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Expected sensitivity to ^{128}Te neutrinoless double beta decay with the CUORE TeO_2 cryogenic bolometers

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Abstract

The CUORE experiment is a ton-scale array of TeO_2 cryogenic bolometers located at the underground Laboratori Nazionali del Gran Sasso of Istituto Nazionale di Fisica Nucleare (INFN), in Italy. The CUORE detector consists of 988 crystals operated as source and detector at a base temperature of $\sim$ 10 mK. Such cryogenic temperature is reached and maintained by means of a custom built cryogen-free dilution cryostat, designed with the aim of minimizing the vibrational noise and the environmental radioactivity. The primary goal of CUORE is the search for neutrinoless double beta decay of ^{130}Te, but thanks to its large target mass and ultra-low background it is suitable for the study of other rare processes as well, such as the neutrinoless double beta decay of ^{128}Te. This tellurium isotope is an attractive candidate for the search of this process, due to its high natural isotopic abundance of 31.75%. The transition energy at (866.7 $\pm$ 0.7) keV lies in a highly populated region of the energy spectrum, dominated by the contribution of the two-neutrino double beta decay of ^{130}Te. As the first ton-scale infrastructure operating cryogenic TeO_2 bolometers in stable conditions, CUORE is able to achieve a factor > 10 higher sensitivity to the neutrinoless double beta decay of this isotope with respect to past direct experiments.

Keywords Neutrinoless double beta decay · Tellurium · 128-Te · Cryogenic bolometers

1 Introduction: Neutrinoless Double Beta Decay

The double beta decay is a rare second order Fermi weak nuclear transition where two neutrons are simultaneously transformed into two protons. The most suitable candidates for the observation of this process are heavy even-even nuclei, when

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single β decay is energetically forbidden. Two distinct decay modes are usually accounted for when this transition is discussed. The Standard Model-allowed one is the two-neutrino double beta decay ($2\nu\beta\beta$): this process is characterized by the emission of two electrons and two anti-neutrinos in the final state, ensuring that the Lepton Number is conserved. The $2\nu\beta\beta$ decay has been directly measured in 11 nuclei (^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{100}Ru, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{150}Sm) [1]. On the contrary, the hypothesized neutrinoless double beta decay ($0\nu\beta\beta$) has not yet been observed. If $0\nu\beta\beta$ decay is possible, then Lepton Number symmetry would be violated by two units, making this an important Beyond the Standard Model process. The double beta decay can be observed by measuring the summed energy of the two electrons: in the $2\nu\beta\beta$ case, this forms a continuous spectrum from 0 to the Q-value of the reaction, due to the presence of the two neutrinos in the final state carrying part of the momentum. The expected signature for $0\nu\beta\beta$ decay is instead a monochromatic peak at the Q-value, since the two electrons carry the total amount of energy. A large international effort is currently put in the experimental search of $0\nu\beta\beta$ decay, as its observation would shed light on several important open questions in Particle Physics [2]: it would demonstrate that the Lepton Number is not a conserved physical quantity; it would prove that neutrinos have a Majorana component ($\nu = \bar{\nu}$), giving rise to a new possible description of the ν mass production via the see-saw mechanism; it would provide a possible explanation of the matter-antimatter asymmetry origin via Leptogenesis.

2 CUORE: Cryogenic Underground Observatory for Rare Events

The CUORE experiment is a 1 ton-scale array of TeO_2 cryogenic bolometers whose main Physics goal is to search for the $0\nu\beta\beta$ decay of ^{130}Te. This element is characterized by a high natural isotopic abundance of 34.167%, and a Q-value of 2527.518 keV [3]. The CUORE detector is located at the underground Laboratori Nazionali del Gran Sasso of Istituto Nazionale di Fisica Nucleare (INFN), in Italy, and is comprised of 988 natural TeO_2 crystals for a total mass of 742 kg, including 206 kg of ^{130}Te, operated as thermal detectors at $\sim$ 10 mK. Such cryogenic temperature is reached and maintained thanks to a custom built cryogen-free structure: the cooling power is provided by the simultaneous operation of five pulse tubes until the 4 K cold stage, and by a ^{3}He/^{4}He Dilution Refrigerator down to the base temperature [4]. The CUORE cryostat was designed with the aim of an ultra-low background level, which was measured to be $(1.49 \pm 0.04) \times 10^{-2}$ cts/(keV $\cdot$ kg $\cdot$ y) in the region of interest of (2490 - 2575) keV, i.e. in the vicinity of the ^{130}Te $0\nu\beta\beta$ decay Q-value. At this energy, the FWHM resolution in physics data resulted to be (7.8 $\pm$ 0.5) keV [5].

