CUORICINO results and

CUORE R & D

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on behalf of the
CUORE Collaboration

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Neutrino-less Double Beta Decay

The standard lore: light Majorana neutrino exchange

\[ \text{chirality flip: } m_\nu \neq 0 \]
\[ \nu_{\text{majorana}}: \nu \equiv \bar{\nu} \]
\[ (\text{Lepton number violation}) \]

If observed:

Proof of Majorana nature of Neutrino

\[ \left( \tau_{1/2}^{0\nu\beta\beta} \right)^{-1} = G(Q, Z) |M_{\text{nucl}}|^2 |m_{\beta\beta}|^2 \]
\[ m_{\beta\beta} = \sum m_{\nu_k} U_{ek}^2 \]

Schetcher, Valle *Phys. Rev. D25 2951 1982*
Does 0νββ measure the mass?

\[ m_{\beta\beta} = \sum m_{\nu_k} U_{ek}^2 = \cos^2 \theta_{13} (m_1 \cos^2 \theta_{12} + m_2 e^{2i\alpha} \sin^2 \theta_{12}) + m_3 e^{2i\beta} \sin^2 \theta_{13} \]

Strumia, Vissani  hep/ph 0606054

Degenerate and inverted hierarchy testable by “realistic” experiments
The 0νββ elements shall have:

\[ (\tau_{1/2}^{0\nu\beta\beta})^{-1} = G(Q, Z) |M_{nucl}|^2 |m_{\beta\beta}|^2 \]

- A large Q
  - because rate \( \propto Q^5 \)
  - because the natural \( \gamma \)-lines end around 2.6 MeV \( ^{208}\text{Tl} \) from \( ^{232}\text{Th} \)

- A large matrix element

- A large isotopic abundance

- Should be \((A-Z)\) even-even nuclei: 2νββ suppressed

\[ ^{48}\text{Ca}, ^{76}\text{Ge}, ^{82}\text{Se}, ^{100}\text{Mo}, ^{116}\text{Cd}, ^{130}\text{Te}, ^{136}\text{Xe}, ^{150}\text{Nd} \]
2νββ background-ΔE

Reducible bkg will accumulate proportionally to the window dictated by energy resolution. You can always hope to reduce the background and alleviate the problem.

Irreducible background however cannot be reduced; 2νββ tail will always be there.

\[ \delta = \frac{\Delta E_{FWHM}}{Q_{ββ}} \]

\[ \frac{S}{B} \approx \frac{m_e}{7Q_{ββ}} \delta^6 \frac{T_{2ν}^2}{T_{1/2}^{0ν}} \]

Please note \[ \delta^6 \]

\[ T_{0ν} \approx 10^{28} \text{y} \quad S/B = 1 \]

\[ T_{2ν} \approx 10^{20} \text{y} \quad Q \approx 3 \text{MeV} \]

\[ \delta = \frac{\Delta E_{FWHM}}{Q} \approx 2.5\% \]
The less noble background

- Internal to source
  - Primordials ($^{238}\text{U}$, $^{232}\text{Th}$, $^{40}\text{K}$)
  - Cosmogenic activation

- External to source
  - Cosmic rays
  - Neutrons
  - Primordials in surrounding materials

- Detector specific

- Bkg estimate and reduction: hard (few counts/y): intermediate size experiment often required

On the back of the envelope

$\tau_{1/2}^{0\nu} = \ln2 \cdot a \cdot N_a \cdot M \cdot T / N_{\beta\beta} \quad (\tau_{1/2}^{0\nu} \gg T)$

50 meV $m_{\beta\beta}$ implies half lifes $\sim 10^{26-27}$ y: 1 event/y $\Rightarrow 10^3$ isotope moles $\Rightarrow O(100\text{kg})$

now you can only loose: nat. abundance, efficiency, background....
Two techniques

Source $\subseteq$ detector

- $M$, $\Delta E$, $\varepsilon$
- Topology, bkg

- $^{76}$Ge diodes (MAJORANA, GERDA)
- $^{130}$Te bolometers (CUORE)
- $^{48}$Ca, $^{116}$Cd, $^{160}$Gd, $^{136}$Xe scintillators (EXO)

