Topological detection of $\beta\beta$-decay with NEMO-3 and SuperNEMO

Motivation and Concept
- $\beta\beta$-decay and New Physics
- Experimental approaches

NEMO-3
- Detector
- Results

SuperNEMO
- Physics reach
- R&D results
- Demonstrator
- Schedule

Ruben Saakyan
University College London
Particle Physics Seminar
University of Birmingham
25 January 2012
Neutrinos are massive and they mix

PMNS matrix

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\times
\begin{pmatrix}
\cos \theta_{13} & 0 & e^{-i\delta_{\text{CP}}} \sin \theta_{13} \\
0 & 1 & 0 \\
-e^{i\delta_{\text{CP}}} \sin \theta_{13} & 0 & \cos \theta_{13}
\end{pmatrix}
\times
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\times
\begin{pmatrix}
1 & 0 & 0 \\
0 & 0 & e^{i\alpha/2} \\
0 & e^{i\alpha/2+\beta} & 0
\end{pmatrix}
\]

\[\Delta m_{23}^2 = \Delta m_{\text{atm}}^2 = 2.3 \times 10^{-3} \text{eV}^2\]
\[\theta_{23} \approx 45^\circ \text{ (maximal?)}\]
\[\theta_{13} < 11^\circ \text{ (early indications 5\^\circ - 11^\circ?)}\]
\[\Delta m_{12}^2 = \Delta m_{\text{sol}}^2 \approx 7.7 \times 10^{-5} \text{eV}^2\]
\[\theta_{23} \approx 34^\circ\]

Different from quark sector. Can CP-violation in lepton sector address matter-antimatter puzzle?

Plots: Courtesy of MINOS collaboration
Key Questions to Answer

- Number of neutrinos: Are there sterile neutrinos?
- $\theta_{13}$ (first hints from T2K and reactors?),
  Precision values of mixing angles and $\Delta m^2$’s
- Absolute neutrino mass value. Only limits so far.
  Tritium: $m_{\nu_e} < 2.3$ eV
  Cosmology: $\sum m_{\nu_i} < 1$ eV
- Neutrino mass spectrum: Normal ($m_1 < m_2 < m_3$)
  Inverted ($m_3 < m_1 < m_2$) or Quasi-degenerate ($m_1 \approx m_2 \approx m_3$)?
- Origin of matter-antimatter asymmetry.
  CP-violation in lepton sector: $\delta \neq 0, \pi$ and/or $\alpha, \beta \neq 0, \pi$?
- Nature of Neutrinos: Majorana ($\nu = \text{anti-}\nu$) or Dirac ($\nu \neq \text{anti-}\nu$)?
  Full lepton number violation (required in most Grand Unification Theories).

addressed by $0\nu\beta\beta$ decay
Nature of Neutrinos: Majorana ($\nu = \text{anti-}\nu$) or Dirac ($\nu \neq \text{anti-}\nu$)?

$\Delta L \neq 0$  $\Delta L = 0$

Directly related to fundamental symmetries of particle interactions

Provides important information on origin of neutrino mass

SEE-SAW

$$m_\nu \equiv m^L_M = \frac{m^2_D}{M} << m_D$$

To obtain $m_3 \sim (\Delta m^2_{\text{atm}})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{15}\text{GeV}$ (GUT!)

Lepton number violation is one of the key ingredients of leptogenesis as the mechanism to generate the baryon asymmetry of the Universe.

More matter than anti-matter!
Double Beta Decay in the Standard Model
(Goeppert-Mayer, 1935)

Recall pairing term in SEMF

\[ \frac{1}{T_{1/2}^{2\nu}} = G^{2\nu}(Q_{\beta\beta}, Z) |M^{2\nu}|^2 \]

- NME: Nasty Nuclear Matrix Element

\( M(A,Z) > M(A,Z+2) \)
\( Q_{\beta\beta} = M(A,Z) - M(A,Z+2) \)

NME is measured in \( 2\nu\beta\beta \)

- Second order process ⇒ rare (~\(10^{19}-10^{21}\) yr)
- Nevertheless observed for 11 nuclei
- Experimental input for NME calculation
Double Beta Decay Beyond the Standard Model

□ Neutrinoless Double Beta Decay (Furry, 1939).

\[
\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q_{\beta\beta}, Z) |M^{0\nu}|^2 \eta^2
\]

\[\Delta L = 2!\]

Lepton number violating parameter

\[\eta \text{ can be due to } \langle m_\nu \rangle, V+A, \text{ Majoron, SUSY, } H^- \text{ or a combination of them}\]

“Minimal” scenario - light Majorana mass

\[\langle m_\nu \rangle = \left| \sum U_{ei}^2 m_i \right| = |U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha_{21}} + U_{e3}^2 m_3 e^{i\alpha_{31}}|\]

Coherent sum over neutrino amplitudes
Double Beta Decay. What is measured?

\[(E_1 + E_2) \in \left[ 0, Q_{\beta\beta} \right]\]

\[\frac{(E_1 + E_2)}{Q_{\beta\beta}} \approx 1\]

[⊗ resolution]
Double Beta Decay. Isotope Candidates.

