Results from CUORE-0, Status of CUORE

Reina Maruyama (Yale University) 
on behalf of the CUORE Collaboration
CUORE in context

Current Projects

<table>
<thead>
<tr>
<th>Project</th>
<th>Isotope</th>
<th>Isotope Mass (kg fiducial)</th>
<th>Currently Achieved ($10^{26}$ yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUORE</td>
<td>$^{130}$Te</td>
<td>206</td>
<td>$&gt;0.028$</td>
</tr>
<tr>
<td>MAJORANA</td>
<td>$^{76}$Ge</td>
<td>36.8</td>
<td></td>
</tr>
<tr>
<td>GERDA</td>
<td>$^{76}$Ge</td>
<td>18-20</td>
<td>$&gt;0.21$</td>
</tr>
<tr>
<td>EXO200</td>
<td>$^{136}$Xe</td>
<td>79</td>
<td>$&gt;0.11$</td>
</tr>
<tr>
<td>NEXT-100</td>
<td>$^{136}$Xe</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>SuperNEMO</td>
<td>$^{82}$Se+</td>
<td>7</td>
<td>$&gt;0.001$</td>
</tr>
<tr>
<td>KamLAND-Zen</td>
<td>$^{136}$Xe</td>
<td>434</td>
<td>$&gt;0.19$</td>
</tr>
<tr>
<td>SNO+</td>
<td>$^{130}$Te</td>
<td>160</td>
<td></td>
</tr>
<tr>
<td>LUCIFER</td>
<td>$^{82}$Se</td>
<td>8.9</td>
<td></td>
</tr>
</tbody>
</table>

Primary goals:
- Demonstrate background reduction for next generation experiment
- Extend sensitivity to $T_{1/2} \sim 10^{26}$ years.

Inverted Hierarchy Coverage

$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} \cdot |M_{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$

Figure source: A. Dueck, W. Rodejohann, and K. Zuber, Phys. Rev. D83 (2011) 113010.
TeO$_2$ Bolometers for 0νββ Search

- $^{130}$Te is a good 0νββ source
  - high isotopic abundance
  - high Q-value
- TeO$_2$ bolometer provides excellent energy resolution (0.2% at Q-value)

$\Delta T_{\text{crystal}} \sim 10 - 20 \, \mu \text{K}/\text{MeV}$
The CUORE 0νββ Search

Cuoricino (2003-2008)

CUORE-0 (2013-2015)

CUORE (2015-2020)

$T_{1/2}^{0\nu\beta\beta} > 2.8 \times 10^{24}$ y (90% C.L.)

$\langle m_{\beta\beta}\rangle_{90\% \text{ C.L.}} = 300 - 710$ meV

Surpass Cuoricino w/ ~1-yr data

$T_{1/2}^{0\nu\beta\beta} > 9.5 \times 10^{25}$ yr (90% C.L.)

$\langle m_{\beta\beta}\rangle_{90\% \text{ C.L.}} = 51 - 133$ meV

Projected

Surpass Cuoricino w/ ~1-yr data

arXiv:1109.0494


EPJC 74, 2956 (2014)
CUORE at LNGS

Gran Sasso National Laboratory

Average depth ~ 3600 m.w.e.

- $\mu$: $3 \times 10^{-8}$ $\mu$/s/cm$^2$
- $n < 10$ MeV: $4 \times 10^{-6}$ n/s/cm$^2$
- $\gamma < 3$ MeV: 0.73 $\gamma$/s/cm$^2$
CUORE

Top Floor

CUORE Hut

Class 1000 Clean Room for Detector Assembly and Storage
CUORE Suspension & Detector Systems
CUORE Cryostat

- Suspension
- Dilution unit
- Pulse tubes
- Roman lead ~6 tons
- TeO₂
- 300 K
- 40 K
- Motion boxes
- Lead shield
- Lead shield
- Guide tubes
- Bolometers @ ~10 mK
- Detector support plate
- Guide tubes
- 300 K
- 40 K
- 4 K
- 0.6 K
- 50 mK
- 10 mK

R. Maruyama (Yale): CUORE - DBD2014
Lowering Background: Shielding

- Improved shielding

  - Neutron shield (18 cm PET + 2cm of H$_3$BO$_3$)
  - External lead shield (thickness >35 cm)
  - Low-radioactivity copper for cryostat vessels and flanges
  - Internal lead shield (low-radioactivity/ancient lead)
Lowering Background: Crystals & Copper

**Ultra-pure TeO2 crystal array**

**Bulk activity** 90% C.L. upper limits:
8.4 \( \cdot \) 10\(^{-7}\) Bq/kg \(^{232}\)Th), 6.7 \( \cdot \) 10\(^{-7}\) Bq/kg \(^{238}\)U), 3.3 \( \cdot \) 10\(^{-6}\) Bq/kg \(^{210}\)Po

