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Status and prospects for CUORE

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Abstract. CUORE is a cryogenic detector consisting of 988 TeO_2 crystals, 750 g each, and will be operated at a temperature of ∼10 mK, to search for neutrinoless double beta decay ($0\nu\beta\beta$) of ^{130}Te. The detector, in the final stages of construction at the Laboratori Nazionali del Gran Sasso (Italy), will start its operations in 2016. CUORE-0, its pilot experiment, has proven the feasibility of CUORE, demonstrating that the target background of 0.01 counts/keV/kg/y and the energy resolution of 5 keV are within reach. CUORE-0 also made the most precise measurement of the $2\nu\beta\beta$ decay. The expected sensitivity of CUORE to the $0\nu\beta\beta$ ^{130}Te half-life is $9 \cdot 10^{25}$y, for 5 years of data taking. Here, we report the most recent results of CUORE-0, their implications for CUORE, and the current status of the CUORE experiment.

1. Introduction

Double beta decay ($2\nu\beta\beta$) is an extremely rare nuclear transition from a nucleus to its isobar, with the emission of two electrons and two anti-neutrinos. The transition occurs via a Standard Model allowed process and it has been observed in several nuclides with half-lives of the order of 10^{19}-10^{24} years. Neutrinoless double-beta ($0\nu\beta\beta$) decay is a hypothesized process that, if observed, would establish the Majorana nature of the neutrino [1]. The decay can occur through the exchange of a massive Majorana neutrino, and its occurrence violates lepton number conservation, thus implying physics beyond the Standard Model. In the $0\nu\beta\beta$ decay, two neutrons simultaneously decay into two protons, with two electrons and no neutrinos in the final state. The $0\nu\beta\beta$ decay amplitude is related to the effective Majorana mass $m_{\beta\beta}$ through the formula $m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$ where U_{ei} are the elements of the neutrino mixing matrix and m_i are the neutrino mass eigenstates. The rate of the $0\nu\beta\beta$ decay can be written as: $[T_{1/2}^{0\nu}]^{-1} = G_{0\nu}|M_{0\nu}|^2 {m_{\beta\beta}}^2$ where $G_{0\nu}$ is the precisely calculable phase space factor and $M_{0\nu}$ is the nuclear matrix element (NME) for the $0\nu\beta\beta$ transition which, at present, has a relatively large uncertainty. The experimental signature is a mono-energetic peak in the spectrum of summed electron energies, located at the Q-value. Despite this simple signature, the detection of $0\nu\beta\beta$ decay is extremely challenging due to the fact that the predicted half-life for this kind of decay is greater than 10^{25} - 10^{26} y. The CUORE experiment will search for $0\nu\beta\beta$ decay of the isotope ^{130}Te, using an array of TeO_2 cryogenic bolometers. Until recently, the predecessor Cuoricino had the best limit on the $0\nu\beta\beta$ decay of ^{130}Te ($2.8\cdot10^{24}$ y, 90% C.L.).

In this proceeding, we report on the most recent results of the prototype CUORE-0, with the implications for CUORE. We also discuss the current status of the CUORE detector and briefly report on the future generation of bolometer detectors for a further improvement of the sensitivity.

2. The CUORE detector

The CUORE (Cryogenic Underground Observatory for Rare Events) experiment will search for $0\nu\beta\beta$ decay of the isotope ^{130}Te using an array of TeO_2 cryogenic bolometers. The basic working principle of CUORE is based on the calorimetric technique: the energy released in an absorber is measured through its temperature rise, which is read out by a sensitive thermal sensor attached to the absorber. CUORE is made of 988 natural TeO_2 cryogenic detectors, mounted in a cylindrical compact and granular structure of 19 towers, each made by 52 crystals arranged in 13 floors of 4 detectors each. The absorbers are cubic crystals ($5\times5\times5$ cm^3 each), with a total active mass of 742 kg (206 kg of isotope ^{130}Te). The temperature sensors that convert the thermal variation into an electrical signal are neutron transmutation doped (NTD) germanium semiconductor thermistors, glued on the absorber. The crystals are arranged in a copper structure, which serves as the heat bath. When operated at cryogenic temperature ($\sim$10 mK), the heat capacity of a 750 g TeO_2 crystal is so low that an energy deposition of 1 MeV induces a temperature variation of $\sim100\mu$K. The corresponding variation of the NTD resistivity is of the order of few %, and can be easily read out with low-noise room temperature electronics. The expected background rate in the Region of Interest is 0.01 counts/(keV·kg·y), mainly from contaminations from the surface and bulk of the bolometer components and from the shielding. To achieve this background level, stringent criteria have been applied both on the selection of the material used in the construction of the detector and in the cleaning procedure, handling and storage of the materials. Moreover, the whole detector construction took place in a dedicated clean room (class 1000) in the CUORE hut, using a set of specially designed glove boxes, to keep the detector parts under constant nitrogen flux and out of contact with the rest of the environment of the clean room [2].