Over 40 nuclei can undergo $\beta\beta$-decay (including $\beta^+\beta^+$ and 2K-capture)
Only ~10 experimentally feasible

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Nat. Abundance (%)</th>
<th>Phase Space*, $G^{0\nu}\times10^{-15}\text{yr}^{-1}$</th>
<th>$Q_{\beta\beta}$ (MeV)</th>
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<tbody>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>0.187</td>
<td>75.8</td>
<td>4.274</td>
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<td>$^{76}\text{Ge}$</td>
<td>7.8</td>
<td>7.6</td>
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<td>$^{96}\text{Zr}$</td>
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<td>69.7</td>
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<td>$^{100}\text{Mo}$</td>
<td>9.6</td>
<td>54.5</td>
<td>3.035</td>
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<td>$^{116}\text{Cd}$</td>
<td>7.6</td>
<td>58.9</td>
<td>2.809</td>
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<td>$^{130}\text{Te}$</td>
<td>34.5</td>
<td>52.8</td>
<td>2.530</td>
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<td>$^{136}\text{Xe}$</td>
<td>8.9</td>
<td>56.3</td>
<td>2.462</td>
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<tr>
<td>$^{150}\text{Nd}$</td>
<td>5.6</td>
<td>249</td>
<td>3.367</td>
</tr>
</tbody>
</table>


more energetic decay : easier to separate from background

Isotope choice

- $Q_{\beta\beta}$
- $T_{1/2}(2\nu)$ (the longer the better)
- Isotope abundance
- Enrichment opportunities
- NME - Input from 2$\nu$ measurements is useful
- Phase space

enrichment often possible, always expensive!
Sensitivity Milestones

“Immediate” Future: $\sim$0.1 eV to check K-K claim

Next step $\langle m_\nu \rangle \sim \sqrt{\Delta m^2_{atm}} \sim 0.05$ eV

And then $\sim$ 0.01 eV to cover I.H.
Experimental Sensitivity

\[ T_{1/2}^{0\nu} \left( 90\% \ C.L. \right) = 2.54 \times 10^{26} \text{y} \left( \frac{\varepsilon \times a}{W} \right) \sqrt{\frac{M \times t}{b \times \Delta E}} \]

- **maximise** efficiency & isotope abundance
- **maximise** exposure = mass \( \times \) time
- **minimise** background & energy resolution

\[ T_{1/2}^{0\nu} \propto \sqrt{M \times t} \]
\[ \langle m_\nu \rangle \propto (M \times t)^{1/4} \]
gets tedious pretty quickly …

\[ \beta \beta \text{ is about background suppression!} \]
Experimental Approaches

Calorimeter-only. **Source = Detector**

- Main observable: Deposited energy
- Excellent $\Delta E/E$
- High efficiency
- Relatively compact
- Some particle ID capability

Main limiting factor: background

HPGe, Bolometers, (Liquid)-Scintillators, LXe.

Tracking + Calorimetry. **Source ≠ Detector**

(ala NEMO3 and SuperNEMO)

- Strong background suppression and control
- “Smoking gun” $0\nu\beta\beta$ signature. Any isotope can be studied.
- Sensitivity to different physics mechanisms of $0\nu\beta\beta$
- Main limiting factor: efficiency

Full Topology Reconstruction

R&D on technologies that include elements of both CdZnTe, HPXe TPC
A take-away message

• We need to measure different isotopes with different experimental approaches
  – NME uncertainties
  – Tiny signal - Huge Background. Will you ever trust a single positive measurement?
  – Disentangle underlying physics mechanism

We need Diversity
...and we have it!