**Surface activity** 90% C.L. upper limits:
2 \( \cdot \) 10\(^{-9}\) Bq/cm\(^2\) \(^{232}\)Th), 1 \( \cdot \) 10\(^{-8}\) Bq/cm\(^2\) \(^{238}\)U), 1 \( \cdot \) 10\(^{-6}\) Bq/cm\(^2\) \(^{210}\)Po

- Crystal holder design optimized to reduce passive surfaces (Cu) facing the crystals
- Developed ultra-cleaning process for all Cu components:
  - Tumbling
  - Electropolishing
  - Chemical etching
  - Magnetron plasma etching
- Benchmarked in dedicated bolometer run at LNGS
  - Residual \(^{232}\)Th / \(^{238}\)U surface contamination of Cu: < 7 \( \cdot \) 10\(^{-8}\) Bq/cm\(^2\)
- Validated by CUORE-0
- All parts stored underground, under nitrogen after cleaning
Tower Assembly

Gluing

Tower Construction

Wire bonding

Before

After

NTD

Heater

Storage

Figure 7: Gluing photos for Crystal 80736, Tower 11, position: 2-FIORI
Detector Towers

Assembly of all 19+ towers is complete!
Cryogenic System & Commissioning

• Cryostat assembled, passed commissioning tests.

• Dilution unit delivered to LNGS, series of integration and commissioning runs being carried out to ensure full operation in 2015.

• Full integration of DU in cryostat ongoing
  • 6 mK stable base temperature achieved!
Status of CUORE
Status of CUORE: Cryogenics
Status of CUORE: Cryogenics

Commissioning Plan

**Phase I: 4K system check**
- Outer/Inner vacuum chamber test
- Cryogenic verification of detector calibration system
- Commissioning test of DU

**Phase II: full cryostat vessel check**
- Full assembly of cryostat
- Cool down of cryostat
- Integration of test tower, calibration system

Physics run start expected in 2015
The CUORE $0\nu\beta\beta$ Search

Cuoricino (2003-2008)

$T_{1/2}^{0\nu\beta\beta} > 2.8 \times 10^{24} \text{ y (90\% C.L.)}$

$\langle m_{\beta\beta}\rangle_{90\% \text{ C.L.}} = 300 - 710 \text{ meV}$


Surpass Cuoricino w/ ~1-yr data

CUORE-0 (2013-2015)

EPJC 74, 2956 (2014)

Projected

$T_{1/2}^{0\nu\beta\beta} > 9.5 \times 10^{25} \text{ yr (90\% C.L.)}$

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CUORE (2015-2020)

arXiv:1109.0494

R. Maruyama (Yale): CUORE - DBD2014
CUORE-0

- A single CUORE-like tower ~11 kg of $^{130}$Te running in CUORICINO shielding & cryostat since March 2013
- Goals:
  - Validate new cleaning and assembly procedures for CUORE
  - stand-alone DBD experiment
  - First results (Phase I data analysis) *EPJC 74, 2956 (2014).*
  - Phase II data w/ improved detector operation condition ongoing.
  - Expect to reach CUORICINO sens. with ~ 1yr lifetime (unblind early 2015)
CUORE-0 Energy Resolution

CUORE-0 Calibration Spectrum (Phase II)

- Total $^{232}$Th activity of 100 Bq via two thoriated wires outside the cryostat
- Improved detector operation in Phase II
  - CUORE goal of 5 keV FWHM near ROI achieved.
CUORE-0 Background Measurement

- α-dominated bkg: 6-fold reduction
  - Ultra-cleaning of CUORE-0 Cu surfaces
- 2.5-fold reduction of bkg in ROI
  - Stringent radon control in CUORE-0
- β/γ bkg from cryostat $^{232}$Th remains the same
- **Consistent with the Cuoricino bkg model**

<table>
<thead>
<tr>
<th></th>
<th>$^{0}\nu\beta\beta$ region [c/keV/kg/yr]</th>
<th>2700-3900 keV * [c/keV/kg/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUORICINO $\varepsilon=83%$</td>
<td>0.153 +/- 0.006</td>
<td>0.110 +/- 0.001</td>
</tr>
<tr>
<td>CUORE-0 $\varepsilon=78%$</td>
<td>0.063 +/- 0.006</td>
<td>0.020 +/- 0.001</td>
</tr>
</tbody>
</table>

* excluding the $^{190}$Pt peak region
CUORICINO Result


No evidence of neutrinoless double beta decay in $^{130}$Te.

Background: $0.169 \pm 0.006 \text{ counts/keV/kg/y}$

Half-life limit ($^{130}$Te) $\geq 2.8 \times 10^{24}$ y (90% C.L.)

Upper limit, Majorana mass: $m_{\nu_e} < 300 – 710$ meV

data: 2003 – 2008

19.75 kg-yr $^{130}$Te exposure

$Q_{\beta\beta}=2527.5$ keV

R. Maruyama (Yale): CUORE - DBD2014
CUORE-0 DBD Region

Blinded data

Salted Peak
NOT 0νDBD

Energy [keV]

Event Rate [counts/keV/kg/y]

Analysis improvements underway

- Noise reduction - decorrelation
  - see J. Ouellet’s talk: CM.00007 Wed Oct. 8 @ 8:45 PM
- heater-less gain stabilization
- calibration, pulse-shape, and multiplicity-cuts
- Low-energy PSA for dark matter searches
- background model

- Region of Interest was blinded by “salting”: exchange a small (and blinded) fraction of the events in $^{208}$Tl peak with events in the 0νDBD region to produce an artificial peak.