Source $\neq$ detector

- Bkg topology, different isotopes
- $M$, $\Delta E$, $\varepsilon$

- Tracking chamber: $^{82}$Se, $^{100}$Mo, $^{96}$Zr (NEMO, MOON)
CUORICINO: the bolometric way

(Very) Low temperature homogeneous calorimeter:

- basic physics of Bolometry: \( \Delta T = \frac{E}{C} \)
  \[ \Rightarrow \text{low } C \]
- diamagnetic dielectrics @ low \( T_0 \) (~ 10mK):
  \[ C \sim (T/\Theta_D)^3 \sim 2 \text{ nJ/K} \sim 10^{10} \text{eV/K} \]
  \[ G \sim 4 \text{ nW/K} \]

Thermometer: NTD Ge thermistor

\[ R \sim R^0 \exp(T^0/T)^{-0.5} \]
\[ \Delta T \Rightarrow \Delta R \]
\[ \Rightarrow 0.1 \text{ mK/MeV} \Rightarrow 0.1 \text{mV/MeV} \]

Bonus: no intrinsic limit to \( \sigma(E) \)

\[ \sigma(E) = (K_BT^2)^{0.5} \sim 10 \text{ eV} \]

(Not for all) Typical pulse decay time: \( t \sim C/G \sim 10^{2-3} \text{ ms} \)
Why Tellurium?

- Active isotope: $^{130}$Te

- Transition energy
  $$Q_{\beta\beta} = (2530.30 \pm 1.99) \text{ keV}$$

  *Nuclear Physics A 729 (2003) 337*

Natural abundance

33.9% $\Rightarrow$ low cost

Nuclear matrix element

- Absorber material: TeO$_2$
  - Low heat capacity
  - Possibility to grow large crystals
  - Good intrinsic purity

Between the highest natural $\gamma$ line ($^{208}$Tl) and Compton edge
**CUOR(ICINO) @ LNGS**

Cuoricino experiment is installed in the Underground National Laboratory of Gran Sasso, L’Aquila – ITALY. The mountain providing a 3500 m.w.e. shield against cosmic rays.

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**CUORE (hall A)**

**Cuoricino**

**R&D final tests for CUORE (hall C)**
CUORICINO: the demonstrator

11 modules: 4 detector 5x5x5 cm³ = 790 g each

2 modules 9 detector 3x3x6 cm³ = 330 g each

4 enriched: 2 @ 75% $^{130}$Te  
2 @ 82.3% $^{128}$Te

Total Active mass:
- $\text{TeO}_2$ = 40.7 kg
- $^{130}\text{Te}$ = 11.34 kg

Started on April 2003

Faraday cage
Anti-Radon box
neutron shield

External Pb shield
Roman lead shield

He liquifier

Vacuum pumps
Calibration spectra: energy resolution

**Sum calibration spectra**

- **FWHM @ 2615 keV \(^{208}\)Tl \(\gamma\)-line**
  - 5x5x5 cm\(^3\) crystal: FWHM 7.5±2.9 keV
  - 3x3x6 cm\(^3\) crystal: FWHM 9.6±3.5 keV

- \(^{232}\)Th \(\gamma\)-source external to the cryostat: 3 days measurement every month
CUORICINO 0νββ result

- Total statistics: 8.38 kg $^{130}$Te•y
- Bkg (ββ0ν region):
  $0.18 \pm 0.01$ counts/keV/kg/y
- FWHM measured on bkg spectrum
  @ 2.6 MeV $\sim 8$ keV
- Detector efficiency: $\sim 86.4\%$
- ML fit in 2475-2550 keV region
  - flat bkg + 2505 keV peak
  - peak shape = N-gaussian
    to account for the different – measured - energy resolutions
  - best fit yields negative effect

$$\tau_{1/2}^{0ν\beta\beta} > 2.4 \cdot 10^{24} \text{ y} @ 90 \text{C.L.} \implies \langle m_{\beta\beta} \rangle < [0.18 \div 0.94] \text{ eV}$$