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Isotope(s)</th>
<th>Technique</th>
<th>Main characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEMO-3</td>
<td>$^{100}$Mo, $^{82}$Se, other</td>
<td>Tracking + calorimeter</td>
<td>Bckg rejection, isotope choice, topology</td>
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<tr>
<td>SuperNEMO</td>
<td>$^{82}$Se, $^{150}$Nd, other</td>
<td>Tracking + calorimeter</td>
<td>Bckg rejection, isotope choice, topology</td>
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<td>Cuoricino</td>
<td>$^{130}$Te</td>
<td>Bolometers</td>
<td>Energy resolution, efficiency</td>
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<td>CUORE</td>
<td>$^{130}$Te</td>
<td>Bolometers</td>
<td>Energy resolution, efficiency</td>
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<tr>
<td>GERDA</td>
<td>$^{76}$Ge</td>
<td>Ge diodes</td>
<td>Energy resolution, efficiency</td>
</tr>
<tr>
<td>Majorana</td>
<td>$^{76}$Ge</td>
<td>Ge diodes</td>
<td>Energy resolution, efficiency</td>
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<td>COBRA</td>
<td>$^{130}$Te, $^{116}$Cd</td>
<td>CdZnTe semi-conductors</td>
<td>Efficiency, particle ID</td>
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<tr>
<td>EXO</td>
<td>$^{136}$Xe</td>
<td>TPC ionisation + scintillation</td>
<td>Mass, efficiency, particle ID</td>
</tr>
<tr>
<td>MOON</td>
<td>$^{100}$Mo</td>
<td>Tracking + calorimeter</td>
<td>Compactness, Bckg rejection</td>
</tr>
<tr>
<td>CANDLES</td>
<td>$^{48}$Ca</td>
<td>CaF$_2$ scintillating crystals</td>
<td>Efficiency, Active background vetoing</td>
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<tr>
<td>SNO++</td>
<td>$^{150}$Nd</td>
<td>Nd loaded liquid scintillator</td>
<td>Mass, efficiency</td>
</tr>
<tr>
<td>XMASS</td>
<td>$^{136}$Xe</td>
<td>Liquid Xe</td>
<td>Mass, efficiency</td>
</tr>
<tr>
<td>CARVEL</td>
<td>$^{48}$Ca</td>
<td>CaWO$_4$ scintillating crystals</td>
<td>Mass, efficiency</td>
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<td>Yangyang</td>
<td>$^{124}$Sn</td>
<td>Sn loaded liquid scintillator</td>
<td>Mass, efficiency</td>
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<td>DCBA</td>
<td>$^{150}$Nd</td>
<td>Gaseous TPC</td>
<td>Bckg rejection</td>
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<td>KamLAND-Zen</td>
<td>$^{136}$Xe</td>
<td>Xenon balloon</td>
<td>Mass, efficiency</td>
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<tr>
<td>NEXT</td>
<td>$^{136}$Xe</td>
<td>Gaseous TPC</td>
<td>Bckg rejection, efficiency</td>
</tr>
</tbody>
</table>
NEMO-3 and SuperNEMO

Unique Detection principle: reconstruct topological signature

- Reconstruct two electrons in the final state ($E_1 + E_2 = Q_{\beta\beta}$)
- Measure several final state observables
  - Individual electron energies
  - Electron trajectories and vertices
  - Time of flight
  - Angular distribution between electrons
- Powerful Background rejection through particle ID: $e^-, e^+, \alpha, \gamma$

⇒ “Smoking gun” evidence for 0νββ
⇒ Open-minded search for any lepton violating process
⇒ Possibility to disentangle underlying physics mechanism
Topology reconstruction: Open-minded search for any 0νββ mechanism

\[ \langle m_\nu \rangle \]

\[ V+A \]

Majoron emission

\[ \Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}_0 |M^{0\nu}|^2 \chi^2 \]

Topology detection is a more sensitive method for phenomena with continuous spectra, e.g. 2νββ, 0νββχ (Majoron)

\[ \Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}_0 |M^{0\nu}|^2 \lambda^{2}_{V+A} \]

Topology can be used to disentangle underlying physics mechanism
Neutrino Ettore Majorana Observatory 3

Data taking: Feb’03 - Jan’11

Laboratoire Souterrain de Modane (LSM)
Modane, France
(Tunnel Frejus, depth of ~4,800 mwe)

> $10^6$ suppression factor for cosmic muons!
NEMO-3 - 20 sectors with ~10 kg of isotopes

- Magnetic field: 25 Gauss
- Gamma shield: 18 cm of pure iron
- Neutron shield:
  - 30cm borated water (external wall)
  - 40cm wood (top and bottom)
- Anti-Radon “factory” and “tent”

\[^{100}\text{Mo} \quad 6.914 \text{ kg} \quad Q_{\beta\beta} = 3034 \text{ keV}\]

\[^{82}\text{Se} \quad 0.932 \text{ kg} \quad Q_{\beta\beta} = 2995 \text{ keV}\]

\[^{116}\text{Cd} \quad 405 \text{ g} \quad Q_{\beta\beta} = 2805 \text{ keV}\]

\[^{96}\text{Zr} \quad 9.4 \text{ g} \quad Q_{\beta\beta} = 3350 \text{ keV}\]

\[^{150}\text{Nd} \quad 37.0 \text{ g} \quad Q_{\beta\beta} = 3367 \text{ keV}\]

\[^{48}\text{Ca} \quad 7.0 \text{ g} \quad Q_{\beta\beta} = 4272 \text{ keV}\]

\[^{130}\text{Te} \quad 454 \text{ g} \quad Q_{\beta\beta} = 2529 \text{ keV}\]

\[^{\text{nat}}\text{Te} \quad 491 \text{ g}\]

\[\text{Cu} \quad 621 \text{ g}\]
NEMO-3 design

• Tracker for full event reconstruction
  – 6180 drift cells in Geiger mode:
    Helium + 4% ethyl alcohol + 1% Ar + 0.1% H₂O