The CUORE hut is built at the LNGS underground facility at an average depth of 3650 m water equivalent. The muon flux at LNGS is $\sim$3 10^{-8} $\mu/(\text{s}\cdot\text{cm}^2)$, about six orders of magnitude smaller than that at the sea level [3]. A heavy shield consisting of layers of borated polyethylene, boric-acid powder, and lead bricks surrounds the cryostat to attenuate neutron and γ-ray backgrounds. More lead shielding is added inside the cryostat, including ancient Roman lead to further suppress the γ-rays from the cryostat materials. With a background index of 0.01 counts/(keV·kg·y), the projected half-life sensitivity for CUORE is $9.5\cdot10^{25}$y (90 % C.L.), corresponding to an upper limit on the effective Majorana mass in the range of 50 –

130 meV, depending on the adopted NME calculation.

In order to host and cool down the CUORE detector, a custom made cryostat has been built. The main challenge was to satisfy the cryogenic requirements and the low-radioactivity ones simultaneously. The CUORE cryostat is cryogen-free, and the first stage of cooling, down to 4 K is provided by 5 pulse tube coolers. The base temperature <10 mK is provided by a dilution refrigerator, designed and built by Leiden Cryogenics, with a cooling power of 3μW at 10 mK. The different stages of the cryostat with their thermal shields are made of OFHC (oxygen-free high thermal conductivity) copper, specially chosen for its low hydrogen content, low bulk radioactivity and high thermal conductivity. The detectors are surrounded by different lead shields. The first one is a 6-cm-thick lateral shield, made from ancient Roman lead [4] (see Fig. 4). A 24 cm plate of modern low background lead (16$\pm$4 Bq/kg) shields the detector from above. An additional shield, 25 cm minimum thickness, made out of modern lead (150$\pm$20 Bq/kg) will surround the cryostat.

3. The CUORE-0 detector

CUORE-0 is a single CUORE-like tower built using the low-background assembly techniques developed for CUORE. CUORE-0 has been operated in the Hall A of LNGS from 2013 to 2015, using the old setup already used for the previous CUORE prototypes. Details on the CUORE-0 detector performance and analysis can be found in [5] and [6] while the CUORE-0 result on the search of $0\nu\beta\beta$ is published in [7]. The detectors were calibrated monthly by inserting a source of thoriated tungsten wires close to the outer vessel of the cryostat. The data acquired between two consecutive calibration measurements are referred to as a *dataset*. Using the known energy of gamma lines between 511 keV and 2615 keV we are able to evaluate the calibration curve for each bolometer and for each dataset. We used the strongest line in calibration data (2615 keV from ^{208}Tl) to evaluate the detector response to a monoenergetic deposit near the ROI, for each bolometer and dataset. We estimated the lineshape parameter values by performing a simultaneous, unbinned extended maximum likelihood (UEML) fit to calibration data. The physics-exposure-weighted harmonic mean of the FWHM values for each bolometer and dataset is 4.9 keV, with a corresponding RMS of 2.9 keV. This demonstrates that the CUORE goal of 5 keV of energy resolution is feasible. We evaluated the background index in the alpha-dominated region (between 2700 keV and 3900 keV) as 0.016$\pm$0.001 counts/(keV·kg·y), 6.8 times less than the background achieved by Cuoricino in the same region, 0.110$\pm$0.001 counts/(keV·kg·y). This is a proof that the background mitigation techniques adopted for the cleaning and assembly of the detector were effective. We searched for $0\nu\beta\beta$ decay in the CUORE-0 spectrum corresponding to a total TeO_2 exposure of 35.2 kg·y (or 9.8 kg·y of ^{130}Te). We performed a simultaneous UEML fit in the interval 2470-2570 keV, using a function composed by three parameters: a signal peak at the Q-value of the transition, a peak at $\sim$2507 keV from ^{60}Co double-gammas, and a smooth continuum background attributed to multi-scatter Compton events from ^{208}Tl and surface decays. The result of the fit is shown in Fig. 1 The best-fit values are $\Gamma_{0\nu} = 0.01 \pm 0.12(\text{stat})\pm 0.01(\text{syst}) \times 10^{-24}\text{y}^{-1}$ for the $0\nu\beta\beta$ decay rate and 0.058$\pm$0.004(stat)$\pm$0.002(syst) counts/(keV·kg·y) for the background index in the ROI. With these data, we set a 90% C.L. lower bound on the decay half-life of 2.7×10^{24}y. Combining this result with the 19.75 kg·y exposure of ^{130}Te from the Cuoricino experiment, we find a Bayesian limit of $T_{0\nu} > 4.0\times10^{24}$y (90% C.L.), which is the most stringent limit to date on the ^{130}Te $0\nu\beta\beta$ half-life [7].

