Latest results from NEMO-3 and commissioning status of the SuperNEMO demonstrator

Thibaud Le Noblet - LAPP
On behalf of the NEMO collaboration
Neutrinoless double beta decay

- Process forbidden in the Standard Model
- Test Dirac/Majorana nature of neutrinos
- Half-life strongly suppressed

\[
(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z) |M_{0\nu}|^2 \eta^2
\]

Phase space (well known)  
Nuclear matrix elements (challenging to compute)  
Take into account the mechanism underlying the $0\nu\beta\beta$ process

- Few different mechanisms may induce $0\nu\beta\beta$:
  - Light Majorana neutrino exchange
  - Right-handed current (V+A), Majoron, SUSY etc.
- Different topology in the final state
The tracker-calorimeter technique

- Source separated from detector: many $\beta\beta$ isotopes can be investigated

- Reconstruction of the final state topology and particle identification:
  - Precise background identification and measurement
  - Possible discrimination of mechanism behind $0\nu\beta\beta$ process

- Generally lower energy resolution and detection efficiency than homogeneous detector (HPGe and bolometers)
The NEMO-3 detector

- ββ decay experiment which combines both tracker and calorimetric measurements
- Took data from February 2003 to January 2011
- Located in the Modane underground laboratory (LSM) at ~4800 m.w.e
- Investigated 7 different ββ isotopes
- Divided into 20 identical sectors
The NEMO-3 detector - a sector

Central ββ source plane made of 7 different isotopes: $^{100}$Mo (7 kg), $^{82}$Se (1 kg), $^{130}$Te, $^{116}$Cd, $^{150}$Nd, $^{96}$Zr, $^{48}$Ca

Latest results presented in this talk

+ Ultra-pure Cu and very pure nat Te blank foils to cross check background measurements

Wire drift chamber made of 6180 Geiger cells, $\sigma_{\text{vertex}} = 3$ mm (XY), 10 mm (Z)

Calorimeter made of 1940 polystyrene scintillators coupled with low radioactivity PMTs, FWHM ~15 % at 1 MeV

- 25 Gauss magnetic field for the charge identification

- Gamma and neutron shields, anti-radon tent
Backgrounds

- **Internal backgrounds**
  $2
\nu\beta\beta$ tail and radio-impurities inside the source foil
  $^{208}\text{Tl}$ (from $^{232}\text{Th}$), $^{214}\text{Bi}$ (from $^{238}\text{U}$)

- **External backgrounds**
  Radio-impurities of the detector

- **Radon inside the tracking detector**
  Deposits on the wire near the $\beta\beta$ foil
  Deposits on the surface of the $\beta\beta$ foil

Backgrounds are measured through different background channels using event topologies.
$^{150}$Nd results

- 36.6 g contained in a strip
- $^{150}$Nd : $Q_{\beta\beta} = 3.4$ MeV and the largest phase space of any isotope
- Most precise measurement of the $2\nu\beta\beta$ decay rate to date:
  
  \[
  T^{2\nu}_{1/2} = [9.34 \pm 0.22 \text{ (stat.)} +^{0.62}_{-0.60} \text{ (syst.)}] \times 10^{18} \text{ yr}
  \]

- $0\nu\beta\beta$:
  - First use of BDT to increase sensitivity by 10 %
  - Limits set for different mechanisms
  
  \[
  T^{0\nu\beta\beta}_{1/2} > 2.0 \times 10^{22} \text{ yr (90\% C.L.)}
  \]
  
  $\langle m_\nu \rangle < 1.6 - 5.3$ eV
116Cd results

- 410 g distributed in 5 strips

- 116Cd : \( Q_{\beta\beta} = 2.8 \text{ MeV} \) and is a candidate isotope for future 0νββ experiments (CdZnTe pixels)

- High precision measurement of the 2νββ decay rate:

\[
T^{2\nu}_{1/2} = [2.74 \pm 0.04 \text{ (stat.)} \pm 0.18 \text{ (syst.)}] \times 10^{19} \text{ yr}
\]

- 0νββ:
  - Use of a multivariate analysis
  - Limits set for different mechanisms

\[
T^{0\nu\beta\beta}_{1/2} > 1.0 \times 10^{23} \text{ yr (90\% C.L.)}
\]

\[\langle m_{\nu} \rangle < 1.4 - 2.5 \text{eV}\]
0ν4β results

- Neutrinoless quadruple beta decay
  - Proposed by Heeck and Rodejohann Europhys. Lett. 103, 32001 (2013)
  - Lepton number violating process
  - Neutrinos are Dirac particles and 0νββ is forbidden in this model
  - The best candidate is $^{150}\text{Nd} \rightarrow ^{150}\text{Gd} + 4e$ ($Q_{4\beta} = 2.079$ MeV)