• Calorimeter for energy and time measurement
  – 1940 scintillator blocks coupled to low radioactivity PMTs

• Identify e⁻, e⁺, γ, α

• Identify external and internal events
NEMO-3 $\beta\beta$ event selection

Deposited energy:
$E_1 + E_2 = 2088$ keV

Internal hypothesis:
$(\Delta t)_{\text{mes}} - (\Delta t)_{\text{theo}} = 0.22$ ns

Common vertex:
$(\Delta \text{vertex})_\perp = 2.1$ mm

1 $\beta\beta$ event every 2.5 minutes!
(in $^{100}$Mo)

- 2 tracks with charge < 0
- 2 PMT, each > 200 keV
- PMT-Track association
- Common vertex
- Internal hypothesis (external event rejection)
- No other isolated PMT ($\gamma$ rejection)
- No delayed track ($^{214}$Bi rejection)
Background: The Enemy and how to fight it
**External γ** (if the γ is not detected in the scintillators)

Origin: natural radioactivity of the detector or neutrons
Major bkg for 2νββ but small for 0νββ

\((^{100}\text{Mo} \text{ and } ^{82}\text{Se} \ Q_{\beta\beta} \sim 3 \text{ MeV} > E_\gamma^{(^{208}\text{TI})} \sim 2.6 \text{ MeV})\)
**Background: The Enemy and how to fight it**

- **External γ** (if the γ is not detected in the scintillators)
  Origin: natural radioactivity of the detector or neutrons
  Major bkg for 2νββ but small for 0νββ
  
  \[(^{100}\text{Mo} \text{ and } ^{82}\text{Se}) \ Q_{\beta\beta} \approx 3 \text{ MeV} > E_{\gamma} (^{208}\text{Tl}) \approx 2.6 \text{ MeV} \]

- \(^{232}\text{Th} (^{208}\text{Tl})\) and \(^{238}\text{U} (^{214}\text{Bi})\) contamination inside the ββ source foil
Background: The Enemy and how to fight it

- **External** γ (if the γ is not detected in the scintillators)
  
  Origin: natural radioactivity of the detector or neutrons
  
  Major bkg for 2νββ but small for 0νββ
  
  \( ^{100}\text{Mo} \) and \(^{82}\text{Se} \) \( Q_{\beta\beta} \sim 3 \text{ MeV} > E_{\gamma}(^{208}\text{Tl}) \sim 2.6 \text{ MeV} \)

- **\(^{232}\text{Th} (^{208}\text{Tl}) \) and \(^{238}\text{U} (^{214}\text{Bi}) \) contamination inside the ββ source foil**

- **Radon (\(^{214}\text{Bi}\)) inside the tracking detector**
  
  - deposits on the wire near the ββ foil
  
  - deposits on the surface of the ββ foil
Background: The Enemy and how to fight it

- **External** $\gamma$ (if the $\gamma$ is not detected in the scintillators)
  
  Origin: natural radioactivity of the detector or neutrons
  
  Major bkg for $2\nu\beta\beta$ but small for $0\nu\beta\beta$
  
  $^{100}\text{Mo}$ and $^{82}\text{Se}$ $Q_{\beta\beta} \sim 3$ MeV > $E_{\gamma}(^{208}\text{Tl}) \sim 2.6$ MeV

- $^{232}\text{Th}$ ($^{208}\text{Tl}$) and $^{238}\text{U}$ ($^{214}\text{Bi}$) contamination inside the $\beta\beta$ source foil

- Radon ($^{214}\text{Bi}$) inside the tracking detector
  
  - deposits on the wire near the $\beta\beta$ foil
  
  - deposits on the surface of the $\beta\beta$ foil

Each bkg is measured using the NEMO-3 data
**Pure sample of $^{214}\text{Bi} - ^{214}\text{Po}$ events**

$^{214}\text{Bi} \xrightarrow{\beta} ^{214}\text{Po} \xrightarrow{\alpha} ^{210}\text{Pb}$

Delay time of the $\alpha$ track ($\mu$s)

$T_{1/2} = 162.9 \, \mu$s
Anti-radon “factory” - trapping Rn in cooled charcoal. A must for a low-background lab.

