TeO$_2$ bolometers with Cherenkov signal tagging

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TeO$_2$ crystals are currently used as bolometers in the search for neutrinoless double beta decay: CUORE, an array of 988 TeO$_2$ bolometers, is about to be one of the most sensitive experiments searching for this process.
The sensitivity of this experiment could be further improved by removing the background from alpha particles generated by natural radioactivity of the copper structure holding the crystals.
This goal can be achieved detecting the Cherenkov light emitted from beta particles and not by alpha ones.
For the first time we measured the Cherenkov light emitted by a CUORE crystal, and found it to be 100 eV at the Q-value of the decay. The signal is however small, at the same level of the noise of the bolometric light detectors we are using.
We point out that an alternative light detector technology must be used to obtain TeO$_2$ bolometric experiments able to probe the inverted hierarchy of neutrino masses.

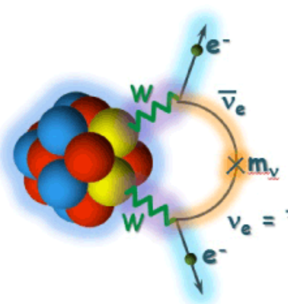
Neutrinoless Double Beta Decay

Nuclear process :

$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$

Not allowed in the Standard Model : $\Delta L = 2$

Never observed



$0\nu\beta\beta$

The half-life is the measurable quantity

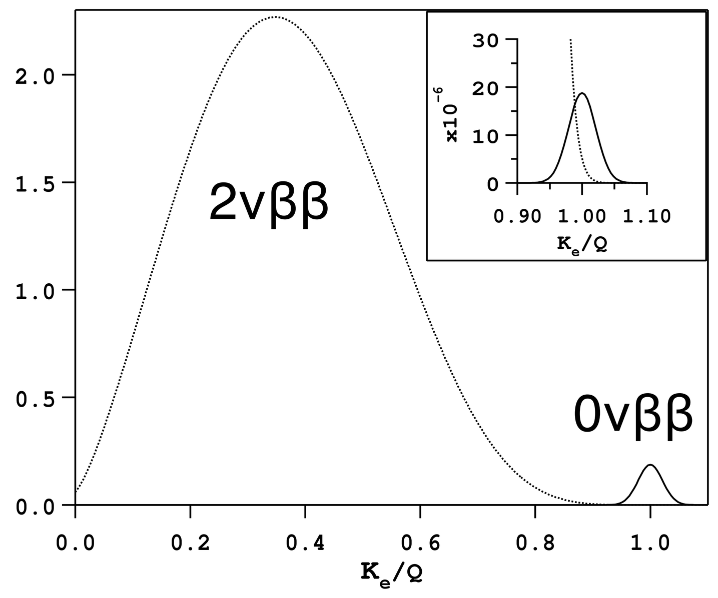
$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Phase space factor : ~ Q^5

Nuclear Matrix Element

Effective neutrino mass

If observed neutrino is a Majorana particle



SIGNAL

By measuring the kinetic energy of the electrons (K_e), the signal is expected as a monochromatic peak at the Q-Value of the reaction

BACKGROUND

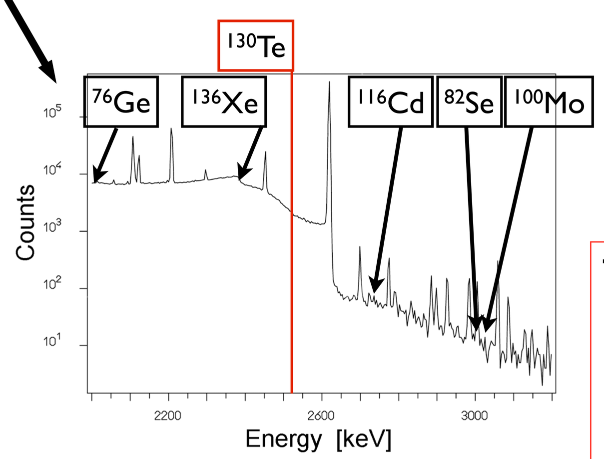
An irreducible background comes from the 2νββ. Natural radioactivity & material selection, if not able to perform particle identification (α,β,γ)