- Exploit the unique ability of NEMO-3 to reconstruct the kinematics of each e-

- No evidence of this decay

$$T^{0\nu4\beta}_{1/2} > (1.1 - 3.2) \times 10^{21} \text{ y}$$

Depending on the model

- World’s first limit on this process
Installation and Commissioning status of the SuperNEMO demonstrator
SuperNEMO demonstrator module

<table>
<thead>
<tr>
<th></th>
<th>NEMO-3</th>
<th>SuperNEMO demonstrator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass [kg] (main isotopes)</td>
<td>7 (^{100})Mo</td>
<td>7 (^{82})Se</td>
</tr>
<tr>
<td>(T^{2\nu}_{1/2} [y])</td>
<td>(7.2 \times 10^{18})</td>
<td>(9.9 \times 10^{19})</td>
</tr>
<tr>
<td>Energy resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FWHM at 1 MeV</td>
<td>15 %</td>
<td>8 %</td>
</tr>
<tr>
<td>FWHM at 3 MeV</td>
<td>8 %</td>
<td>4 %</td>
</tr>
<tr>
<td>Source radiopurity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(A(^{208})TI)</td>
<td>(\sim 100 \mu)Bq/kg</td>
<td>(&lt; 2 \mu)Bq/kg</td>
</tr>
<tr>
<td>(A(^{214})Bi)</td>
<td>(&lt; 300 \mu)Bq/kg</td>
<td>(&lt; 10 \mu)Bq/kg</td>
</tr>
<tr>
<td>Level of radon (A(^{222})Rn)</td>
<td>(\sim 5.0 )mBq/m(^3)</td>
<td>(&lt; 0.15 )mBq/m(^3)</td>
</tr>
<tr>
<td>Sensitivity after 5 y of data taking</td>
<td>(T^{0\nu}_{1/2} &gt; 10^{24} y)</td>
<td>(T^{0\nu}_{1/2} &gt; 6 \times 10^{24} y)</td>
</tr>
</tbody>
</table>

- **Goal of the demonstrator**
  - Run for 2.5 y with 7 kg of \(^{82}\)Se
    \(\rightarrow T_{1/2} > 6 \times 10^{24} y \ m_{\beta\beta} < 0.2 – 0.55 \) eV
  - Prove SuperNEMO module can be a background free experiment in the region of interest
SuperNEMO source foils

- 7 kg of $^{82}\text{Se}$ ($Q_{\beta\beta} = 2.998$ MeV) distributed in 36 foils
- Made of $^{82}\text{Se} + \text{PVA glue} + \text{mylar}$ (mechanical support)
- Different purification methods tested: distillation, chromatography, chemical precipitation
- Very challenging requirements on foil contamination:
  - $A(^{208}\text{Tl}) < 2\mu\text{Bq/kg}$ and $A(^{214}\text{Bi}) < 10\mu\text{Bq/kg}$
- Radiopurity measured in a dedicated detector BiPo

JINST 12 (2017), P06002
SuperNEMO tracker

- 2034 drift cells working in Geiger mode
- Ultrapure materials: copper, steel, duracon. HPGe and radon tested.
- Robotic construction
- Radiopure gas flow, anti-radon sealing
- < 1 % of dead channels
SuperNEMO calorimeter

- 440 x 8” PMT + 272 x 5” directly coupled to polystyrene scintillators
- Energy resolution: 4 % FWHM at 3 MeV ($^{82}$Se Q$_{\beta\beta}$)
- Coincidence time resolution: 400 ps at 1 MeV
- Calibration system maintain stability better than < 1 %

Nucl.Instrum.Meth. under publication (2017)

Thibaud LE NOBLET – NEMO-3 and SuperNEMO
Status of the installation and commissioning

- The 2 calorimeter frames have been assembled and populated with the calorimeter blocks
- The tracker has been installed
- Installation of the source foil during fall 2017
- Demonstrator module starts data taking at end of 2017

- Commissioning of one half of the demonstrator is underway
  
  First event display showing the tracker and the calorimeter working together
Conclusion

- **NEMO 3**:  
  - Final searches for $0\nu\beta\beta$ have been published: $^{100}\text{Mo}$, $^{116}\text{Cd}$, $^{150}\text{Nd}$, $^{48}\text{Ca}$  
  - Most competitive $0\nu\beta\beta$ limit obtained with $^{100}\text{Mo}$, close to the best limits from other experiments, with only 7kg of isotopes $\langle m_\nu \rangle < 0.3 - 0.6$ eV  
  - Final search for $^{82}\text{Se}$, publication is coming up ($2\nu\beta\beta$ and $0\nu\beta\beta$)  
  - Many world leading $2\nu\beta\beta$ measurements  
  - Unique new physics can be performed (e.g. $0\nu4\beta$)