Measurements of $^{222}$Rn activity in the gas of tracker (mBq/m$^3$)

Pure sample of $^{214}$Bi – $^{214}$Po events

$T_{1/2} = 162.9 \, \mu$s

Delay time of the $\alpha$ track ($\mu$s)

Anti-Rn factory: Input=15Bq/m$^3$ → Output 15mBq/m$^3$

Inside the detector:

- Phase 1: Feb’03 → Sep’04
  $A$(Radon) ≈ 40 mBq/m$^3$

- Phase 2: Dec. 2004 → Jan’11
  $A$ (Radon) ≈ 5 mBq/m$^3$
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  $A$(Radon) ≈ 5 mBq/m$^3$

"Handbook" on backgrounds for $\beta\beta$ experiments:
NEMO-3 latest results (2011)

661 g of $^{130}$Te

$T^{2\nu}_{1/2} = [7.0 \pm 0.9\,(stat) \pm 1.1\,(syst)] \times 10^{20}$ yr

*Phys. Rev. Lett. 107, 062504 (2011)*

c.f.

Indirect observations (geochemistry):
- $\sim 2.7 \times 10^{21}$ yrs in $10^9$ yr old rocks
- $\sim 8 \times 10^{20}$ yrs in $10^7$-$10^8$ yr old rocks

Indication from MIBETA

$T^{2\nu}_{1/2} = [6.1 \pm 1.4\,(stat)^+2.9_{-3.5}\,(syst)] \times 10^{20}$ yr

1275 days

$N(2\nu\beta\beta) = 178 \pm 23$
## 2νββ Results

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Mass (g)</th>
<th>$Q_{\beta\beta}$ (keV)</th>
<th>$T_{1/2}$(2ν) (10$^{19}$yrs)</th>
<th>S/B</th>
<th>Comment</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>$^{82}$Se</td>
<td>932</td>
<td>2996</td>
<td>9.6 ± 1.0</td>
<td>4</td>
<td>World’s best</td>
<td>Phys. Rev. Lett. 95(2005) 483</td>
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<tr>
<td>$^{116}$Cd</td>
<td>405</td>
<td>2809</td>
<td>2.8 ± 0.3</td>
<td>10</td>
<td>World’s best</td>
<td>Phys. Rev. C 80, 032501 (2009)</td>
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<tr>
<td>$^{150}$Nd</td>
<td>37</td>
<td>3367</td>
<td>0.9 ± 0.07</td>
<td>2.7</td>
<td>World’s best</td>
<td>Nucl. Phys. A 847(2010) 168</td>
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<tr>
<td>$^{96}$Zr</td>
<td>9.4</td>
<td>3350</td>
<td>2.35 ± 0.21</td>
<td>1</td>
<td>World’s best</td>
<td>Phys. Rev. Lett. 95(2005) 483</td>
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<tr>
<td>$^{48}$Ca</td>
<td>7</td>
<td>4271</td>
<td>4.4 ± 0.6</td>
<td>6.8 (h.e.)</td>
<td>World’s best</td>
<td>Phys. Rev. Lett. 107, 062504 (2011)</td>
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<tr>
<td>$^{100}$Mo</td>
<td>6914</td>
<td>3034</td>
<td>0.71 ± 0.05</td>
<td>80</td>
<td>World’s best</td>
<td></td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>454</td>
<td>2533</td>
<td>70 ± 14</td>
<td>0.5</td>
<td>First direct detection</td>
<td></td>
</tr>
</tbody>
</table>

### Unprecedented accuracy with $^{100}$Mo

- Crucial experimental input for 1) NME calculations
- 2) Ultimate background characterisation for 0ν

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Favor SSD
Search for $0\nu\beta\beta$

Data period: Feb’03 - Dec’09

$^{100}\text{Mo}$: 7kg $\times$ 4.5 years

$^{82}\text{Se}$: 1kg $\times$ 4.5 years

$[2.8-3.2]$ MeV: DATA = 18; MC = 16.4$\pm$1.4

$T_{1/2}(0\nu) > 1.0\times10^{24} \text{ yr at 90}\%\text{CL}$

$<m_\nu> < (0.31 - 0.96) \text{ eV}$

$[2.6-3.2]$ MeV: DATA = 14; MC = 10.9$\pm$1.3

$T_{1/2}(0\nu) > 3.2\times10^{23} \text{ yr at 90}\%\text{CL}$

$<m_\nu> < (0.94 - 2.6) \text{ eV}$

c.f. CUORICINO: $<m_\nu> < (0.3 - 0.7) \text{ eV}$; Combined H-M/IGEX $<m_\nu> < (0.22 - 0.41) \text{ eV}$
Other $0\nu\beta\beta$ modes