Deep underground experiments to shield against cosmic rays

Sensitivity and Isotope choice

$$S^{0\nu} \propto \mathrm{I.A.} \cdot \sqrt{\frac{\mathrm{Mass} \cdot \mathrm{livetime}}{\mathrm{bkg} \cdot \Delta E}}$$

ββ Decay Reaction	Isotopic Abundance [atomic %]	Q-value [keV]
$^{48}Ca \rightarrow ^{48}Ti$	0.2	4274
$^{76}Ge \rightarrow ^{76}Se$	7.6	2039
$^{82}Se \rightarrow ^{82}Kr$	8.7	2996
$^{96}Zr \rightarrow ^{96}Mo$	2.8	3348
$^{100}Mo \rightarrow ^{100}Ru$	9.6	3034
$^{116}Cd \rightarrow ^{116}Sn$	7.5	2814
$^{124}Sn \rightarrow ^{124}Te$	5.8	2288
$^{128}Te \rightarrow ^{128}Xe$	31.8	866
$^{130}Te \rightarrow ^{130}Xe$	34.2	2528
$^{136}Xe \rightarrow ^{136}Ba$	8.9	2458
$^{150}Nd \rightarrow ^{150}Sm$	5.6	3368



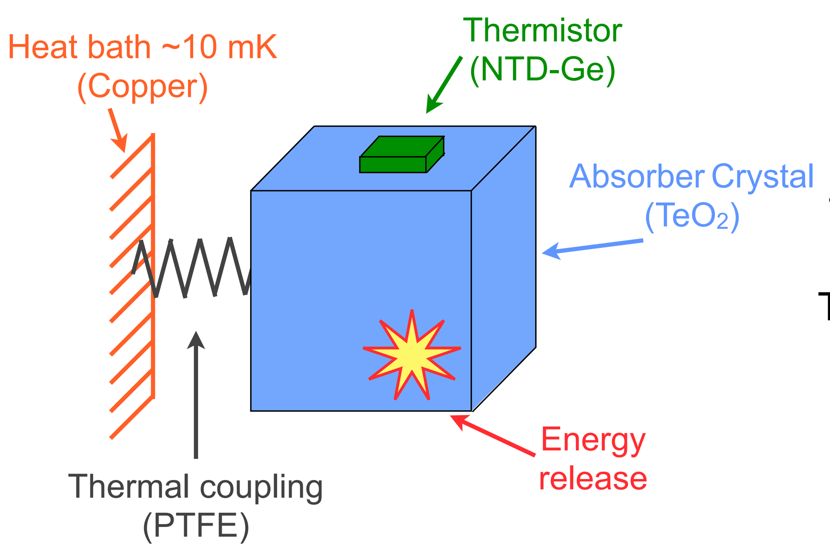
Good energy resolution to disentangle 0νββ from 2νββ

Very high radio purity level to reduce the background

High number of active isotopes

The ^{130}Te is affected by an higher β/γ background compared to other isotopes, but has the highest Isotopic Abundance