We used the CUORE-0 data also for an extended and comprehensive study of the background sources that contribute to the count rate in the region of interest. We built a Geant4-based Monte Carlo (MC) code to study the contribution of particle interactions in the entire CUORE-0 setup (including the detector components, the cryostat and the shielding). We used, as input to the code, the values of the material contaminations obtained from screening measurements (i.e. HPGe and NAA measurements) and we built the energy spectra obtained with the simulation

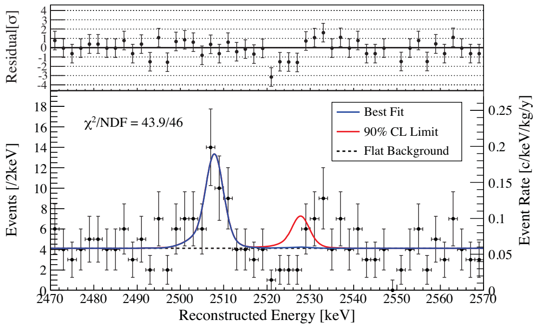

Figure 1. Top: residual of the best fit. Bottom: the $0\nu\beta\beta$ best fit model (solid blue line) superimposed on the CUORE-0 data (black points).

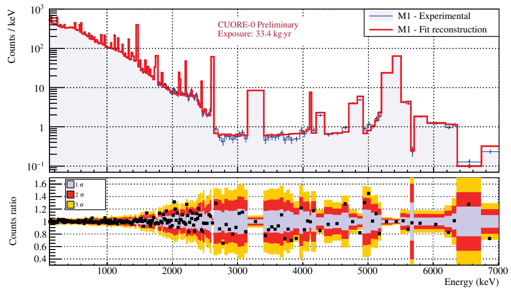

Figure 2. Top: comparison between the experimental spectrum and MC reconstruction. Bottom: ratios between counts in the experimental spectrum over counts in the MC one.

of the contamination sources in different positions of the setup. We simulated 57 sources, with an activity obtained by the fit of the CUORE-0 background data. We performed the fit of the data with a bayesian tool (JAGS) that builds the statistical model and exploits Markov Chain MC simulations to sample the joint posterior PDF of the model parameters. Gaussian (or half-Gaussian) priors are defined when the activity of a source (or its upper limit) is known from screening measurements. Otherwise, uniform non-informative priors from 0 to upper limits higher than the maximum activities compatible with the CUORE-0 data are used. Finally, the joint posterior PDF is used to evaluate the activities of the background sources and their correlations. The reconstruction of the background experimental spectrum is shown in Fig. 2. In order to properly fit the data, the energy spectrum of the summed electrons from $2\nu\beta\beta$ decay must be included. We found that the $2\nu\beta\beta$ decay of ^{130}Te accounts for 10% of the events in the region from 118 keV to 2.5 MeV. The half-life value obtained for $2\nu\beta\beta$ decay of ^{130}Te is $T_{2\nu}$=8.2± 0.2 (stat.)±0.6(syst.)$\cdot 10^{20}$y, where the systematic uncertainty was evaluated by running different fits in which the binning, energy threshold, depth of surface contaminations, priors, list of background sources, and input data were varied. This result is the most precise measurement of the $T_{2\nu}$ decay of ^{130}Te, to date. For more details, see [8].

