Search for double beta decay of ^{130}Te to the excited states of ^{130}Xe in CUORE

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CUORE and the bolometric technique

CUORE is a ton-scale underground bolometer array of **988 TeO_2 cubic crystals** operated at the INFN Gran Sasso National Laboratories (LNGS) with the main aim of searching for the **neutrino-less double beta decay** (DBD) of ^{130}Te and other rare processes [1]. The crystals are arranged in 19 towers placed in a custom built dilution refrigerator able to cool down and keep the detector at the stable temperature of ~ 10 mK.

The energy released by particle interactions in the crystal causes a temperature rise. Neutron Transmutation Doped Ge thermistors transform the temperature pulses induced by particles into voltage pulses. They are biased with a constant current and their voltage is low-pass filtered, amplified and continuously digitized at a sampling frequency f_S = 1 kHz.

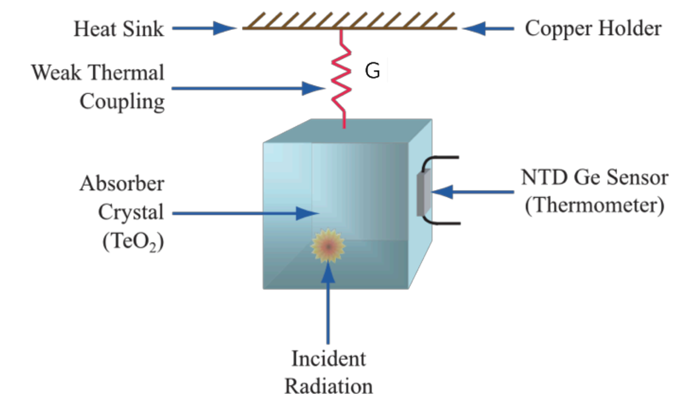


Fig. 1. Scheme of a bolometric detector

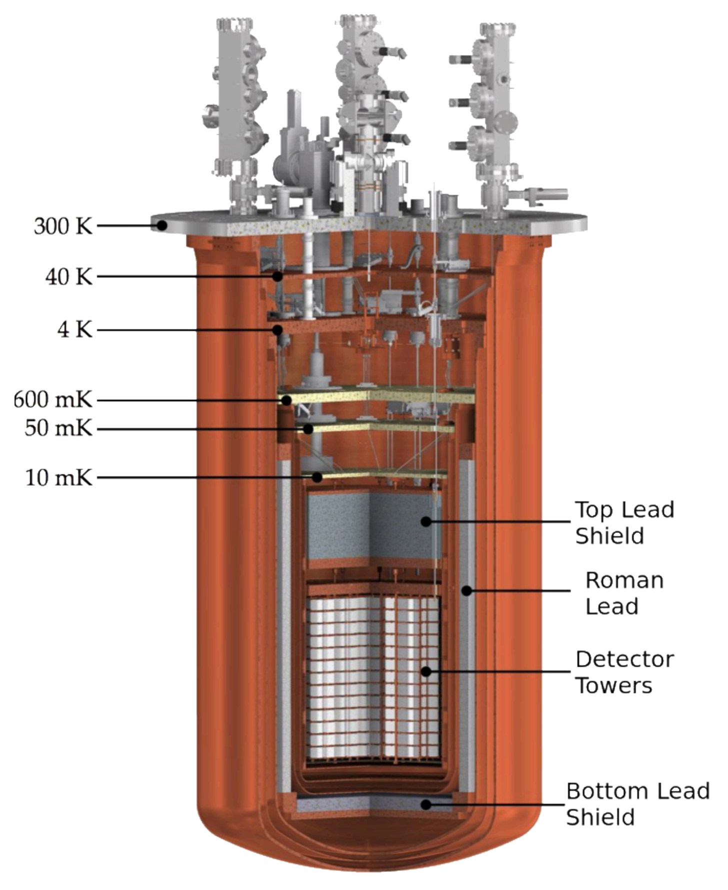


Fig. 2. The CUORE cryostat

$$\Delta T = \frac{\Delta E}{C(T)} \sim 100 \frac{\mu K}{MeV} @ 10 mK \qquad C \propto T^3$$