Bolometric technique with TeO$_2$ crystals

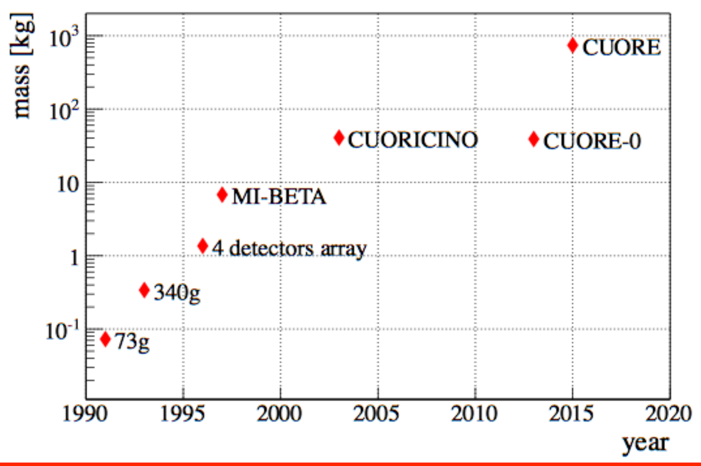


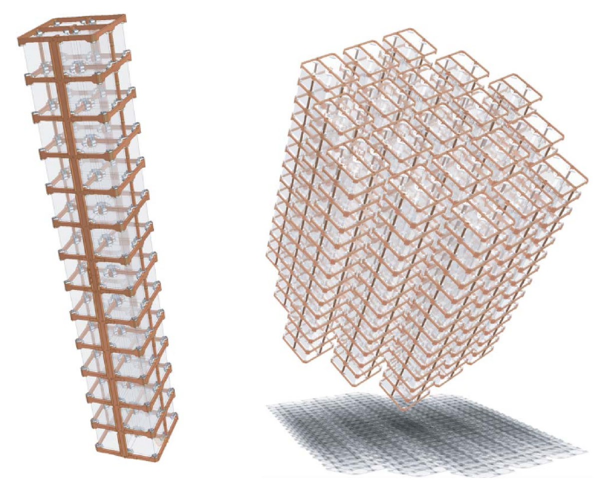
The energy released by particle interactions is converted into phonons inside the absorber

The absorber increases its temperature

The thermistor converts this temperature variation into a resistance variation

The thermistor is biased so that the resistance variation produces a measurable voltage signal





ADVANTAGES

High energy resolution ~ 5 keV @ 2.6 MeV

Scalability

Absorber ≡ 0νββ Source

Crystal with the best bolometric performance

DISADVANTAGES

No particle identification (α,β,γ)

Cleaning technique to increase radio purity at experimental limits

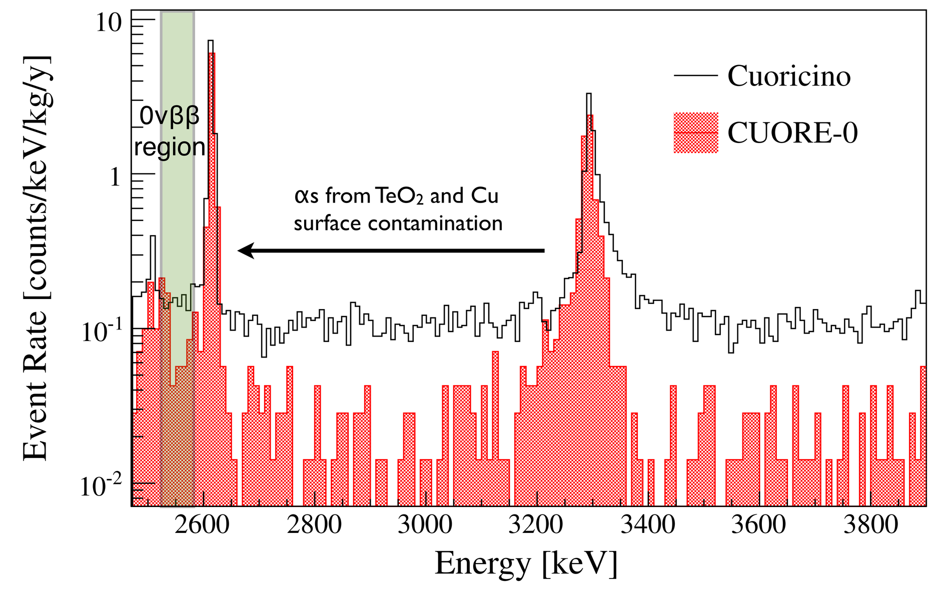
CUORE: an array of 988 bolometers 5x5x5 cm³ of TeO$_2$ @ Gran Sasso Underground Laboratory in Italy (3650 m w.e.)