4. CUORE status

The cryogenic system has been successfully commissioned in spring 2016. During the commissioning run, a small array of 8 TeO_2 crystals was operated in the cryostat, to validate the bolometer performance in the CUORE system. During this run, we were able to operate steadily an experimental volume of ~1 m^3 at a base temperature of 6.3 mK for more that 70 days, with a temperature stability within 0.2 mK (RMS). The encouraging performance of the bolometric detectors operated during this run allowed us to perform a full debug of the system, including the electronic readout chain, the DAQ, the temperature stabilisation and the calibration procedure. After successful commissioning of the cryostat, the 19 towers have been deployed in the cryostat in August of 2016. In Fig. 3 the 19 towers attached to the cryostat plate are shown. We aim to begin operation at base temperature before the end of the year and the first data from the CUORE detector are foreseen to be acquired at the beginning of 2017.

5. Future perspective

The bolometric technique is one of the most promising technologies for future programs to explore the inverted mass hierarchy region, down to $m_{\beta\beta}$ ~10 meV. Recently, the CUPID

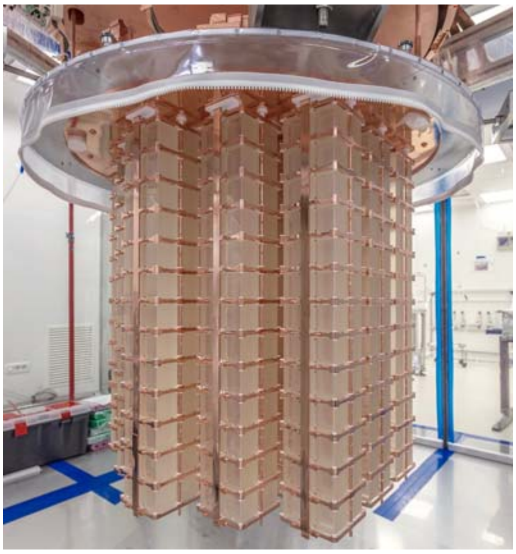

Figure 3. Side view of the 19 CUORE towers deployed in the cryostat.

Figure 4. Roman Lead lateral shield, which surrounds the towers.

(CUORE Upgrade with Particle IDentification) group of interest has formed, in order to coordinate R&D efforts towards the goal of increasing the sensitivity on $T_{0\nu}$[9]. Different approaches are presently investigated, using different isotopes and sensors as well as exploring the viability of enriching ^{130}Te. Strong R&D efforts are currently being made to investigate the different techniques. The goal of CUPID is to probe the entire inverted hierarchy region, with a sensitivity on $T_{0\nu}$ of 2 – 5 10^{27}y with 10 years of data, with a corresponding limit on $m_{\beta\beta}$ between 6 and 20 meV [10].

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[1] W. H. Furry, *Phys. Rev.* 56, 1184 (1939).
[2] E. Buccheri et al., *Nucl. Instrum. Meth.* A 768, 130 (2014).
[3] M. Ambrosio et al., *Phys. Rev.* D 52, 3793, 1995.
[4] A. Alessandrello et al., *Nucl. Instrum. Meth.* B 142, 163 (1998).
[5] C. Alduino et al., *JINST 11* P07009 (2016).
[6] C. Alduino et al., *Phys. Rev. C* 93, 045503 (2016).
[7] C. Alduino et al., *Phys. Rev. Lett. 115*, 102502 (2015).
[8] C. Alduino et al., *arXiv*: 1609.01666, accepted for publication on EPJC.
[9] G. Wang et al., *arXiv*: 1504.03599v1.
[10] G. Wang et al., *arXiv*: 1504.03612v1.