- **SuperNEMO**:  
  - The SuperNEMO demonstrator module is almost completed:  
    - The calorimeter and tracker have been installed  
    - Installation of the source foil this fall  
  - Demonstrator data taking expected to start at the end of this year

**Thank you!**

Thibaud LE NOBLET – NEMO-3 and SuperNEMO
Back-up slides
Internal Backgrounds

Regroups the backgrounds coming from the source foil, mainly come from:

- Radio-impurities inside the source foil
  - $^{208}\text{Tl}$ (from $^{232}\text{Th}$), $^{214}\text{Bi}$ (from $^{238}\text{U}$)
  - Single beta emitter ($^{40}\text{K}$, $^{234m}\text{Pa}$, $^{210}\text{Bi}$)
- $^{214}\text{Bi}$ from radon decay in tracker volume

Backgrounds are measured through different background channels using event topologies:

- $^{208}\text{Tl}$ in 1e1$\gamma$, 1e2$\gamma$ and 1e3$\gamma$
- $^{40}\text{K}$, $^{234m}\text{Pa}$, $^{210}\text{Bi}$ in 1e channel
- $^{214}\text{Bi}$ – $^{222}\text{Rn}$ in 1e1$\alpha$ and 1e1$\gamma$ channel
External Backgrounds

Regroups the backgrounds not coming from the source foil, come from:

- Radio-impurities in detector material \(^{208}\text{Tl},^{214}\text{Bi}\)
- \(\gamma\) from \((n,\gamma)\) reactions
- \(\mu\) Bremsstrahlung

Are measured in 2 main channels, requiring the timing informations:

- external crossing electron
- external \(\gamma \to e\)
$^{214}$Bi and Radon

- $^{214}$Bi is a dangerous background with $Q_\beta = 3.3$ MeV
- Arise from $^{238}$U-chain or $^{222}$Rn emanation
- Measured in 1e1α channel

- Background free measurement
- Alpha track length sensitive to different contamination origin
A two part system has been developed to calibrate the detector

1) Source Deployment system:
   - Introduction of $^{210}$Bi sources into the detector via a system of weights and stepper motors to calibrate the energy scale (~ monthly)

2) Light Injection system:
   - Guarantee the stability of the calorimetric response to 1%.
   - Injection of LED light into each scintillator block via optical fibers (~ daily)
Radon

1. Purge for several $T_{1/2}$
2. Flow through cooled carbon trap
3. Release into electrostatic detector

For reasonable gas flow rates:

$$A (^{222}\text{Rn}) = 150\text{uBq}/\text{m}^3$$

70 atoms per m$^3$ (30 times better than NEMO-3)
Sensitivity vs Exposure

\[ T_{1/2}^{0\nu} > \frac{\ln 2 N_A}{W} \times \epsilon_{0\nu} \times \sqrt{\frac{M \times T}{b \Delta E}} \]

- Constant depends on the isotope
- Efficiency
- Background
- Exposure
- Energy resolution

Graph:
- Background-free
- Background limited
- \( T_{1/2}^{0\nu} \propto \sqrt{M \times t} \)
- \( \langle m_v \rangle \propto (M \times t)^{-1/4} \)
- Gets tedious very quickly …
BiPo-3 detector

- HPGe detectors are not sensitive enough to reach few uBq/kg.
- BiPo is a dedicated detector running at Canfran Underground Laboratory to measured very low contaminations.
- $^{214}\text{Bi}$ and $^{208}\text{Tl}$ measured through process from natural radioactivity chain
- Thin radiopure plastic scintillators coupled to light guides and low radioactivity PMTs
48Ca results

- 7 g distributed in 9 CaF2 disks
- \(^{48}\text{Ca}: \text{highest } Q_{\beta\beta} = 4.3 \text{ MeV above almost all backgrounds}\)
- Most precise measurement of the 2νββ decay rate to date:
  \[
  T_{1/2}^{2\nu\beta\beta} = 6.4^{+0.7}_{-0.6} \text{(stat.)} + 1.2 \text{(syst.)} \times 10^{19} \text{ yr}
  \]