Majoron emission would distort the shape of the energy sum spectrum

<table>
<thead>
<tr>
<th></th>
<th>V+A*</th>
<th>n=1**</th>
<th>n=2**</th>
<th>n=3**</th>
<th>n=7**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo</td>
<td>$&gt;5.7\cdot10^{23}$</td>
<td>$&gt;2.7\cdot10^{22}$</td>
<td>$&gt;1.7\cdot10^{22}$</td>
<td>$&gt;1.0\cdot10^{22}$</td>
<td>$&gt;7\cdot10^{19}$</td>
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<td></td>
<td>$\lambda&lt; 1.4\cdot10^{-6}$</td>
<td>$G_e&lt; (0.4-1.8)\cdot10^{-4}$</td>
<td>$&gt;6\cdot10^{21}$</td>
<td>$&gt;3.1\cdot10^{21}$</td>
<td>$&gt;5\cdot10^{20}$</td>
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<tr>
<td>Se</td>
<td>$&gt;2.4\cdot10^{23}$</td>
<td>$&gt;1.5\cdot10^{22}$</td>
<td>$&gt;6\cdot10^{21}$</td>
<td>$&gt;3.1\cdot10^{21}$</td>
<td>$&gt;5\cdot10^{20}$</td>
</tr>
<tr>
<td></td>
<td>$\lambda&lt; 2.0\cdot10^{-6}$</td>
<td>$G_e&lt; (0.7-1.9)\cdot10^{-4}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

n: spectral index, limits on half-life in years  
* Phase I+Phase II data (including 2008)  

World’s best

$\beta\beta$ decays to excited states

$T_{1/2}^{2\nu}(0^+ \rightarrow 0^{+1}) = 5.7^{+1.3}_{-0.9} \text{ (stat)} \pm 0.8 \text{ (syst)} \times 10^{20} \text{ y}$

$T_{1/2}^{0\nu}(0^+ \rightarrow 0^{+1}) > 8.9 \times 10^{22} \text{ y} @ 90\% \text{ C.L.}$

$T_{1/2}^{2\nu}(0^+ \rightarrow 2^{+1}) > 1.1 \times 10^{21} \text{ y} @ 90\% \text{ C.L.}$

$T_{1/2}^{0\nu}(0^+ \rightarrow 2^{+1}) > 1.6 \times 10^{23} \text{ y} @ 90\% \text{ C.L.}$

From NEMO-3 to SuperNEMO

<table>
<thead>
<tr>
<th>NEMO-3</th>
<th>SuperNEMO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>100Mo</strong></td>
<td><strong>82Se (or 150Nd or 48Ca)</strong></td>
</tr>
<tr>
<td><strong>7 kg</strong></td>
<td><strong>100+ kg</strong></td>
</tr>
<tr>
<td><strong>208Tl</strong>: ~ 100 µBq/kg</td>
<td><strong>208Tl ≤ 2 µBq/kg</strong></td>
</tr>
<tr>
<td><strong>214Bi</strong>: &lt; 300 µBq/kg</td>
<td><strong>214Bi ≤ 10 µBq/kg</strong></td>
</tr>
<tr>
<td><strong>Rn</strong>: 5 mBq/m³</td>
<td><strong>Rn ≤ 0.15 mBq/m³</strong></td>
</tr>
<tr>
<td>8% @ 3 MeV</td>
<td>4% @ 3 MeV</td>
</tr>
<tr>
<td>$T_{1/2}(\beta\beta0ν) &gt; 1 \div 2 \times 10^{24}$ y</td>
<td>$T_{1/2}(\beta\beta0ν) &gt; 1 \times 10^{26}$ y</td>
</tr>
<tr>
<td>$&lt;m_\nu&gt; &lt; 0.3 - 0.9$ eV</td>
<td>$&lt;m_\nu&gt; &lt; 0.04 - 0.1$ eV</td>
</tr>
</tbody>
</table>

R&D since 2006

- Isotope
- Isotope mass M
- Contaminations in the $\beta\beta$ foil
- Rn in the tracker
- Calorimeter energy resolution (FWHM)
- Sensitivity
• Modular design
  • 20 modules, each with 5kg of isotope

• Each Module:
  • Source: (40mg/cm²) 4x2.7m²
    • $^{82}$Se (High Q$_{\beta\beta}$, long T$_{1/2}(2\nu)$, proven enrichment technology)
    • $^{150}$Nd, $^{48}$Ca being looked at
  • Tracking
    • drift chamber ~2000 cells in Geiger mode
  • Calorimeter:
    • 550 PMTs + scintillators
  • Module surrounded by passive shielding (water)
SuperNEMO Physics Studies

Full chain of GEANT-4 based software + detector effects + backgrounds + **NEMO3 experience**

5 yr with 100kg of $^{82}$Se:

$T_{1/2} > 10^{26}$ yr, $<m_\nu> < 50-100$ meV at 90% CL

with target detector parameters

Much more than 1 result!

- Other mechanisms: V+A, Majoron, etc
- Disentangling $<m_\nu>$ and V+A

“Probing new physics models of 0$\nu$ββ with SuperNEMO”, EPJ C (2010) 70, 972-943. (next slide)

- $\beta\beta 0\nu$(and 2$\nu$) to excited states
- Other isotopes
Multi-parameter analysis with SuperNEMO. $\langle m_\nu \rangle$ vs V+A mechanism.

