The SuperNEMO Demonstrator
double beta experiment

A.Jeremie (on behalf of the SuperNEMO collaboration)
February 21, 2019

http://supernemo.org
The SuperNEMO Demonstrator double beta experiment

• Introduction
• From NEMO-3 to SuperNEMO
  • $\beta\beta$ sources
  • Tracker
  • Calorimeter
  • Background reduction
  • Calibration
• Current status and first results
• Future and Conclusion
NEMO: Neutrino Ettore Majorana Observatory

Majorana $\nu$: particle and anti-particle are the same

Looking for these events $\Rightarrow$ New physics

$2\nu\beta\beta$  $0\nu\beta\beta$

NEMO detection principle
NEMO: Neutrino Ettore Majorana Observatory

NEMO-3 (2003-2011)

- Source separated from detector
- Full topological reconstruction, particle identification
- Powerful background suppression
- Ability to discriminate different transition mechanisms
- Modular

NEMO-3 "camembert" (source top view)

- Sources
  - 60 mg/cm² foils
  - 10 kg of ββ isotopes

- Tracker
  - 6180 Geiger cells
  - Vertex resolution: $\sigma_{xy} \sim 3$ mm $\sigma_z \sim 10$ mm

- Calorimeter
  - 1940 optical modules: polystyren scintillators + 3" and 5" PMTs
  - $FWHM_E \sim 15\% / \sqrt{E_{MeV}}$
  - $\tau_c \sim 250$ ps

$^{100}$Mo 6.9 kg
$^{68}$Se 0.93 kg
$^{130}$Te 0.45 kg
$^{116}$Cd 0.40 kg
$^{150}$Nd 36.5 g
$^{95}$Zr 9.43 g
$^{48}$Ca 6.98 g
NEMO-3: rich harvest of results

### 2νββ measurements and 0νββ limits for several isotopes:

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Reference</th>
<th>2νββ Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>100Mo</td>
<td>Phys. Rev. Lett. 95, 182302 (2005)</td>
<td>$T_{1/2}^{2\nu} = [7.11 \pm 0.02 \text{(stat)} \pm 0.54 \text{(syst)}] \times 10^{18} \text{ yr}$</td>
</tr>
<tr>
<td>48Ca</td>
<td>Phys. Rev. D 93, 112008 (2016)</td>
<td>$T_{1/2}^{2\nu} = [6.4 \pm 0.7 \text{(stat)} \pm 1.2 \text{(syst)}] \times 10^{19} \text{ yr}$</td>
</tr>
<tr>
<td>82Se</td>
<td>Eur. Phys. J. C 78, 821 (2018)</td>
<td>$T_{1/2}^{2\nu} = [9.39 \pm 0.17 \text{(stat)} \pm 0.58 \text{(syst)}] \times 10^{19} \text{ yr}$</td>
</tr>
<tr>
<td>150Nd</td>
<td>Phys. Rev. D 94, 072003 (2016)</td>
<td>$T_{1/2}^{2\nu} = [9.34 \pm 0.22 \text{(stat)} \pm 0.62 \text{(syst)}] \times 10^{18} \text{ yr}$</td>
</tr>
<tr>
<td>116Cd</td>
<td>Phys. Rev. D 95, 012007 (2017)</td>
<td>$T_{1/2}^{2\nu} = [2.74 \pm 0.04 \text{(stat)} \pm 0.18 \text{(syst)}] \times 10^{19} \text{ yr}$</td>
</tr>
<tr>
<td>130Te</td>
<td>Phys. Rev. Lett. 107, 062504 (2011)</td>
<td>$T_{1/2}^{2\nu} = [7.0 \pm 0.9 \text{(stat)} \pm 1.1 \text{(syst)}] \times 10^{20} \text{ yr}$</td>
</tr>
<tr>
<td>96Zr</td>
<td>Nucl. Phys. A847, 168-179 (2010)</td>
<td>$T_{1/2}^{2\nu} = [2.35 \pm 0.14 \text{(stat)} \pm 0.16 \text{(syst)}] \times 10^{19} \text{ yr}$</td>
</tr>
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</table>

### Quadruple β decay

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Reference</th>
<th>0νββ Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>150Nd</td>
<td>Phys. Rev. Lett. 119, 041801 (2017)</td>
<td>$T_{1/2}^{0\nu4\beta} &gt; 1.1 \times 10^{21} \text{ years}$</td>
</tr>
</tbody>
</table>
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### From NEMO-3 to SuperNEMO

