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CUORICINO and CUORE: present and future of ^{130}Te neutrinoless double beta decay searches

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The search for neutrinoless double beta decay is a powerful tool to assess the neutrino mass scale and to establish whether the neutrino is a Majorana or a Dirac particle. To date, CUORE is the only fully approved next generation 1-ton size experiment with the goal of approaching the inverted hierarchy region of the effective neutrino mass spectrum. CUORE is an array of 988 TeO2 cryogenic detectors containing 200 kg of Te-130, the neutrinoless double beta decay candidate. It is presently being built in Gran Sasso Underground Laboratory and it is due to start data taking in 2013. The feasibility of this very challenging project has been proved by CUORICINO, the pilot experiment that took data in Gran Sasso Laboratory until 2008, for about five years, with 62 TeO2 cryogenic detectors. In this talk I will present the final analysis of the whole CUORICINO exposure and report about the status of CUORE construction.

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1. Introduction

The double beta decay is a second order weak transition which can be energetically favored for some even-even nuclei belonging to A even multiplets. The $(A,Z) \rightarrow (A,Z+2)+2e^- + 2\bar{\nu}_e$ double beta ($\beta\beta 2\nu$) decay process is allowed by the Standard Model and has been observed for many isotopes. The neutrinoless double beta ($\beta\beta 0\nu$) decay given by $(A,Z) \rightarrow (A,Z+2)+2e^-$ violates lepton number conservation and is therefore forbidden by the Standard Model. The lifetime for the $\beta\beta 0\nu$ decay is expected to be longer than 10^{25} y and only one evidence has been reported for ^{76}Ge so far [2]. The lepton number violating process $\beta\beta 0\nu$ can occur only if the neutrino is a massive Majorana particle (i.e. $\nu \equiv \bar{\nu}$) and it is the only known probe to test whether the neutrino is a Majorana or Dirac particle.

$\beta\beta 0\nu$ 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. $\langle m_\nu \rangle = |\sum_k m_{\nu_k} \eta_k |U_{ek}|^2|$ is the effective electron neutrino, where m_k are the mass eigenvalues of the three neutrino mass eigenstates $|\nu_k\rangle$, η_k are the CP Majorana phases ($\eta_k = \pm 1$ for CP conservation) and U_{ek} are the elements of the electron sector of the neutrino mixing matrix. Therefore $\beta\beta 0\nu$ searches do not measure the neutrino mass directly, but still can provide valuable informations on the neutrino mass hierarchy and absolute scale. Upcoming new generation experiments aim at a 10 meV sensitivity to probe the so called neutrino mass inverted hierarchy ($m_3 \ll m_1 \approx m_2$). If $\beta\beta 0\nu$ decay is discovered with $\langle m_\nu \rangle \geq 10$ meV: then the neutrino is a Majorana particle and the masses are either degenerate ($m_1 \approx m_2 \approx m_3$) or follow an inverted hierarchy. If $\langle m_\nu \rangle \geq\approx 0.05$ eV is found then neutrinos are degenerate and the absolute mass scale can be established. In case the $\beta\beta 0\nu$ decay is not observed and only an upper limit $\langle m_\nu \rangle \leq 10$ meV is set, then, if the neutrino is a Majorana particle, the masses must have a normal hierarchy ($m_1 < m_2 \ll m_3$). To obtain $\langle m_\nu \rangle$ from the experimental observable $\tau^{0\nu}_{1/2}$ the nuclear structure factor $F_N \equiv G^{0\nu}|M^{0\nu}|^2$ must be known. While the phase space $G^{0\nu}$ can be precisely calculated, the nuclear matrix $|M^{0\nu}|$ contains the uncertain details of the nuclear part of the process. In fact there is a large spread in the nuclear matrix elements calculated by different authors with different nuclear models [1, 3].

Searching for $\beta\beta 0\nu$ decay consists in detecting the two electrons emitted in the transition sharing the available energy $Q_{\beta\beta}$. In the calorimetric approach the source is internal to the detector and only the sum energy of the two electrons is measured: therefore the signature for $\beta\beta 0\nu$ decay is a peak at the transition energy $Q_{\beta\beta}$. Calorimeters can have large mass and high efficiency. As calorimeters, low temperature detectors provide high energy resolution and the possibility of studying many different isotopes. Observing the $\beta\beta 0\nu$ of several isotopes is crucial to confirm any positive result and to reduce the impact of the uncertainties on the nuclear matrix elements.