- Limits set for different 0νββ mechanisms
  \[
  T_{1/2}^{0\nu\beta\beta} > 2.0 \times 10^{22} \text{ yr (90\% C.L.)}
  \]
  \[
  \langle m_\nu \rangle < 6.0 - 26 \text{eV}
  \]
  No events observed for E > 3.4 MeV, promising for background free searches with SuperNEMO
- Many models might mediate neutrinoless double beta decay

**Right Handed Current**

\[ n \{ \begin{array}{c} u \\ d \\ d \\ d \\ u \end{array} \} \rightarrow \begin{array}{c} u \\ d \\ d \\ u \end{array} \] \[ W_L \rightarrow \nu_R \rightarrow e^- \]

**Majoron**

\[ n \{ \begin{array}{c} u \\ d \\ d \\ d \\ u \end{array} \} \rightarrow \begin{array}{c} u \\ d \\ d \\ u \end{array} \] \[ W_L \rightarrow \nu_L \rightarrow \chi^0 \rightarrow e^- \]
Many models might mediate neutrinoless double beta decay
Quadruple beta decay 1

Only 3 candidates

<table>
<thead>
<tr>
<th>$^96_{40}$Zr $\to ^{96}_{44}$Ru</th>
<th>$Q_{0\nu 4\beta}$</th>
<th>Other decays</th>
<th>NA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{136}<em>{54}$Xe $\to ^{136}</em>{58}$Ce</td>
<td>0.044</td>
<td>$\tau_{2\nu 2\beta}^{1/2} \approx 2 \times 10^{21}$</td>
<td>8.9</td>
</tr>
<tr>
<td>$^{150}<em>{60}$Nd $\to ^{150}</em>{64}$Gd</td>
<td>2.079</td>
<td>$\tau_{2\nu 2\beta}^{1/2} \approx 7 \times 10^{18}$</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Estimated life-time:

$$\frac{\tau_{0\nu 4\beta}}{\tau_{2\nu 2\beta}} \approx 10^{46} \left( \frac{\Lambda}{\text{TeV}} \right)^4$$

4n4b is killed by the $Q$-dependance of the eight-particle phase space $\sim Q^{23}$ (compared to $Q^{11}$ for 0n4b)
Quadruple beta decay 2

Very uncertain and little phenemenolny in the literature

Due to the absence of a complete theoretical treatment of the kinematics of 0n4b decays, 4 models of the electron energy distribution have been tested

- **Uniform** \( Q_{0n4b} = E_1 + E_2 + E_3 + E_4 \) (distributed uniformly)
- **Symmetric** \( A_m = S \{ 1 \times 1 \} \)
- **Semi-symmetric** \( A_m = S \{ \hat{i} \times (T_k - T_i)^2 \} \)
- **Anti-symmetric** \( A_m = S \{ (T_i - T_j)^2 \times (T_k - T_i)^2 \} \)

\[
\frac{d^4N}{\prod_{i=1}^4 dT_i} \propto A_m \delta \left( Q_{4\beta} - \sum_{i=1}^4 T_i \right) \cdot \prod_{i=1}^4 (T_i + m_e) p_i F(T_i, Z),
\]

\( S \{ \ldots \} \) is a sum over the symmetric interchange of label \( i,j,k,l \) of the four electrons
Decay via the excited states

- The double beta decay can also occur via the excited state of the daughter nucleus.
- Provide additional handle for NME calculations.
- Alternative channel to study an hypothetical $0\nu\beta\beta$ signal.
- Might help to distinguish alternative $0\nu\beta\beta$ decay mechanisms.

- Signature: $2e +$ one or more monoenergetic $\gamma$ in coincidence.
- Background is highly suppressed.
Decay via the excited states 2

- Several isotopes have been investigated:
  - $^{150}$Nd (S. Blondel Ph.D. thesis 2013)
    \[ T_{1/2}({}^{150}\text{Nd}_{0^+\rightarrow0^+}) = [7, 12 \pm 1, 28 \text{ (stat.)} \pm 0, 91 \text{ (syst.)}] \times 10^{19} \text{ ans} \]
  - $^{82}$Se (B. Soulé Ph.D. thesis 2015)
Decay via the excited states

- Several isotopes have already been investigated

<table>
<thead>
<tr>
<th>Decays</th>
<th>$T_{1/2}$ [y] at 90 % C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^{82}$Se</td>
</tr>
<tr>
<td></td>
<td>B. Soulé</td>
</tr>
<tr>
<td>$(g.s \rightarrow 0^+)$</td>
<td>$2\nu\beta\beta$</td>
</tr>
<tr>
<td>$(g.s \rightarrow 0^+)$</td>
<td>$0\nu\beta\beta$</td>
</tr>
<tr>
<td>$(g.s \rightarrow 2^+)$</td>
<td>$2\nu\beta\beta$</td>
</tr>
<tr>
<td>$(g.s \rightarrow 2^+)$</td>
<td>$0\nu\beta\beta$</td>
</tr>
</tbody>
</table>
Searches for periodic modulation in decay rate

- In their *Radiations from Radioactive Substances*, E. Rutherford, J. Chadwick and Charles Ellis concluded:

  « the rate of transformation [...] is a constant under all conditions »


- An experiment performed at Brookhaven National Laboratory (BNL), between 1982 and 1986, by studying silicon-32, found that its half-life modulated around its usual value (172 y) by the order of 0.1 %.