<table>
<thead>
<tr>
<th></th>
<th>NEMO-3</th>
<th>SuperNEMO</th>
</tr>
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<tbody>
<tr>
<td>Isotope</td>
<td>$^{100}$Mo</td>
<td>$^{82}$Se</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>
| $T_{1/2}^{2
\nu}$ | $6.8 \times 10^{18}$ y | $9.4 \times 10^{18}$ y |
| Energy resolution (FWHM @ 1 MeV) | 15%         | 8%           |
| Source radiopurity |             |              |
| $A$ ($^{208}$Tl) | $\sim 100 \mu$Bq/kg | $<2 \mu$Bq/kg |
| $A$ ($^{214}$Bi) | $<300 \mu$Bq/kg | $<10 \mu$Bq/kg |
| $A$ ($^{222}$Rn) | $\sim 5$ mBq/m$^3$ | $<0.15$ mBq/m$^3$ |
| Exposure         | 5 y          | 2.5 y        |
| Sensitivity $T_{1/2}^{0\nu}$ | $>10^{24}$ y | $>5 \times 10^{24}$ y |
| $m_{\beta\beta}$ | $<330-620$ meV | $<260-500$ meV |
|                  |              | $<82-160$ meV |

100kg plan and choice of isotope according to enrichment possibilities
From NEMO-3 to SuperNEMO

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<tr>
<td></td>
<td>Demonstrator</td>
<td>Complete</td>
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<td>Isotope</td>
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<td>$\sim 100 \mu$Bq/kg</td>
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<td>$A^{(208}Tl)$</td>
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</tr>
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<td>$\leq 5 \text{mBq/m}^3$</td>
<td>$\leq 0.15 \text{mBq/m}^3$</td>
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<tr>
<td>Exposure</td>
<td>5 y</td>
<td>2.5 y</td>
</tr>
<tr>
<td>Sensitivity $T_{1/2}^{0\nu}$</td>
<td>$&gt;10^{24}$ y</td>
<td>$&gt;5 \times 10^{24}$ y</td>
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<tr>
<td>$m_{\beta\beta}$</td>
<td>$&lt;330-620$ meV</td>
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Improving resolution, only way to distinguish $2\nu\beta\beta$ from $0\nu\beta\beta$

Strategy:
- reduce background (Radon tent, radiopurity...)
- background rejection (topology, timing)

Start with a demonstrator: 7kg of $^{82}$Se
SuperNEMO demonstrator module

- \(\beta\beta\) source => \(^{82}\text{Se} \sim 50\text{mg/cm}^2\)
- Tracker => \(~2000\) cell drift chamber (Geiger mode) with 95% He+4% \(\text{C}_2\text{H}_5\text{OH}+1\%\ \text{Ar}\)
- Calorimeter => 712 Optical modules (Scintillator + PMT)
- 25G Magnetic field
- Passive shielding => iron + PE/water
- Anti-radon system

LSM, Modane, France
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Six different purification batches for radiopure $^{82}\text{Se}$ production (distillation, chromatography, chemical precipitation)

=> Good opportunity to validate purification techniques

Novel purification process « reverse chromatography » (publ. in prep.)

2 types of $^{82}\text{Se}$ foils (40-60mg/cm$^2$ ~300µm thick, enrichment: 96%-99.9%):

• same as for NEMO-3: in one piece poured into perforated Mylar (12µm)
• new method with standalone pads in raw Mylar (12µm)

Mix $^{82}\text{Se}$ powder with PVA (90%/10%)

Pour mixture

Prepared in an ISO 6 clean room
36 foils: 34 $^{82}$Se (6.3kg) + 2 Cu (0.4kg)
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Tracker Cell Production
2034 cells, ~13,000 wires

4 C-sections assembly

Rn emanation from fully assembled tracker
Target (150 μBq/m³) reached

Commissioned with cosmic rays before installation
Tracker: installation at LSM

Tracker with wires

Calorimeter blocks

Source foils
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- 712 Optical Modules
- Polystyrene-based scintillator
- Hamamatsu 8” PMT (some 5” PMT outer rows)
- Teflon and Mylar wrapping
- Individual pure iron magnetic shields (25 G)
- PMT directly coupled to scintillator (no light guide)

Each block characterized

\[ \chi^2 / \text{ndf} = 79.55 / 93 \]
\[ \text{Constant} = 340.3 \pm 3.1 \]
\[ \text{Mean} = 0.9991 \pm 0.0004 \]
\[ \text{Sigma} = 0.03258 \pm 0.00031 \]

\[ \chi^2 / \text{ndf} = 40.52 / 4 \]
\[ \text{Constant} = 7.223 \pm 0.02922 \]