Experimental signature

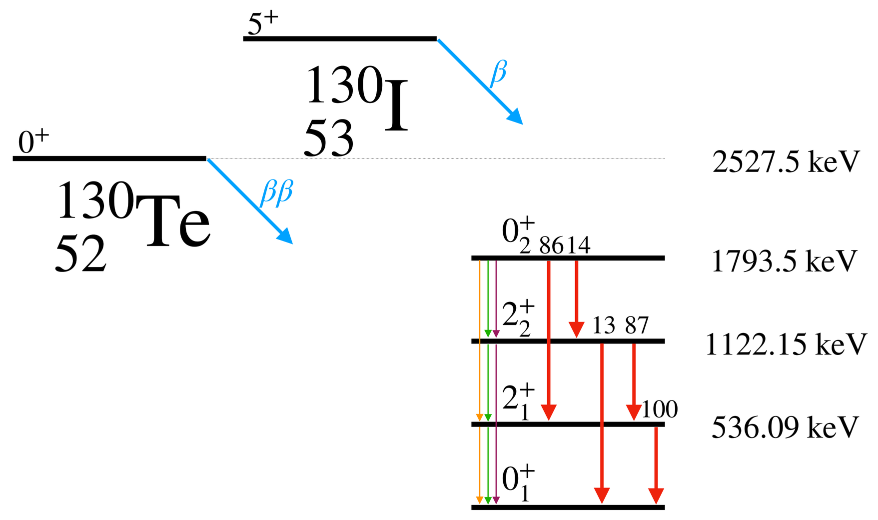
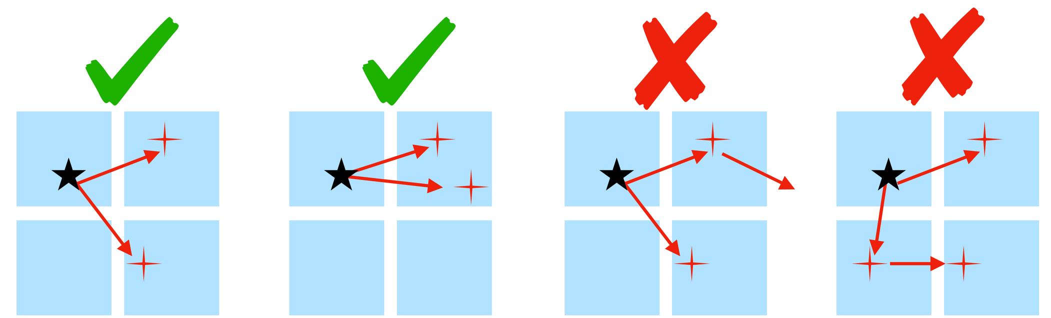


Fig. 3. Decay scheme of ^{130}Te to the excited states of ^{130}Xe

Double beta decay of ^{130}Te has **never been observed** on excited states (ES). The motivations to search for double beta decay to ES are twofold. A decay rate measurement in the Standard Model $2\nu\beta\beta$ channel would validate the theoretical calculations of Nuclear Matrix Elements (NME) [3]. A discovery in the $0\nu\beta\beta$ channel would prove that neutrinos have a non-vanishing Majorana mass component and provide insight on the neutrino mass scale and hierarchy. The decay to ES has a smaller phase space with respect to the one on the ground state (GS), hence it is **strongly suppressed**. NME instead are of the same order of magnitude [3][4]. Nonetheless, it is followed by a set of de-excitation γ rays. Three γ patterns are possible, with different branching fractions, and allow to effectively reject background.

To select candidate decays we require, for each emitted particle, **full containment** of the energy release in a single crystal.



★ ββ energy release + γ energy release ↗ γ path

Efficiency

The **dominant efficiency contribution** comes from the full containment requirement, quantifies the probability that a GS-ES decay reconstructs within each considered experimental signature. It is evaluated via Monte Carlo (MC) simulations.