CUORICINO and CUORE-0: the α background

	flat background 0νββ [counts/keV/kg/y]	flat background 2.7-3.9 MeV [counts/keV/kg/y]
CUORICINO	0.153±0.006	0.110±0.001
CUORE-0	0.071±0.011	0.019±0.002

CUORE collaboration, arXiv:1402.0922 [physics.ins-det]
See the update in Oliviero Cremonesi's talk

The cleaning procedure could not remove completely surface contamination



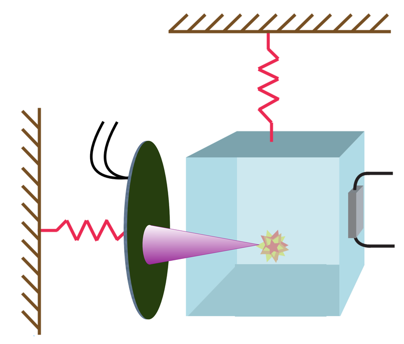
α background rejection

The α background rejection is possible tagging the Cherenkov signal emitted at the low energy of natural radioactivity only by electrons

Cherenkov threshold	@ 0νββ ROI	Cherenkov energy
$E_{e^-} > 54$ keV →	Cherenkov	~ 740 eV
$E_{\alpha} > 400$ MeV →	No Cherenkov	

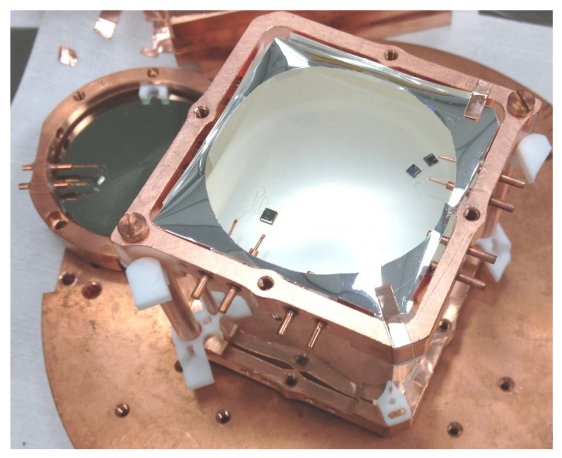
Using a light detector it is possible to detect the Cherenkov radiation and disentangle signal from background

The light detector must work @ 10 mK.