7.8% FWHM @ 1 MeV
Scintillator + 8” PMT
(target: 8% FWHM @ 1 MeV)
Calorimeter: installation at LSM

Front of Main Wall

Back of Main Wall

Nucl.Inst.Meth. A 868 98-108

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Reduce background: Radon

SuperNEMO $^{222}\text{Rn}$ target: $\leq 150 \mu\text{Bq/m}^3$

Remove Radon from experiment

Anti-radon tent:
- Black polycarbonate (shown in blue)
- Flushed with radon free air (dedicated facility with radon trap)

Measure Radon before installation

Rn emanation setup

Rn permeability setup

Rn concentration line for Rn measurements

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Materials screening using HPGe in LSM, Bordeaux, Boulby 0.1-1mBq/kg

Lots of tools to check radiopurity of demonstrator components

Dedicated BiPo detector to measure $\beta\beta$ source foil contamination, 10μBq/kg for $^{214}$Bi, 2 μBq/kg for $^{208}$Tl — operating since 2013 at LSC (Canfranc, Spain)

Also ICP-MS at UCL
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Absolute energy calibration: $^{207}\text{Bi}$ sources

- Rn tight automatic deployment system of $^{207}\text{Bi}$ sources
- To be periodically deployed for calibration

Spatial distribution of calibration sources

Deployment of $^{207}\text{Bi}$ sources between source foils
• Monitor the calorimeter response with a precision of 1%.
• 20 pulsed UV LEDs => inject light into calorimeter modules via fiber optics
• Reference OM with $^{241}$Am for LED stability monitoring
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Demonstrator (active part) assembled at LSM November 2018
Half-detector commissioning with Argon

Commissioning on one assembled calorimeter main wall (December 2018)

Energy deposit in an OM (Scint. + PMT)

SuperNEMO Preliminary
Sampling 2.56 GS/s - 12 bits

Reflectometry

Preliminary
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Next steps

- Progressive start-up of remaining demonstrator components
  - Coil installation
    - Anti-radon tent installation
      - Passive shielding installation

...Data taking throughout...
• SuperNEMO tracker-calorimeter technique
  => multi-observable signal identification + background rejection
• Detector construction challenging
• Optical Modules with exceptional performances: 7.8% FWHM @ 1 MeV
• Radiopure tracker construction: 150 μBq/m³ reached
• Novel source foil production: ~7kg of $^{82}$Se
• Possibility for other isotopes: $^{150}$Nd and $^{48}$Ca for example
• Calibration within 1%: Light Injection and $^{207}$Bi sources
Particles

Tracker hits appear as circles (radius depends on drift time)

Individual electron energy and time

\[ E = 2.01 \pm 0.05 \text{ MeV} \]
\[ t = 2.02 \pm 0.14 \text{ ns} \]

Electrons curve this way on this side of the foil...

... and this way on this side

Plan view (partial)

Calorimeter hit with no track

E = 0.43 \pm 0.02 \text{ MeV}
\[ t = 5.37 \pm 0.31 \text{ ns} \]

Short, straight tracks a few μs after an electron are characteristic of alpha particles from $^{214}\text{Bi}$-$^{214}\text{Po}$ decays.

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How To Build a $\beta\beta$-Experiment

- **maximise efficiency ($\varepsilon$) & isotope abundance ($a$)**
- **maximise exposure = mass ($M$) × time ($t$)**

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

$W$ = atomic weight

**minimise background ($b$) & energy resolution ($\Delta E$)**
**Dedicated BiPo** detector to measure $\beta\beta$ source foil contamination, 10$\mu$Bq/kg for $^{214}$Bi, 2 $\mu$Bq/kg for $^{208}$Tl — operating since 2013 at LSC (Canfranc, Spain)

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**Principle:** $^{82}$Se foil placed between two PS scintillators + 5” PMTs

$^{212}$Bi-$^{212}$Po effect

$^{232}$Th

$^{212}$Bi

(60.5 min)

$\beta$

$^{212}$Po

(300 ns)

$\alpha$

$^{208}$Tl

(3.1 min)

36%

$^{208}$Pb (stable)

$^{208}$Tl measured by electron-alpha coincidence from $^{212}$BiPo cascade with $\Delta T \sim 300$ ns

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**Source foil**

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**Scintillator**

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**Time**

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$e^-$

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$^{212}$BiPo

$\alpha$

$\sim 299$ ns