  The modulation appeared to be almost in phase with the varying distance of the Earth to the Sun: in January, when the Earth is closest, the decay rate was faster; in July, when the Earth is farthest, it was slower.

- The variation of the decay rate have also been claimed for Manganese-54 [arXiv:0808.3156](http://arxiv.org/abs/0808.3156)

- The results are controversial, and the physics community is skeptical. Very small deviation and what about the stability of the detectors?
Searches for periodic modulation in decay rate

- Nuclear decays are governed by various fundamental forces and are considered unaffected by the external temporal or environmental effects.

- Modulations in nuclear decay rate may point toward physics beyond standard model.

- Some experiments claim the observation of modulation of decay rate (BNL : $^{32}$Si)

- NEMO-3 ran during over 7 years.

- Use the $^{100}$Mo sample (largest and cleanest $\beta\beta$ sample in NEMO-3)

- First search for periodic variation in the $2\nu\beta\beta$ decay rate

- No evidence of periodic modulations has been found (publication soon)
### Choice of the isotopes

- Only 35 nuclei can decay by $0\nu\beta\beta$

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$Q_{\beta\beta}$ [keV]</th>
<th>Nat. abund. (enrich.) [%]</th>
<th>$G_{0\nu}$ [$10^{-14}$ y$^{-1}$]</th>
<th>$T^{2\nu}_{1/2}$ [$10^{19}$ y]</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>4270</td>
<td>0.187 (73)</td>
<td>6</td>
<td>$4.2^{+2.1}_{-1.0}$</td>
<td>NEMO3</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>2039</td>
<td>7.8 (86)</td>
<td>1</td>
<td>$150\pm10$</td>
<td>GERDA</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>2995</td>
<td>8.7 (97)</td>
<td>3</td>
<td>$9.0\pm0.7$</td>
<td>NEMO3</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>3350</td>
<td>2.8 (57)</td>
<td>6</td>
<td>$2.0\pm0.3$</td>
<td>NEMO3</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>3034</td>
<td>9.6 (99)</td>
<td>4</td>
<td>$0.71\pm0.04$</td>
<td>NEMO3</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>2802</td>
<td>7.5 (93)</td>
<td>5</td>
<td>$3.0\pm0.2$</td>
<td>NEMO3</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>2527</td>
<td>34.5 (90)</td>
<td>4</td>
<td>$70\pm10$</td>
<td>NEMO3</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>2480</td>
<td>8.9 (80)</td>
<td>4</td>
<td>$238\pm14$</td>
<td>KamlandZEN</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>3367</td>
<td>5.6 (91)</td>
<td>19</td>
<td>$0.78\pm0.7$</td>
<td>NEMO3</td>
</tr>
</tbody>
</table>
## NEMO-3: Physics Highlights (2νββ)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Mass [g]</th>
<th>$Q_{\beta\beta}$ [keV]</th>
<th>$T_{1/2} \times 10^{19}$ yrs</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>6914</td>
<td>3034</td>
<td>$0.71 \pm 0.05$</td>
<td>World’s Best</td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>932</td>
<td>2996</td>
<td>$10.07 \pm 0.56$</td>
<td>World’s Best</td>
</tr>
<tr>
<td>$^{130}\text{Te}$</td>
<td>454</td>
<td>2528</td>
<td>$70 \pm 14$</td>
<td>World’s Best &amp; First (Direct)</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>410</td>
<td>2814</td>
<td>$2.74 \pm 0.18$</td>
<td>World’s Best</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$</td>
<td>37</td>
<td>3371</td>
<td>$0.934 \pm 0.066$</td>
<td>World’s Best</td>
</tr>
<tr>
<td>$^{96}\text{Zr}$</td>
<td>9.4</td>
<td>3350</td>
<td>$2.35 \pm 0.21$</td>
<td>World’s First &amp; Best</td>
</tr>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>7</td>
<td>4272</td>
<td>$6.4 \pm 1.4$</td>
<td>World’s Best</td>
</tr>
</tbody>
</table>