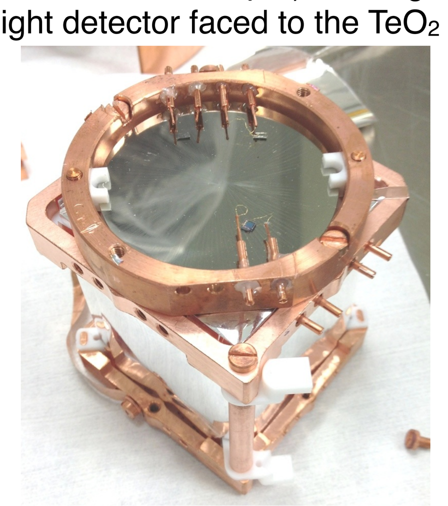


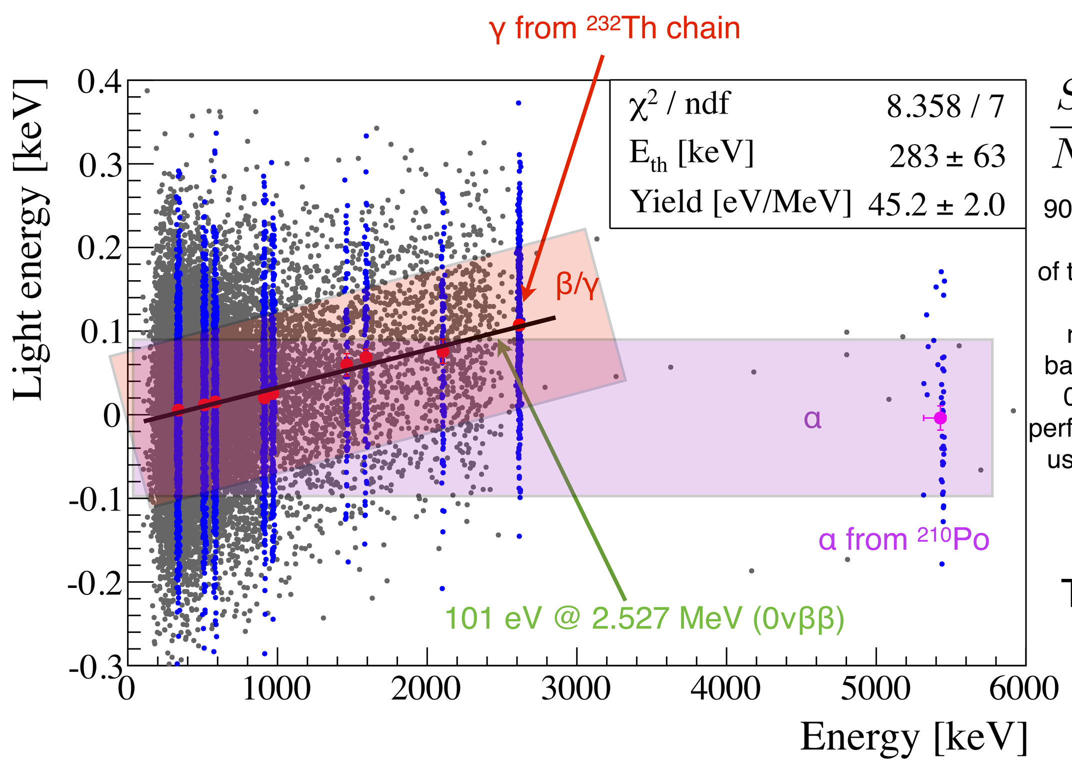
T. Tabarelli de Fatis, Eur. Phys. J. C 65 359, 2010

TeO$_2$ bolometer 5x5x5 cm³, covered with VM2002 reflective foil



Germanium bolometer (diameter 50 mm, thickness 300 μm) working as light detector faced to the TeO$_2$

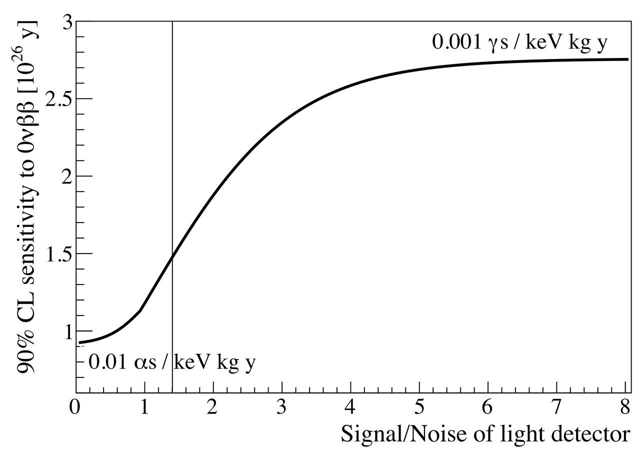




N. Casali, M. Vignati et al 2014 arXiv:1403.5528

$$\frac{S}{N} = \frac{101\ eV}{72\ eV} = 1.4$$

90% C.L. sensitivity to the half-life of ^{130}Te as a function of the signal to noise ratio of the light detectors, under the reasonable hypothesis of a background index in CUORE of 0.01 counts/(keV kg y). The performance of the light detectors used in this work, S/N = 1.4, is clearly too low.



