogenic Underground Observatory for Rare Events) [5] is an array of 988 natural TeO$_2$ cryogenic detectors arranged in a cylindrical compact and granular structure of 19 towers, each of them made by 13 planes of 4 detectors $5 \times 5 \times 5 \text{cm}^3$ each. The total active mass will be of 741 kg, for a $^{130}$Te mass of 203 kg. This huge mass, together with its holding structure, must be cooled and steadily operated at $\sim 10 \text{mK}$. Therefore one of the technological challenges of CUORE will be the cryogenic system, which has to host additionally about 10 ton of internal lead shielding and guarantee at the same time a low mechanical vibration input on the detector.
The CUORE experiment is presently being built in Hall A of Gran Sasso Laboratory, besides Cuoricino facility. The experimental hut is almost completed, the next steps will be the installation of the utilities, of the clean room and of the external shielding. Then the custom-made cryostat will be set up. Assembly of the detector in a controlled radioclean environment is foreseen for 2011 and the data taking start is expected in 2012.

CUORE $\beta\beta0\nu$ sensitivity will strongly depend on the background level, as already discussed. In 5 years of measuring time with a FWHM energy resolution of $\sim 5$ keV, a conservative assumption of 0.01 counts/keV/kg/y in the energy region of the $^{130}$Te $\beta\beta0\nu$ transition translates into a 1 $\sigma$ sensitivity on $r_{1/2}^{0\nu}$ of about $2.1 \times 10^{26}$ y ($m_{\beta\beta} \leq 24-83$ meV). If all background sources were controlled at the level of 0.001 counts/keV/kg/y, then the sensitivity could be improved to $6.5 \times 10^{26}$ y ($m_{\beta\beta} \leq 14-47$ meV), deep inside the inverted hierarchy region of the neutrino mass pattern.

A MonteCarlo projection of presently measured radioactive contaminations onto CUORE background around 2.5 MeV shows that almost all identified sources are controlled at the level of $10^{-3}$ counts/keV/kg/y but surface U and Th contents, which settle the current background extrapolation at 0.04 counts/keV/kg/y. Therefore special efforts are devoted to crystal production and copper surface cleaning. A dedicated radioclean facility has been set-up by the chinese company in charge of making the TeO$_2$ crystals, with the aim of keeping every step of the crystal growth under control, from the selection of the starting materials to the final surface polishing and packaging of the crystals. The delivery to Gran Sasso is made by ship to reduce cosmogenic activation and the underground storage area, that will also host all other detector components, is constantly flushed with nitrogen. The copper producer has been carefully selected according to the quality and technical characteristics of the raw material (radiopurity, thermal conductivity, mechanical properties) as well as the guaranteed exposure to cosmic rays of the material from casting to delivery. Almost all copper components of the detector mounting structure are being manufactured by electrical discharge machining, thus avoiding possible contamination sources like lubricants, and kept above ground strictly for the time needed for production. The final surface cleaning procedure of the machined copper pieces has been worked out in a facility at the Laboratori Nazionali di Legnaro (PD, Italy), and includes tumbling, electrochemical and chemical etching, and magnetron sputtering.

A final proof of the background achievements will be obtained by operating CUORE-0, the first complete CUORE tower, inside Cuoricino experimental facility. Moreover, from the physics point of view, this measurement with 52 TeO$_2$ detectors 750 g each, will be a self-consistent experiment by itself, soon overtaking Cuoricino $\beta\beta0\nu$ sensitivity. CUORE-0 assembly is foreseen in 2010 and the data taking will continue until CUORE start.

5. Conclusions

CUORE will be the first next generation $\beta\beta0\nu$ experiment. CUORE has the potentiality to probe deeply the inverted hierarchy region of the neutrino mass pattern. The feasibility of the experiment has been demonstrated by Cuoricino, the pilot experiment taking data until 2008 in Gran Sasso Underground Laboratory, that is the second most sensitive $\beta\beta0\nu$ experiment worldwide. CUORE is presently being built at Gran Sasso Laboratory and the data taking is foreseen by 2012.

References
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