Search for Neutrinoless Double Beta Decay with CUORE

Daniel Lenz
on behalf of the CUORE collaboration
CUORE Family

Cryogenic Underground Observatory for Rare Events

- main purpose: search for $0\nu\beta\beta$ of $^{130}\text{Te}$
- also other rare event searches: i.e. $0\nu\beta\beta$ of $^{128}\text{Te}$, WIMPS, Axions, $\beta^+$/EC of $^{120}\text{Te}$,...

Cuoricino

- 2003 -2008
- 1 tower
- 62 crystals (44 cuore type+ 18 small)
- $^{130}\text{Te} = 11.3$ kg
- $\text{b(ROI)} = 0.169 \pm 0.006$ cts / (keV kg y)

Cuore-0

- 2011 - 2014
- 1 tower
- 52 crystals
- $^{130}\text{Te} = 11$ kg
- $\text{b(ROI)} \sim 0.05$ cts / (keV kg y)

CUORE

- 2014 -2019
- 19 towers
- 988 crystals
- $^{130}\text{Te} = 206$ kg
- $\text{b(ROI)} \sim 0.01$ cts / (keV kg y)
Bolometers Working Principle

• real calorimetry, i.e. all energy measured in form of heat

\[
\text{Heat bath } \rightarrow 10 \text{ mK}
\]

\[
\text{Weak thermal coupling } G
\]

\[
\text{Thermometer}
\]

\[
\text{Absorber crystal}
\]

• temperature rise: \( \Delta T \sim \Delta E/C \)

\[
T \downarrow \Rightarrow C \downarrow \Rightarrow \Delta T \uparrow
\]

• decay time: \( \tau \sim C/G \)

\[
T \downarrow \Rightarrow C \downarrow \Rightarrow \tau \downarrow
\]

typical pulse shape parameters for large bolometers:

• rise time: \( \sim 50 \text{ ms} \)

• decay constant of pulse: \( \sim 200 \text{ ms} \)

• total pulse length several seconds

Debye Law:

\[
C(T) \sim (T/T_D)^3
\]
CUORE Bolometers

TeO$_2$: dielectric and diamagnetic

\[ C \approx 2 \times 10^{-9} \frac{J}{K} \quad @ \quad 10 \text{ mK} \]

\[ \Delta T \approx 0.1 \frac{mK}{MeV} \quad @ \quad 10 \text{ mK} \]

Weak thermal coupling:

\[ G \approx 2 \times 10^{-9} \frac{W}{K} \]

Temperature sensor:

- NTD Ge thermistor

\[ R(T) = R_0 e^{\frac{\sqrt{T_0}}{T}} \quad \Delta R \approx 3 \frac{M \Omega}{MeV} \]

- resistance change converted into voltage pulse

\[ \Delta V \approx 0.3 \frac{mV}{MeV} \]

- non-linear energy response
CUORE Bolometers

- made from natural TeO$_2$

- high natural abundance of $^{130}$Te of 34.2%
  => no need for enrichment
- high Q-value, 2528keV, above most natural $\gamma$-lines
- possible to grow large crystals with low radioactive contamination

- large bolometers: 5x5x5 cm
- 750 g per crystal
  => M($^{130}$Te) $\sim$ 208 g per crystal

Energy resolution:
- FWHM $\sim$ 5 keV @2528 keV
- All experiments of CUORE family located in Hall A (R&D in Hall C) of Gran Sasso National Lab (LNGS), L’Aquila, Italy

- overburden of $\sim 1400$ m rock corresponding to $\sim 3100$ m.w.e. (relative to flat overburden) *Phys. Rev. D73 053004*

- Muon flux: $\phi_\mu = (2.58 \pm 0.3) \times 10^{-8}$ $\mu/(s \ cm^2)$ with average $E_\mu = 270$ GeV

- Neutron flux: $\phi_n \sim 4 \times 10^{-6}$ $n/(s \ cm^2)$ with $E < 10$ MeV

- Gamma flux: $\phi_\gamma \sim 0.73$ $\gamma/(s \ cm^2)$
44 crystals: 5cm x 5cm x 5cm (CUORE-type)  FWHM ~6 keV
18 crystals: 3cm x 3cm x 6cm  FWHM ~10 keV
4 are enriched  FWHM ~14 keV

- $M(\text{TeO}_2) = 40.7 \text{ kg} \Rightarrow M^{\text{130Te}} = 11.3 \text{ kg}$
- Total exposure 19.75 kg y (from 2003-2008)