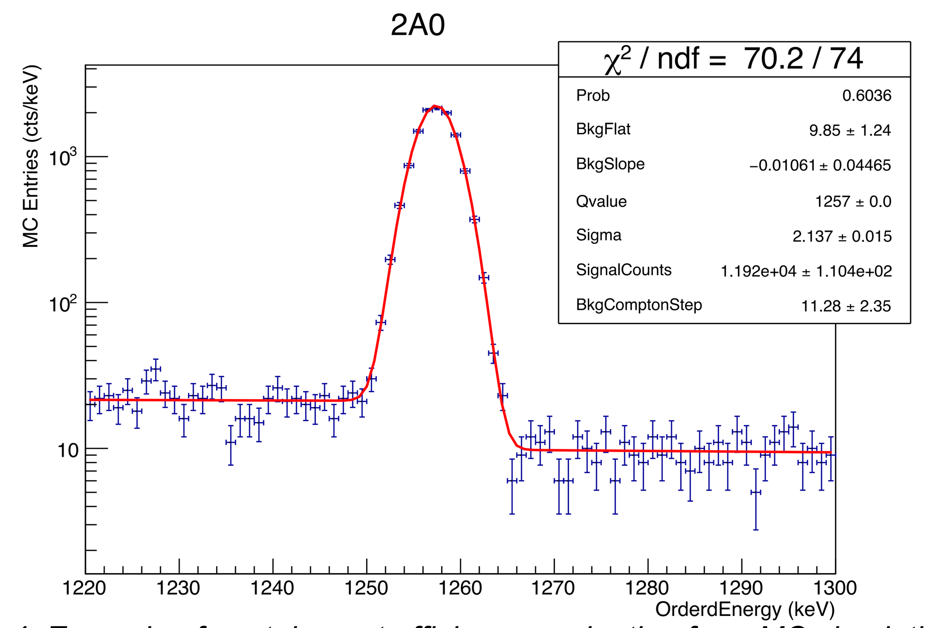


Fig. 4. Example of containment efficiency evaluation from MC simulations

The other included contributions come from channel-based data quality, pile-up rejection and pulse-shape cuts used to reject non-physical events ε_{cut} and the probability of accidental coincidences ε_{acc}. For each signature s the efficiency reads

$$\epsilon_s = \left[\sum_p \mathrm{BR}_p \cdot \frac{\left[N_{MC}^{(sel)}\right]_p^{(s)}}{\left[N_{MC}^{(tot)}\right]_p} \right] \epsilon_{cut}^M \, \epsilon_{acc}$$

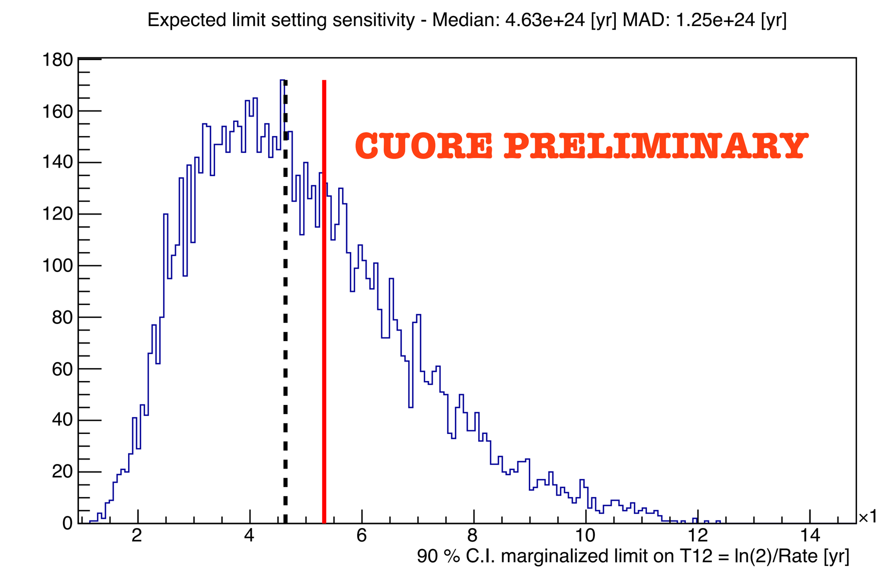
where BR_p is the de-excitation channel's branching ratio, N_{MC} the number of MC events.