$\langle m \rangle$ range from various QRPA calculations: Rodin, Faessler, Simkovic, & Vogel Nucl. Phys. A 766 107 (2006)
Staudt, Kuo & Klapdor-Kleingrothaus, PRC 46 871 (1992)
In the parameter space

KK: $0.24 \, eV < m_{\beta\beta} < 0.58 \, eV \iff m_{\beta\beta}^{\text{best}} = 0.44 \, eV$


CUORICINO:

$m_{\beta\beta} < [0.18 - 0.94] \, eV$

With 3 years live time:

$\tau_{1/2}^{0\nu\beta\beta} > 5.4 \cdot 10^{24} \, y \, @ \, 90 \, C.L.$

$\left\langle m_{\beta\beta} \right\rangle < [0.11 \div 0.63] \, eV$

$m$ range from various QRPA calculations:

Staudt, Kuo & Klapdor-Kleingrothaus, PRC 46 871 (1992)
The Moore's Law of Bolometry


Mass [kg]

10000,00
1000,00
100,00
10,00
1,00
0,10
0,01


Year

Mibeta
4 detectors array


CUORE

73 g
340 g
Cryogenic Underground Observatory

Single dilution refrigerator ~10 mk

for Rare Events

• $\beta\beta 0\nu$, Cold Dark Matter, Axion searches
  proposal hep/ph 0501010

Closed packed array of $988 \text{ TeO}_2$ 5x5x5 cm$^3$ crystals $\Rightarrow 741 \text{ kg TeO}_2 \Rightarrow 204\text{ kg }^{130}\text{Te}$
CUORE Housing

Basement already completed ... the rest is coming
CUORE sensitivity

CUORE 0νββ sensitivity will depend strongly on the bkg level and detector performance.

1st generation exp: proof of technology
2nd generation exp: explore inverted hierarchy

CUORE GOAL:
- test inverse hierarchy: 19-50 meV

Projected sensitivity of CUORE (1σ)

Spread due to NME uncertainties: main obstacle to answer ν mass question
CUORICINO bkg in the $0\nu\beta\beta$ region

- All lines identified all over the whole spectrum: $U$ & $Th$ chains, $^{40}K$, $^{207}Bi$, $^{60}Co$

- In $0\nu\beta\beta$ region:
  - $30 \pm 10\%$ $^{208}Tl$ (2614.5 keV line) via multi-Compton events from $^{232}Th$ in cryostat shields
  - $10 \pm 5\%$ from crystals surface $^{238}U$ and $^{232}Th$ contamination
  - $50 \pm 20\%$ from degraded $\alpha$ produced by $^{238}U$ and $^{232}Th$ contaminations of mounting structure
    main candidate the copper surface
  - negligible contribution from $2505$ (1173$\gamma$+1332$\gamma$) keV $^{60}Co$ tail due Cu cosmogenic activation

$^{60}Co$

$Q_{\beta\beta} = (2530.30 \pm 1.99) \text{ keV}$

$^{208}Tl$

$0.18 \pm 0.01 \text{ counts/keV/kg/y}$

$^{214}Bi$
Background reduction

- Cryostat $^{232}$Th bulk contamination contribution reduced by properly shielding in CUORE cryostat
  + selection of construction materials: $\text{bkg} = < 10^{-3} \text{ c/keV/kg/y}$
- Cosmogenic Cu and Te activation reduced by underground storage of materials
- Surface contribution:
  - test with new crystals surface cleaning (etching, lapping with 2$\mu$m SiO$_2$ clean powder)
    reduction of a factor 4
  - test with new Cu cleaning (etching, electro-polishing, passivation) and
    complete coverage of Cu facing the crystal with ~50$\mu$m PET film
    reduction of ~40% of flat continuum background

Hall C cryostat has different shields than CUORICINO resulting in higher rates < 2.6 MeV. Possible to study $\alpha$ bkg only.
The extrapolated contribution to CUORE are