- two independent analyses, US and Italy:
  (very similar, agreeing, results)
- max. likelihood fit with 8 free parameters:
  - $0\nu\beta\beta$ rate
  - $^{60}\text{Co}$ sum energy
  - 3x flat background rates
  - 3x $^{60}\text{Co}$ rates
- $b(\text{ROI}) = 0.169 \pm 0.006 \text{ cts / (keV kg y)}$
- $T^{0\nu}_{1/2} (^{130}\text{Te}) > 2.8 \times 10^{24} \text{ y (90\% C.L.)}$
- $<m_\nu> < 300 - 710 \text{ meV (depending on choice of NME)}$
• Single CUORE-like tower
  • test of CUORE assembly and cleaning procedures
  • deliver information about backgrounds
  • sensitive 0νββ experiment

• 52 TeO₂ crystals randomly chosen from CUORE crystals
  • same geometry thermistors but different doping
  • same assembly procedures as CUORE
  • same cleaning procedure as CUORE
  • very similar copper frames and Teflon holder

• Operated in refurbished Cuoricino cryostat
  • different suspension than CUORE
  • different shielding and thus internal backgrounds
• Preparation in progress and on schedule
• Dummy towers built
• CUORE-0 tower construction will start Sept. 2011
• Data taking starts within 2011

**Detector Parameters:**

\[
M(^{130}\text{Te}) \sim 11\text{kg}
\]

\[
\Delta E \sim 5-6\text{ keV}
\]

• irreducible background from Cuoricino cryostat

\[
b_{\text{cryo}} \sim 0.05\text{ cts/(keV kg y)}
\]

• max. background surface contribution (estimated from R&D efforts):

\[
b_{\text{surf}} \sim 0.06\text{ cts/(keV kg y)}
\]

within \sim 1.5\text{ years CUORE-0 may improve current Cuoricino limit by factor 2

preliminary
CUORE Experiment

• array of 988 bolometers 19 towers, 13 planes, 4 bolometers /plane /tower

• total active detector mass 741 kg
• total Te mass 592 kg
  \[ M(^{130}\text{Te}) \sim 206 \text{ kg or } 9.6 \times 10^{26} \text{ nuclei} \]
  \[ M(^{128}\text{Te}) \sim 189 \text{ kg or } 8.9 \times 10^{26} \text{ nuclei} \]

• mostly radiopure materials in detector area: copper, teflon, TeO₂ (all measured)

• less radiopure but low mass: cable, thermistors

• at least 30 cm of lead shielding, inner lead shields made from ancient roman lead (\(^{210}\text{Pb} < 4\text{mBq/kg}\))

• 5% borated polyethylene neutron shield ~20cm thick

• goal: reach a flat bkg of 0.01 cts/(keV kg y) in ROI
  • demonstrated within factor 2 - 4
CUORE Calibration

- CUORE bolometers are not sensitive to position of energy deposit, only mean to distinguish background from signal is energy resolution

- uncertainty in $\Delta E$ is systematic uncertainty on $T_{0v}^{1/2}$
  - Cuoricino: $\pm 0.4$ keV
  - Cuore goal: $\pm 0.05$ keV

- calibration against known $\gamma$-lines from $^{232}$Th done ~ monthly
- between calibrations heater pulses help stabilize detector response

- large shielding & good self shielding requires sources inside detector array to provide even illumination of all crystals

- 6 radioactive source inserted in between towers @ 10 mK
- 6 outside of inner detector region

- different layouts simulated, symmetric yields most even illumination

- slow detector response requires low activity sources:
  $A_{\text{int}} \sim 3.9$Bq  
  $A_{\text{ext}} \sim 19$Bq
CUORE Calibration System

- Source design: Kevlar strings with 30 copper crimps housing $^{232}$Th wire, calibrating 500keV - 3000keV

- 12 source strings move under own weight 300K to 10mK without shifting detector base temperature

- Several sensors and precautions to monitor and ensure smooth deployment and extraction of sources

- Heat load requirements very strict: sources need to be at 4K

- Dedicated thermalization mechanism prototyped, tested and now under construction

- Motion box-0 construction finished, guide tubes under construction
CUORE Experiment - Status

now:
• CUORE experimental hut with clean room, fully equipped for tower assembly
• cryostat main support in place and eigenfrequencies measured
• more than 500 bolometers ready and stored underground at LNGS; tests ongoing
• smooth transition between Italian and US bolometer production
• outer cryostat vessels being welded
• calibration system under construction
• dilution unit testing in progress: 5.3 mK reached
• copper cleaning started and on track
• CUORE data taking 2014
CUORE Projected Sensitivity