Process	Containment	Cut	Accidentals	Total
0νββ	10.0%	88.7%	98.7%	8.7%
2νββ	6.8%			5.9%

Table 3. Summary of efficiency contributions. Containment efficiencies are summed over signatures, the others (dataset-dependent) are exposure-weighted averages

Exclusion sensitivity

A **blinded fit** (the data are superimposed to a randomly generated signal contribution) allows the extraction of an **estimate of the background parameters** before the result is extracted from unblinded data. The candidate events are selected and projected on one energy axis according to Tab. 2, then fit with a phenomenological channel-dataset dependent model for the detector response. The background is modeled either as flat or 1st order polynomial.



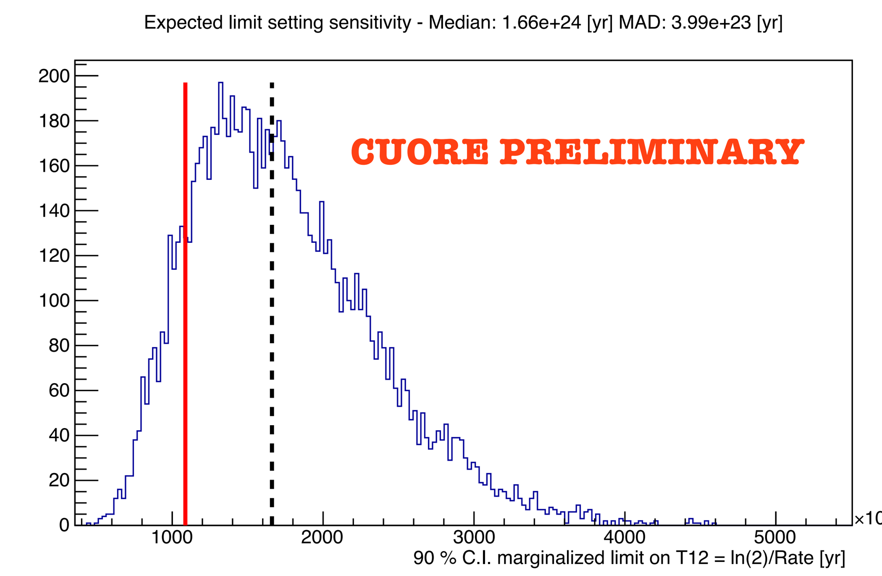


Figure 5. The distribution of the expected 90 % C.I. Bayesian lower limits on the $T_{1/2}$ parameter for the S+B model of 0νββ (top) and 2νββ (bottom) is shown. The entries are extracted from fits to 10^4 toy Monte Carlo experiments produced in the background only hypothesis. The median expected limit setting sensitivity (black dashed line) is shown together with the fit result to unblinded data (red solid line). The unblinded fit results lie within the 95% smallest interval of the distribution of limits.

Event selection

Neglecting single-site events, 22 combinations of fully contained final state particles can be defined. Merging combinations that share the same expected energy release, 15 independent signatures are found. They are ranked according to their analytical approximate contribution to the total discovery sensitivity. Just the signatures that **contribute more than 3%** to the total sensitivity are included.

Signature	Cuts	Source
2A0 - 2B1	1247 keV $< E^*_{min} <$ 1280 keV 1247 keV $< E_{max} <$ 1280 keV	E_{min}: $\gamma_{(A1)} / \gamma_{(B1)} + \gamma_{(B2)}$ (1257 keV) E_{max}: $\beta\beta$ (734 keV) + $\gamma_{(A1)} / \gamma_{(B3)}$ (536 keV)
2A2 - 2B3	523 keV $< E^*_{min} <$ 573 keV 1981 keV $< E_{max} <$ 2001 keV	E_{min}: $\gamma_{(A2)} / \gamma_{(B3)}$ (536 keV) E_{max}: $\beta\beta$ (734 keV) $\gamma_{(A1)} / \gamma_{(B1)} + \gamma_{(B2)}$ (1257 keV)
3A0	526 keV $< E_{min} <$ 546 keV 700 keV $< E^*_{med} <$ 760 keV 1247 keV $< E_{max} <$ 1267 keV	E_{min}: $\gamma_{(A2)} / \gamma_{(B3)}$ (536 keV) E_{med}: $\beta\beta$ (734 keV) E_{max}: $\gamma_{(A1)} / \gamma_{(B1)} + \gamma_{(B2)}$ (1257 keV)