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 ~ 3600 m.w.e, searching for ^{130}Te $\beta\beta 0\nu$ with low temperature detectors. 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. Fortyfour detectors were made of $5 \times 5 \times 5\,cm^3$ crystals with a mass of about 790 g, the other eighteen were $3 \times$

$3 \times 6\,\mathrm{cm}^3$ crystals with a mass of about 330 g. The detectors were arranged in a pile of thirteen modules – the Cuoricino *tower*: eleven modules were made of four of the 790 g detectors in a 2×2 square arrangement, the other two modules consisted of nine of the smaller detectors in a 3×3 arrangement. Four of the 330 g crystals were made of enriched Te: two were enriched in ^{130}Te and two in ^{128}Te.

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

The Cuoricino *tower* was installed in a low background dilution refrigerator in the Gran Sasso Underground Laboratory and operated at a temperature of about 10 mK [4]. The refrigerator was 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 was provided by a 1 cm thick roman lead layer. A neutron shield was also introduced late in the measurement. The whole set-up was enclosed in a plexiglass box flushed with nitrogen to remove the radon gas, and in a Faraday cage.

The total analyzed exposure adds up to 19.75 y×kg of ^{130}Te. The average FWHM energy resolution of the entire array was about 8 keV at the ^{130}Te transition energy (2527 keV). The final sum spectrum is obtained with the detectors operated in anticoincidence, to reduce background contributions from Th and U on the crystal surfaces and from external γs presumably due to Th contamination of the refrigerator. The achieved background level in the $\beta\beta0\nu$ energy region is ~ 0.169 counts/keV/kg/y, which translates into a 90% C.L. lower limit on the half life of ^{130}Te $\beta\beta0\nu$ of $\tau^{0\nu}_{1/2} > 2.8 \times 10^{24}$ y. The corresponding upper limit for the effective Majorana mass is $\langle m_\nu \rangle < 0.3 \div 0.7$ 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 by H.V. Klapdor-Kleingrothaus and his co-workers [2].

A careful analysis of the background level above the highest natural γ line of ^{208}Tl shows a continuum up to about 4 MeV which clearly extends in the region of interest and accounts for most ($\sim$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 Underground 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 γ transition, $\sim$70% is ascribed to degraded alphas coming from U and Th surface contaminations of the TeO_2 crystals and of the inert materials surrounding the detectors, most probably the copper of the detector holders.

3. CUORE

From statistical considerations, the sensitivity $\Sigma(\tau^{0\nu}_{1/2}) \propto \varepsilon\, i.a.\, (M t_{meas}/(\Delta E\, bkg))^{1/2}$, where ε, $i.a.$, M, t_{meas}, ΔE, 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 – about 33.8 % – 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 ΔE, 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 45% at best – is extremely important.

In order to probe the inverted hierarchy region the $\langle m_\nu \rangle$ Cuoricino upper limit must be improved by a factor of 10, which means to improve $\Sigma(\tau^{0\nu}_{1/2})$ 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 γ contribution, by a better surface cleaning, to reduce the degraded α continuum, and by an improvement of the design, to reduce the amount of material facing the detectors.

The CUORE (Cryogenic Underground Observatory for Rare Events) [5] experiment is the straightforward evolution of Cuoricino. The CUORE detector is made of 19 towers which improve the Cuoricino design. 988 natural TeO_2 detectors will make up a 750 kg granular and compact calorimeter containing 200 kg of ^{130}Te. With a target background of at least 0.01 c/keV/kg/y and an energy resolution FWHM of about 5 keV, a 1σ sensitivity on $\tau^{0\nu}_{1/2}$ of about 2.1×10^{26} y can be reached in 5 year ($\langle m_\nu \rangle \leq 0.035 \div 0.082$ eV). Presently the infrastructure in the Gran Sasso Underground Laboratory and the cryogenic system [6] are being built, while the crystal production is in progress and about half of the TeO_2 crystals are already stored in the Gran Sasso Underground Laboratory. CUORE is due to start data taking in 2013. While waiting for the final detector assembly many efforts are being carried out to refine and validate the surface cleaning procedures. A Montecarlo projection of recent measurements 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 around $0.02 \div 0.04$ counts/keV/kg/y. More work is progress to further improve these results.

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 2011 and the data taking will continue until CUORE start.

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