“Probing new physics models of $0\nu\beta\beta$ with SuperNEMO”, EPJ C (2010) 70, pp. 972-943.

Exploit topological reconstruction available in SuperNEMO (angular distributions and individual electron energies) to disentangle/constrain new physics

If K-K claim is correct, O(100) events with virtually no background (2-3 expected BG events)
Main Calorimeter Wall

$\Delta E/E \sim 7.2\%$ (FWHM) at 1 MeV equiv. to $4\%$ @ $Q_{\beta\beta} = 3$ MeV

Target resolution has been reached with hexagonal and cubic blocks.

8” High-QE PMT: Hamamatsu R5912MOD
SuperNEMO Tracker

- Automated wiring robot design to mass produce under ultra low background conditions
  - 500,000 wires to be strung, crimped and terminated
- Basic design developed and verified with several prototypes
  - Resolution: 0.7mm transverse, 1cm longitudinal
  - Cell efficiency > 98%
- Readout electronic being developed:
  - Allow for single and double-cathode readout
  - Differentiate anode signal
Source Radiopurity

- ~2.7m “composite” foil strips of 40-50 mg/cm² (~80 µm)
- Radiopurity (82Se)
  - 208Tl < 2 µBq/kg
  - 214Bi < 10 µBq/kg

HPGe detectors are used for screening but not sufficient to reach required levels

Dedicated BiPo detector developed and installed in Canfranc (running in 2012)
Radon activity measurement

**Requirement:** Rn activity inside tracker < 150 µBq/m³

- Measurements of Rn emanation from materials
- Rn permeability measurements through membranes/seals

**Radon Concentration Line sensitivity < 50 µBq/m³ (90%CL)**
SuperNEMO Demonstrator

**Technology**
Ultimate proof of BG levels

**Physics**
Sensitive to K-K claim

7kg of $^{82}$Se (5 kg in hand)
Bgrd $\leq 0.06$ events/yr in the RoI

**A Zero-Background Experiment**

$$T_{1/2}^{0v} (90\%CL) = 2.56 \times 10^{24} \times t \text{ yrs}$$

Gerda-I sensitivity in 2.5 years -
6.5$\times 10^{24}$ yr (equivalent to 3$\times 10^{25}$yr with $^{76}$Ge)
SuperNEMO Demonstrator Construction has started

Construction of optical modules for tracker frame

Assembly hall prepared for tracker integration and commissioning

NEMO3 dismantled and removed to free underground space at LSM for Demonstrator
SuperNEMO Schedule

- Demonstrator Module construction and commissioning
- Demonstrator running
- K-K claim probed
- Installation in LSM
- Construction, deployment and running successive SuperNEMO modules
- Continuous operation of ≥1 SuperNEMO module

SuperNEMO in planned LSM extension

Modularity of SuperNEMO makes distributed location in different underground labs possible and even beneficial (provided resources availability).
# Figure of Merit

\[
T_{1/2}^{0\nu} (90\%CL) = 2.54 \times 10^{26} y \left( \frac{\varepsilon}{W} \right) \sqrt{\frac{M \times t}{b \times \Delta E}}
\]

\[
FOM = T_{1/2}^{0\nu} (90\%CL) \times \frac{G^{0\nu}}{G^{0\nu}_{76\text{Ge}}}
\]

Phase-space factor normalised to $^{76}\text{Ge}$

Normalised to exposure 500 kg yr and assuming the same NMEs

<table>
<thead>
<tr>
<th>Project</th>
<th>Isotope</th>
<th>$\varepsilon$ in $Q_{\beta\beta}$ window</th>
<th>$b$ [cnts kg$^{-1}$ keV$^{-1}$ yr$^{-1}$]</th>
<th>FWHM keV</th>
<th>Total B, counts</th>
<th>$T_{1/2}$ (90%CL) yr</th>
<th>$\frac{G^{0\nu}}{G^{0\nu}_{76\text{Ge}}}$</th>
<th>F.O.M yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>GERDA</td>
<td>$^{76}\text{Ge}$</td>
<td>80%</td>
<td>0.01</td>
<td>4</td>
<td>40</td>
<td>2.1×10$^{26}$</td>
<td>1</td>
<td>2.1×10$^{26}$</td>
</tr>
<tr>
<td>Super-NEMO</td>
<td>$^{82}\text{Se}$</td>
<td>17%</td>
<td>$6\times10^{-5}$</td>
<td>120</td>
<td>7</td>
<td>1×10$^{26}$</td>
<td>4.4</td>
<td>4.4×10$^{26}$</td>
</tr>
<tr>
<td>CUORE</td>
<td>$^{130}\text{Te}$</td>
<td>80%</td>
<td>0.01</td>
<td>5</td>
<td>185</td>
<td>5.7×10$^{25}$</td>
<td>6.9</td>
<td>4×10$^{26}$</td>
</tr>
<tr>
<td>EXO200</td>
<td>$^{136}\text{Xe}$</td>
<td>70%</td>
<td>$6.3\times10^{-4}$</td>
<td>94</td>
<td>73</td>
<td>7.6×10$^{25}$</td>
<td>7.4</td>
<td>5.6×10$^{26}$</td>
</tr>
<tr>
<td>SNO+</td>
<td>$^{150}\text{Nd}$</td>
<td>70%</td>
<td>$7.5\times10^{-4}$</td>
<td>300</td>
<td>3996</td>
<td>9.4×10$^{24}$</td>
<td>32.8</td>
<td>3.1×10$^{26}$</td>
</tr>
</tbody>
</table>