*Table. 2. 0νββ (top) and 2νββ (bottom) energy selections for each signature. The projected component is highlighted with a * superscript.*

Signature	Cuts	Source
2A0 - 2B1	620 keV $< E_{min} <$ 1150 keV 1220 keV $< E^*_{max} <$ 1300 keV	E_{min}: $\beta\beta$ (0 – 734 keV) $\gamma_{(A1)} / \gamma_{(B3)}$ (536 keV) E_{max}: $\gamma_{(A1)} / \gamma_{(B1)} + \gamma_{(B2)}$ (1257 keV)
2A2 - 2B3	523 keV $< E^*_{min} <$ 573 keV 1360 keV $< E_{max} <$ 1990 keV	E_{min}: $\gamma_{(A1)} / \gamma_{(B3)}$ (536 keV) E_{max}: $\beta\beta$ (0 – 734 keV) $\gamma_{(A1)} / \gamma_{(B1)} + \gamma_{(B2)}$ (1257 keV)
3A0	400 keV $< E_{min} <$ 523 keV 523 keV $< E^*_{med} <$ 573 keV 1779 keV $< E_{med} + E_{max} <$ 1807 keV	E_{min}: $\beta\beta$ (0 – 734 keV) E_{med}: $\gamma_{(A2)} / \gamma_{(B3)}$ (536 keV) E_{max}: $\gamma_{(A1)} / \gamma_{(B1)} + \gamma_{(B2)}$ (1257 keV)

The CUORE data taking is divided in ~ 1 month long *datasets*. Triggered pulses that pass *base* (pile-up rejection) and *PSA* (pulse-shape rejection of non-physical events) are used to build coincidence multiplets of energy releases within the ± 5 ms time resolution of the detector. The number of coincident triggers is called **Multiplicity** (M). Experimental signatures are defined by M, originating de-excitation pattern, combination of final state particles in the M selected crystals. Energy releases within multiplets are sorted in descending order of reconstructed energy, then candidates for each multiplicity are selected.

Signature	Sensitivity 0ν	Sensitivity 2ν	Crystal 1 [keV]	Crystal 2 [keV]	Crystal 3 [keV]
2A0-2B1	38.5%	39.8%	536 + ββ	1257	-
2A2-2B3	24.7%	21.6%	1257 + ββ	536	-
3A0	20.3%	25.5%	1257	ββ	536

Results

The analyzed data set corresponds to a **$^{nat}TeO_2$ exposure of 372.5 kg yr** as in [5]. No evidence for either decay mode was observed and a marginalized Bayesian **upper limit at 90% C.I. was set** for each rate parameter. The Bayesian fit was performed both with a minimal model and extended ones in order to decouple the effect of each nuisance parameter. The minimal model (MM) includes, with uniform priors:

- positive signal rate, shared among the selected experimental signatures
- background parameters, coefficients of the polynomial background, one per signature

All other inputs are constants, such as the resolution functions and efficiencies.

The combined full model (FM) includes, at once:

- all the parameters of the minimal model
- detector response dependence on energy together with the bias of the reconstructed energy scale (6 parameters / dataset, multivariate prior)
- containment efficiency uncertainty (1 parameter / signature, gaussian prior)
- cut efficiency uncertainty (1 parameter / dataset, gaussian prior)
- accidental coincidences efficiency uncertainty (1 parameter / dataset, gaussian prior)
- ^{130}Te isotopic abundance uncertainty (1 parameter, gaussian prior)

A +18% (+17%) more stringent limit is obtained for 2ν (0ν) due to the improved detector response model.