CUORE started its operation at the beginning of 2017, and its data taking is currently proceeding; the milestone of 1 ton $\cdot$ y acquired data was recently achieved, and from the analysis of this exposure a new 90% C.I. Bayesian limit on ^{130}Te $0\nu\beta\beta$ decay half life of $T^{0\nu}_{1/2} > 2.2 \times 10^{25}$ y was obtained [5].

3 ^{128}Te Neutrinoless Double Beta Decay Search with CUORE

The ton-scale mass and low background level of CUORE make it suitable for the investigation of other rare events, among which is the search for $0\nu\beta\beta$ decay of ^{128}Te [6]. With its natural isotopic abundance of 31.75% [7], this tellurium isotope is characterized by one of the highest natural abundances among the nuclei that can undergo $0\nu\beta\beta$ decay, together with ^{130}Te: this feature makes it an attractive candidate for the $0\nu\beta\beta$ decay search. A particular interest for the study of such a process also comes from the theoretical point of view: indeed, information on this decay can provide a discriminator among the different models that try to describe the mechanism underlying $0\nu\beta\beta$ decay [8]. The Q-value of (866.7 ± 0.7) keV [9] of this transition lies in a highly populated region of the spectrum, where the dominant source of background is due to the $2\nu\beta\beta$ decay of ^{130}Te. Its half-life was recently measured by CUORE and resulted to be $7.71^{+0.08}_{-0.06}(\text{stat.})^{+0.12}_{-0.15}(\text{syst.}) \times 10^{20}$ y [10]. Additionally, several γ lines due to natural radioactivity also contribute to this region of energy. For this reason, past direct search experiments that operated tens of kg of TeO_2 were characterized by a poor sensitivity to this decay. The latest lower limit on the half life of ^{128}Te $0\nu\beta\beta$ decay from direct experiments was published in 2003 by MiDBD, that set a limit of $T^{0\nu}_{1/2} > 1.1 \times 10^{23}$ y with 6.8 kg of TeO_2 and two crystals enriched in ^{128}Te at 82.3% [11]. More stringent limits were instead extracted from geochemical experiments, which measured the ratio between ^{130}Te and ^{128}Te half lives[1] [12]. The latest published value of $T^{^{128}\text{Te}}_{1/2}$ was calculated by exploiting this ratio and an average of the ^{130}Te half lives from CUORE-0 [13] and CUORE [3], and resulted to be $T^{^{128}\text{Te}}_{1/2} = (2.0 \pm 0.3) \times 10^{24}$ y [1].

The 742 kg TeO_2 detectors of CUORE include 188.5 kg of the ^{128}Te isotope, corresponding to 9.51×10^{26} ^{128}Te nuclei. Since the sensitivity to the $0\nu\beta\beta$ decay half life scales proportionally to the square root of the experimental mass - in the non-zero background condition -, a factor ~ 10 higher sensitivity with respect to MiDBD is expected in CUORE, which might be able to set a limit competitive with the geochemical results. In this work, we calculate the expected CUORE sensitivity to ^{128}Te $0\nu\beta\beta$ decay from the Background Model knowledge.

3.1 Analysis Strategy

The statistical approach for the investigation of ^{128}Te $0\nu\beta\beta$ decay in CUORE consists of a Bayesian binned fit based on the BAT (Bayesian Analysis Toolkit) software, which samples from the posterior distribution of all the model parameters with a Markov Chain Monte Carlo [14]. The goal of the analysis is to make a statistical inference on the parameter of interest, i.e. the $0\nu\beta\beta$ decay signal rate $\Gamma^{0\nu}$. As a first

[1] The geochemical technique consists of measuring the ratio of the amount of parent and daughter nuclei in ancient ores of tellurium, therefore the decay mode cannot be distinguished; the extracted half life refers thus to the sum of 2ν and 0ν double beta decay modes, and can be considered as a measurement of the half life of the dominant $2\nu\beta\beta$ decay.