Reliability of expected performance numbers is not taken into account
Ton-experiment, 10 meV and other speculations

- O(100kg) generation will reach FOM \( \sim 4 \times 10^{26}\) yr by 2018-2020. \(<m_v> = 50-100\) meV
- To exclude IH, i.e. to get 10-20 meV, we need FOM = \(\sim 10^{28}\) yr.
- Example: A \(^{76}\)Ge experiment even with ambitious \(b = 0.001\) cnts/(kg keV yr) would need 30 tons (!) of enriched (!!) \(^{76}\)Ge measured over 5yr! Similar for other projects.
- Thus for 10 meV stage we have to find a "background-free" solution

- Example: \(150\)kg x 5 yrs of \(^{48}\)Ca, if no background and \(\varepsilon \sim 40\%\), gives required FOM = \(10^{28}\) yr.
  - NEMO-3 had virtually no background in this region after 8 years of running!
  - But we need to learn how to enrich \(^{48}\)Ca (0.19% nat. abundance)

Future “Ton” experiments

\(^{222}\)Rn poses serious challenge
(How to control \(\sim 1\) atom/N\(\times\)m\(^3\) contamination?)
Future may belong to “Big Three”

\(^{48}\)Ca 4.27 MeV
\(^{96}\)Zr 3.4 MeV
\(^{150}\)Nd 3.4 MeV

\(^{214}\)Bi 3.27 MeV

\(T_{1/2}^{0\nu} \propto \sqrt{M \times t}\)
\(\langle m_v \rangle \propto (M \times t)^{1/4}\)
• **0νββ** is the **only way** to answer questions on Full **Lepton Number violation** and nature and **mechanism** behind **neutrino mass**

• Reach **interplay** with **other areas**
  – Neutrino mass from end-point β-decay, cosmology, neutrino oscillations

• Several next generation experiments **starting** in the **next few years**
  – K-K “claim” tested
  – Benchmark sensitivity of 50 meV

• **NEMO-3** demonstrated feasibility of **topological** detection of **ββ**
  – Competitive **0νββ** result with open-minded approach to **mechanism of LNV**
  – **2νββ** measurements with **unprecedented accuracy**. Many more results.

• **SuperNEMO** will probe **50 meV** region with a **unique topological detection** approach
  – Different isotopes can be probed. Possibility to **disentangle** underlying **physics** if \(<m_\nu> \geq 100 \text{ meV}\).
  – Excited states, precision SM ββ-studies

• Need a **common strategy** to get down to **10 meV** (and lower?).

• **Topological ββ detection** could provide an **alternative to (multi)ton-scale detectors** if enrichment of **high-Q_{ββ}** isotopes proves feasible
BACKUP
The Roadmap

Scenario 1
\[ \langle m_v \rangle \sim 0.1 \text{ eV} \]

2012 2015 2020

Measurements with several isotopes. Possibility to disentangle LNV physics mechanism (almost background free with e.g SuperNEMO). Possibility to access Majorana CP phases.

Scenario 2
\[ \langle m_v \rangle \ll 0.1 \text{ eV} \]

2012 2015 2020

Understanding backgrounds and limiting factors (Radon?) with \( O(100\text{kg}) \) experiments Isotope enrichment technology.

“Background-free” detector technology and isotope(s) choice.

“Ton” detector construction

“Ton” Experiment must have the sensitivity to establish or exclude the IH
LSM Extension

Provisional Schedule

• Safety tunnel construction start - Sep 2009
• Safety tunnel, end of civil construction - 2013
• Detailed study of LSM extension (ULISSE) - 2010
• Deadline for final decision/money commitment - 2012
• Excavation of new Lab completed - 2014
• Outfitting completed, Lab ready to host experiments - 2015

45,000m³ (100m long), 10M€ excavation + 3M€ outfitting

2ᵈ ULISSE workshop in October’09. 11 LOIs received.