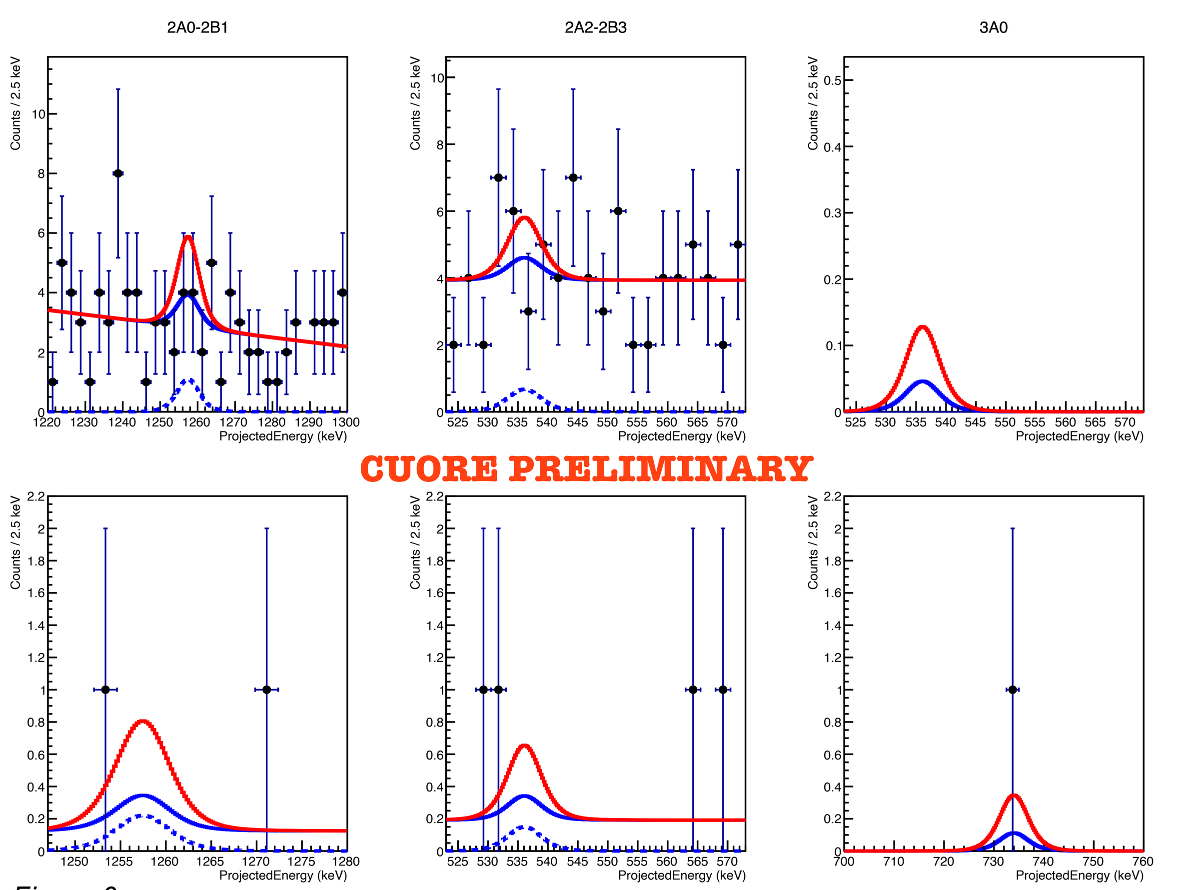


Figure 6. A Bayesian upper limit at 90% C.I. on the 2νββ (top) and 0νββ (bottom) half life is reported. Energy spectra with best fit model (blue solid), 90% lower limit on $T_{1/2}$ (red solid) and signal component (blue dashed) are shown.

$$T_{1/2}^{0\nu} > 5.4 \cdot 10^{24}\ \mathrm{yr}\ (90\,\%\ \mathrm{C.I.}) \qquad T_{1/2}^{2\nu} > 1.1 \cdot 10^{24}\ \mathrm{yr}\ (90\,\%\ \mathrm{C.I.})$$

References:

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5. D.Q.Adams et al. (CUORE Collaboration), Improved Limit on Neutrinoless Double-Beta Decay in ^{130}Te with CUORE, Phys. Rev. Lett. 124, 122501 (2020), arxiv:1912.10966