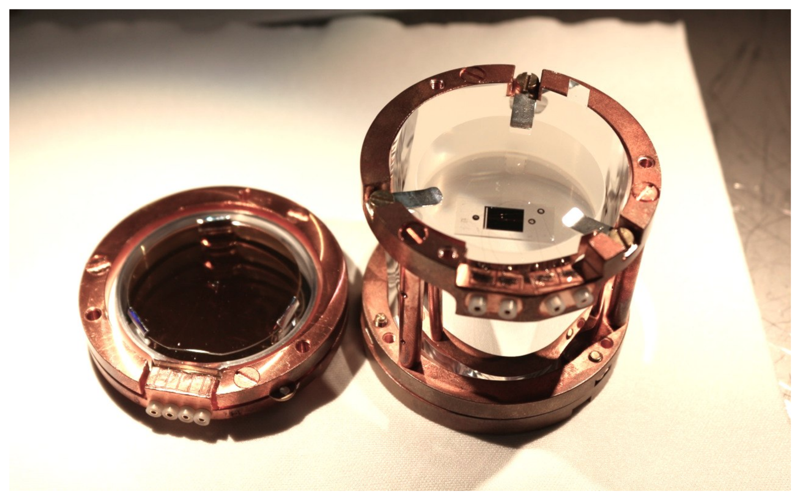
Test measurement performed in the Hall C of the Gran Sasso Underground Laboratory; the germanium light detector was developed by the LUCIFER collaboration.

J W Beeman et al 2013 JINST **8** P07021

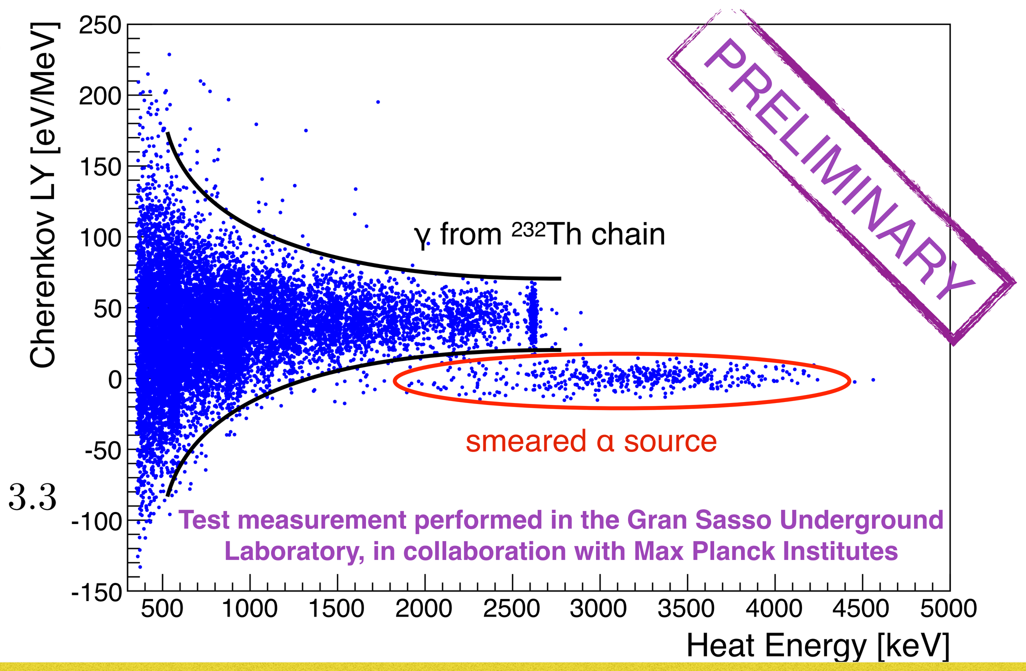
TeO$_2$ and Light Detector with Transition Edge Sensor

Silicon on sapphire wafer, 4cm diameter, W-TES as thermometer

TeO$_2$ bolometer 4 cm diameter and height , W-TES as thermometer, covered with VM2002 reflective foil



$$\frac{S}{N} = \frac{117\ eV}{35\ eV} = 3.3$$



We tested the possibility to discriminate the background in CUORE by tagging the signal from β particles through the detection of Cherenkov light. The detected light at the ^{130}Te Q-value is around 100 eV for β/γ particles and no light is detected from α interactions, confirming the validity of this technology. The signal is however small, at the same level of the noise of the bolometric light detector equipped with NTD. Using light detector equipped with TES the signal to noise ratio increases at a level able to reject the α background. Combining the light readout with an enrichment in ^{130}Te from the natural 34% to ~90% this technology is able to explore the entire inverted hierarchy of neutrino masses.

NEUTRINO 2014, June 2-7, Boston, U.S.A.