CUORE Sensitivity at 1σ:

\[ T_{1/2}^{0\nu} \sim 2 \times 10^{26} \text{ y at 1σ} \]

\[ <m_\nu> \sim 50 \text{ meV} \]

(depending on NME)

• start probing inverted hierarchy

• 5 years live time and bkg of \( b = 0.01 \text{ cts/ (keV kg y)} \)

CUORicino exclusion 90% C.L.

\[ \Delta m^2_{\nu} < 0 \]

\[ \Delta m^2_{\nu} > 0 \]

preliminary
Summary

• $0\nu\beta\beta$ is only experimentally feasible way to distinguish Dirac vs. Majorana neutrinos

• CUORE-family experiments use bolometers made of natural TeO$_2$ to search for $0\nu\beta\beta$ of $^{130}\text{Te}$

• calibration is challenging: 12 strings with 30 sources brought into cryostat from 300K to 10mK, without changing detector base temperature

• Good progress being made:
  • CUORE-0 data-taking starts within 2011
  • CUORE data-taking 2014

• Goal of background in ROI of 0.01 cts/(keV kg y); demonstrated within factor 2-4

• CUORE sensitivity at 1$\sigma$ $T_{1/2}^{0\nu} \sim 2 \times 10^{26}$ y $\Rightarrow <m_\nu> \sim 50$ meV
  start probing inverted hierarchy
Motivation – 0νββ

- 0νββ is only experimentally feasible way to distinguish Dirac vs. Majorana neutrinos

\[ \nu \neq \bar{\nu} \quad \nu = \bar{\nu} \]

- if 0νββ observed:
  - lepton number violation
    \[ \Delta L = 2 \]
  - Schechter-Valle theorem
    \[ \nu = \bar{\nu} \]
  - hint for seesaw type 1
    \[ m_\nu = m_D^2 / M_R \ll m_D \]
  - possible to determine absolute \( \nu \) mass scale and \( \nu \) hierarchy
Motivation – $0\nu\beta\beta$

- $0\nu\beta\beta$ is only experimentally feasible way to distinguish Dirac vs. Majorana neutrinos

- if $0\nu\beta\beta$ observed:
  - lepton number violation
    \[ \Delta L = 2 \]
  - Schechter-Valle theorem
    \[ v = \bar{v} \]
  - hint for seesaw type 1
    \[ m_v = m_D^2 / M_R \ll m_D \]
  - possible to determine absolute $\nu$ mass scale and $\nu$ hierarchy

- any other process than $0\nu\beta\beta$ depositing energy in ROI is background
$0\nu\beta\beta$ Decay Rate & Neutrino Mass Hierarchy

• Measurable quantity is decay rate $\Gamma^{0\nu}$

$$\Gamma^{0\nu} \propto G^{0\nu}(Q, Z) \cdot |M^{0\nu}|^2 \langle m_\nu \rangle^2$$

$G^{0\nu}$ : Phase Space factor
$|M^{0\nu}|^2$ : Nuclear Matrix Element
$\langle m_\nu \rangle$ : Effective Majorana neutrino mass

$\langle m_\nu \rangle$ effective majorana neutrino mass:

$$\langle m_\nu \rangle = \left| \sum_i m_i U_{ei}^2 \right|$$

$U_{ei}$ are the corresponding entries of the PMNS matrix

Strumia, Vissani, NPB 726
• sensitivity to Klapdor-Kleingrothaus claim

Assume $T_{1/2}^{0v}(^{76}\text{Ge}) = (2.23^{+0.34}_{-0.31}) \times 10^{25} \text{y}$

- b (ROI) = 0.05 cts/ (keV kg y)
- inner band: best fit value + NME uncertainty
- outer band: including uncertainty in $T_{1/2}$
CUORE Cryogenics

Requirements:

- mass of $\sim 1.5$ t cooled to $T \leq 10$ mK
- experimental area: 1m heigh and 0.94m wide
- instrumented with $\sim 2600$ wires
- vibration have to be minimized

Cooling:

- combination of 5 pulse tubes (PT) (cryogen-free) and a custom build 3He/4He dilution unit (DU) will provide cooling power
- OVC at room temperature
- IVC at 4K, 2$^{nd}$ stage of the PT
- innermost shield connected to MC of DU
  $T_{MC} \leq 10$ mK

Suspension:

- detector is independently suspended from y-beam with 3 composite stainless rods and Kevlar ropes below STILL