step towards the event selection, the fraction of $0\nu\beta\beta$ events corresponding to the two electrons fully absorbed by the same single CUORE crystal was evaluated. This efficiency can be extracted from Monte Carlo simulations of the ^{128}Te $0\nu\beta\beta$ decay in CUORE: from the ratio between the number of events reconstructed at the Q-value peak and the number of simulated decays, this efficiency resulted to be 97.6%. The choice of a region of interest (ROI), and thus the contributions to be included in the Bayesian fit model, followed the identification of the background structures in the proximity of the Q-value. This information was obtained from the CUORE Background Model (BM) simulated spectrum. The energy region under investigation is shown in Fig. 1, where two structures are well visible: the left peak corresponds to a γ line at 834.8 keV from ^{54}Mn, whose presence is attributed to the cosmogenic activation of the copper structures near the detectors, while the right peak is due to a 860.6 keV γ emission from ^{208}Tl, a nucleus belonging to the ^{232}Th chain. The Bayesian fit model includes, besides these two lines, a continuum contribution modelled with a linear function and the posited ^{128}Te $0\nu\beta\beta$ signal peak.

The Bayesian fit method was tested and validated on toy Monte Carlo simulations (toyMC) of the ROI spectrum components. The parameters according to which such components were generated are the ^{54}Mn rate $\Gamma^{\mathrm{toy}}_{\mathrm{Mn}}$, the ^{208}Tl rate $\Gamma^{\mathrm{toy}}_{\mathrm{Tl}}$, the continuous background rate $\mathrm{BI}^{\mathrm{toy}}$, and the background slope $\mathrm{slope}^{\mathrm{toy}}$, all extracted from a binned maximum likelihood fit on the BM simulations (Fig. 1). These values are summarized in Table 1. These toyMC were used to test the Bayesian fit, and to calculate the expected CUORE Limit Setting Sensitivity to the $0\nu\beta\beta$ decay of ^{128}Te.

3.2 Expected CUORE Limit Setting Sensitivity from Background Model knowledge

If no evidence of $0\nu\beta\beta$ decay is found, an upper limit on the decay rate can be set. This is taken as the rate corresponding to the 90% of the marginalized posterior (i.e.

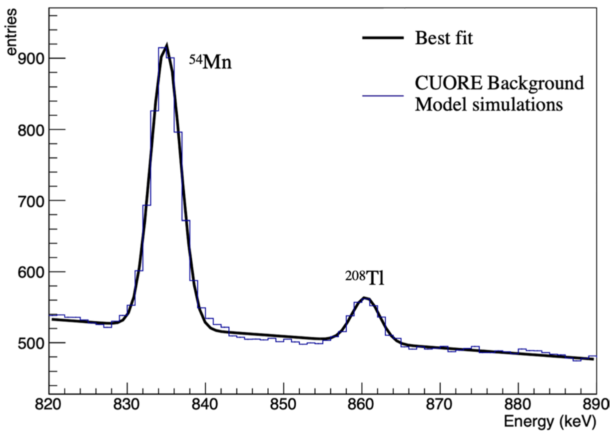

Fig. 1 CUORE single hit spectrum from BM simulations and binned extended maximum likelihood fit to extract the ^{54}Mn and ^{208}Tl decay rates, the linear background rate and its slope. These values were then used to produce the toy Monte Carlo simulations to test the fit procedure. (Color figure online)

Table 1 Results of the fit on the CUORE BM spectrum. These values were used to produce the toyMC simulations of the ^{128}Te ROI.

Parameter	Units	Value for toyMC
Γ^{toy}_{Mn}	cts/(kg · y)	16.27
Γ^{toy}_{Tl}	cts/(kg · y)	0.95
BI^{toy}	cts/(keV · kg · y)	1.68
$slope^{toy}$	1/keV	−0.4