- **Crystal Surface contamination contribution** \(<3 \cdot 10^{-3} \text{ counts/keV/kg/y}\)
- **Copper Surface contamination contribution** \(<5 \cdot 10^{-2} \text{ counts/keV/kg/y}\)
- **New structure with reduced Cu amount** is being tested right now
  - **MC simulation Cu contribution** \(< 2.5 \cdot 10^{-2} \text{ counts/keV/kg/y}\)

**still a factor no less than 2.5 to go**

*New passive procedure (plasma cleaning) under test*

*most exp. efforts now concentrated in the reduction of surface impurities*

*alternative viable way:*

*adopt a smarter, yet more complex, bkg recejction system:*

*Surface Sensitive Bolometers*
CUORE R&D: active bkg rejection

Surface sensitive detectors: composite bolometer with a thin Ge, Si, TeO$_2$ crystal

Thin shield Bolometer and its thermistor

TeO$_2$ Bolometer

classic pulse

fast and high pulse

![Graph showing pulse amplitude vs. rise time]
**Conclusion**

- **Dirac or Majorana** neutrino nature is a fundamental question that needs to be answered at (almost) all cost(s)
- **Neutrino-less DBD** might be the sole chance to give a measure of neutrino mass

- **CUORICINO:**
  - The most sensitive $0\nu\beta\beta$ decay running experiment:
    \[ \tau_{1/2}^{0\nu\beta\beta} > 2.4 \cdot 10^{24} \text{ y @ 90 C.L.} \Rightarrow \langle m_{\beta\beta} \rangle < [0.18 \div 0.94] \text{ eV} \]
  - Good chances to confirm Klapdor-Kleingrothaus claim
  - CUORICINO proved the feasibility of CUORE
  - Crucial informations for background identification

- **CUORE:**
  - Hut construction already started
  - Intense R&D activity to reduce background and optimize construction
  - Enrichment or alternative options ($^{48}\text{Ca}$, $^{100}\text{Mo}$, $^{116}\text{Cd}$, $^{150}\text{Nd}$) still open
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neutron & \( \gamma \) background

- **External neutron flux:**
  \[ \Phi = 3.7 \times 10^{-6} \text{n/s/cm}^2 \]
  (measurement E<10MeV + \( \mu \)-induced neutrons simulation in the rock)
  Total anti-coincidence \( \text{bkg} \sim 10^{-5} \) counts/keV/kg/y

- **Muon-induced neutrons in the shieldings**
  \[ \Phi = (3.2 \pm 0.2) \times 10^{-4} \text{\( \mu \)/s/m}^2 \]
  induced neutron flux on detector \( \Phi \sim 10^{-7} \text{n/s/cm}^2 \)
  total anti-coincidence \( \text{bkg} = (3.0 \pm 0.3) \times 10^{-4} \) counts/keV/kg/y

- **External radiation:**
  \[ \Phi = 7.7 \times 10^6 \gamma / \text{d/cm}^2 \]
  measured with Ge detector
  \( \text{bkg} = 1.5 \times 10^{-5} \) counts/kg/keV/y with 24 cm external Pb shield

- **External Pb shield contamination:**
  \( 100 \mu \text{Bq/kg} \)
  \( \text{bkg} = 2.4 \times 10^{-4} \) counts/keV/kg/y

- **Internal shield**
  - **Roman lead contamination (6cm Pb):**
    \[ 60 \pm 17 \mu \text{Bq/kg} \]
    \( \text{bkg} = 6 \times 10^{-3} \) counts/keV/kg/y
  - **DownRun Pb**
    \[ <22 \mu \text{Bq/kg} \]
    \( \text{bkg} < 2 \times 10^{-3} \) counts/keV/kg/y
  (but \( ^{60}\text{Co} \) contamination & 27 Bq/kg \( ^{210}\text{Pb} \))

- **Cu shield contamination:**
  \[ <12 \mu \text{Bq} \]
  \( \text{bkg} < 2.4 \times 10^{-3} \) counts/keV/kg/y
  (better for Th contamination.. worse for \( ^{60}\text{Co} \) contamination and neutron activation)