EpjC 74, 2956 (2014)

Unblinding in 2015
CUORE-0 Sensitivity

CUORE-0 expected to surpass Cuoricino at ~ 1 year of live time.

**CUORICINO vs. CUORE-0:** improved $\delta E$ & bgd

$\delta E$: 4.8 keV FWHM @ ROI

background: $0.063 \pm 0.006$ cnts/(keV·kg·yr)

EPJC 74, 2956 (2014)
Projected CUORE Background

- **CUORE-0** - provides benchmark for remaining background with new assembly & crystal/Cu cleaning protocols
- **CUORE** - results of CUORE-0 + screening campaign results -> CUORE MC

**CUORE Preliminary**

<table>
<thead>
<tr>
<th>Region</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near Surfaces:</td>
<td>TeO₂</td>
</tr>
<tr>
<td>Near Surfaces:</td>
<td>Cu NOSV or PTFE</td>
</tr>
<tr>
<td>Near Bulk:</td>
<td>TeO₂</td>
</tr>
<tr>
<td>Near Bulk:</td>
<td>Cu NOSV</td>
</tr>
<tr>
<td>Cosm. Activ.:</td>
<td>TeO₂</td>
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<tr>
<td>Cosm Activ:</td>
<td>Cu NOSV</td>
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<tr>
<td>Near Bulk:</td>
<td>small parts</td>
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<tr>
<td>Far Bulk:</td>
<td>COMETA Pb top</td>
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<td>Far Bulk:</td>
<td>Inner Roman Pb</td>
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<tr>
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<td>Steel parts</td>
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<td>Far Bulk:</td>
<td>Cu OFE</td>
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<td>muons</td>
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<tr>
<td>Environmental:</td>
<td>neutrons</td>
</tr>
<tr>
<td>Environmental:</td>
<td>gammas</td>
</tr>
</tbody>
</table>

Conservatively extrapolate measured α-region bkg from CUORE-0 assuming all bkg is from \(^{238}\text{U}/^{232}\text{Th}/^{210}\text{Po}\) individually

**CUORE-0 Background Spectrum (\(^{210}\text{Po}\) Line)**

- Bkg GOAL: 0.01 c/keV/kg/y
- 90% CL limit
- Full color area = value
- Dashed area = 90% CL upper limit
- Counts/ROI/ton/y (ROI ~ 5 keV)

Detailed studies of surface vs. bulk contamination underway

Work in progress w/ improved α resolution
CUORE Sensitivity

- CUORE sensitivity goal:
  - $T_{1/2}^{\nu\beta\beta} > 9.5 \times 10^{25}\text{ yr} @ 90\% \text{ C.L.}$

- Effective Majorana mass 51 - 133 meV @ 90\% C.L.
  - Assumptions: 5 keV FWHM ROI resolution (δE), background rate (b) of 0.01 counts/(keV·kg·yr), 5 years of live time.

arXiv:1109.0494
The CUORE 0νββ Search

CUORE Program

- CUORICINO (2003-2008)
- CUORE-0 (2013-2015)
- CUORE (2015-2020)

Theoretical Aspects

- Bolometers

Andrea Giachero (Andrea.Giachero@mib.infn.it)

The status of the CUORE experiment

NPA5 2011, April 5th, 2011

90% C.L. = 300 - 710 meV

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- EPJC 74, 2956 (2014)

Projected

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arXiv:1109.0494

R. Maruyama (Yale): CUORE - DBD2014
R&D for Future Bolometric 0νββ Searches

- Increase mass: enrich in $^{130}$Te
  - B. Wang’s talk: DM.00009, Thurs., Oct. 9, 11 AM
- Reduce background via particle ID
  - e.g. LUCIFER: L. Pattavina’s talk 2WM.00005 Tues., Oct. 7, 4PM
- Cleaner detectors, tag backgrounds, active veto
- Explore other/multiple isotopes

Bolometer R&D:
- CALDER
- Cherenkov/TeO$_2$
- LUCIFER
- LUMINEU
Summary

• CUORE builds on the success of CUORICINO and its predecessors
• CUORE-0 has been running since March 2013. It demonstrates:
  • successful background mitigation and confirms the Cuoricino background model
  • Goal of < 5 keV FWHM for ROI energy resolution reached
  • further analysis underway.
• CUORE tower assembly is complete and cryogenic system commissioning is underway.
• Physics data taking expected to start in late 2015.
• R&D effort is underway for 0νββ search beyond CUORE.
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Other talks at this meeting -
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- B. Wang: DM.00009, Thurs., Oct. 9, 11 AM
- L. Pattavina: 2WM.00005 Tues., Oct. 7, 4PM