the posterior distribution integrated over all the parameters of the fit but the signal rate); this corresponds to a lower limit on the decay half life. To extract the expected CUORE Limit Setting (or Exclusion) Sensitivity, 10^4 toyMC were simulated with background components only, according to the parameters listed in Table 1; the Bayesian fit with signal plus background contributions was independently run on each toyMC. The Limit Setting Sensitivity is defined as the median of the distribution of the 90% C.I. limits on $T^{0\nu}_{1/2}$; thus, all the extracted 90% C.I. half life limits were used to construct the distribution in Fig. 2. The corresponding median is the CUORE expected Exclusion Sensitivity to ^{128}Te $0\nu\beta\beta$ decay, and is equal to $\hat{T}_{1/2} = 2.2 \times 10^{24}$ y. This value provides a reliable indication of the actual CUORE Exclusion Sensitivity, and demonstrates that over a factor 10 improvement on the ^{128}Te $0\nu\beta\beta$ decay half life limit with respect to past direct experiments can be obtained with the CUORE data, and that this can possibly overcome the geochemical results for the first time. CUORE has already collected enough statistics to achieve this sensitivity, and the analysis on real data is currently being finalized; therefore, new results on ^{128}Te $0\nu\beta\beta$ decay search with CUORE are expected to be released soon.

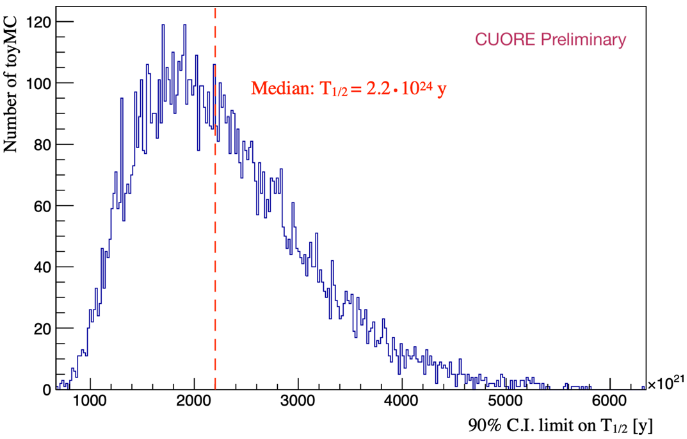

Fig. 2 Distribution of the 90% C.I. half life limits from the Bayesian fits on the toyMC simulation, produced exploiting the BM knowledge. The median of such distribution is the expected exclusion sensitivity of CUORE to ^{128}Te $0\nu\beta\beta$ decay. (Color figure online)

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References

1. A. Barabash, Universe **6**, 159 (2020). https://doi.org/10.3390/universe6100159
2. L. Canetti, M. Drewes, M. Shaposhnikov, New J. Phys. **14**, 095012 (2012). https://doi.org/10.1088/1367-2630/14/9/095012
3. I. Nutini, CUORE Collaboration et al., J. Low Temp. Phys. **199**, 519–528 (2020). https://doi.org/10.1007/s10909-020-02402-9
4. D.Q. Adams, CUORE Collaboration et al., Prog. Part. Nucl. Phys. **122**, 103902 (2022). https://doi.org/10.1016/j.ppnp.2021.103902
5. D. Q. Adams et al, (CUORE Collaboration), arXiv:2104.06906 (2021)
6. A. Campani, V. Dompè, G. Fantini, Universe **7**, 212 (2021). https://doi.org/10.3390/universe7070212
7. M.A. Fehr, M. Rehkamper, A.N. Halliday, Int. J. Mass Spectrom. **232**, 83–94 (2004). https://doi.org/10.1016/j.ijms.2003.11.006
8. F. Deppisch, H. Päs, Phys. Rev. Lett. **98**, 232501 (2007). https://doi.org/10.1103/PhysRevLett.98.232501
9. M. Wang, W.J. Huang, F.G. Kondev, G. Audi, S. Naimi, Chin. Phys. C **45**, 030003 (2021). https://doi.org/10.1088/1674-1137/abddaf
10. D.Q. Adams et al., Phys. Rev. Lett. **126**, 171801 (2021). https://doi.org/10.1103/PhysRevLett.126.171801
11. C. Arnaboldi et al., Phys. Lett. B **557**, 167–175 (2003). https://doi.org/10.1016/S0370-2693(03)00212-0
12. T. Bernatowicz, J. Brannon, R. Brazzle, R. Cowsik, C. Hohenberg, F. Podosek, Phys. Rev. Lett. **69**, 2341–2344 (1992). https://doi.org/10.1103/PhysRevLett.69.2341
13. C. Alduino et al., Eur. Phys. J. C **77**, 13 (2017). https://doi.org/10.1140/epjc/s10052-016-4498-6
14. A. Caldwell, D. Kollar, K. Kroninger, Comput. Phys. Commun. **180**, 2197–2209 (2009). https://doi.org/10.1016/j.cpc.2009.06.026

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