Searching for the neutrinoless double beta decay with the SuperNEMO experiment: Development of reconstruction algorithms and analysis tools. Integration and commissioning of the demonstrator.

Steven Calvez PHENIICS days 2016, 05/10/16

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Outline

- Neutrinoless double beta decay
- The SuperNEMO experiment
- \( \gamma \) reconstruction algorithms
- Analysis software development
- Sensitivity studies
- Demonstrator integration and commissioning
Brief reminder

- The neutrino is the only neutral fundamental fermion
- Mass and nature unknown:

\[ \text{Dirac particle} \Leftrightarrow \, \nu \neq \bar{\nu} \]
\[ \text{Majorana particle} \Leftrightarrow \, \nu \equiv \bar{\nu} \]

- If neutrinos are Majorana particles:
  - Lepton number violation
  - See-Saw mechanism (small neutrino masses)
  - Leptogenesis (matter/antimatter asymmetry)
- Best known experimental way:
  search for the \textit{neutrinoless double beta decay}
Double beta decay

- Radioactive decay naturally occurring in a few even-even nuclei where the single beta decay is energetically impossible ($^{48}$Ca, $^{76}$Ge, $^{82}$Se, $^{96}$Zr, $^{100}$Mo, $^{116}$Cd, $^{130}$Te, $^{136}$Xe, $^{150}$Nd, ...)

![Graph showing the relationship between atomic number (Z) and mass excess (MeV)]
Double beta decay

$2\nu2\beta$

- Allowed in the Standard Model and already observed
- Second order process:
  \[ T_{1/2}^{2\nu2\beta} \sim 10^{18} - 10^{21} \text{ years} \]

$0\nu2\beta$

- Forbidden by the Standard Model
- Only if Majorana neutrinos
  \[ T_{1/2}^{0\nu2\beta} > 10^{24} - 10^{25} \text{ years} \]
Double beta decay

- Allowed in the Standard Model and already observed
- Second order process:
  \[ T^{2\nu2\beta}_{1/2} \sim 10^{18} - 10^{21} \text{ years} \]

- Forbidden by the Standard Model
- Only if Majorana neutrinos
  \[ T^{0\nu2\beta}_{1/2} > 10^{24} - 10^{25} \text{ years} \]
Double beta decay: Experimental signature

- Two different energy spectra

- $2\nu\beta\beta$: continuous $\beta$-like spectrum, the neutrinos escape the detection

- $0\nu\beta\beta$: peak at the transition energy $Q_{\beta\beta}$, all the energy is carried by the two electrons
The SuperNEMO experiment

- Neutrinoless double beta decay
- The SuperNEMO experiment
- $\gamma$ reconstruction algorithms
- Analysis software development
- Sensitivity studies
- Demonstrator integration and commissioning
NEMO experimental principle

\[ \beta\beta \text{ source foil} \]
NEMO experimental principle
NEMO experimental principle

ββ source foil

2β vertex

Particle individual energy and TOF

β−

β−

β−

Segmented calorimeter
NEMO experimental principle

- **2β vertex**
- **Charged particle trajectory**
- **Particle individual energy and TOF**

**ββ source foil**

**Tracking chamber**

**+ magnetic field**

**Segmented calorimeter**
The SuperNEMO experiment

Located in Modane (LSM) under 4200 m.w.e.

x 20 = SuperNEMO
SuperNEMO demonstrator

$\beta\beta$ source foil:
7 kg of $^{82}\text{Se}$ ($d = 53 \text{ mg/cm}^2$)
SuperNEMO demonstrator

\[ \beta \beta \text{ source foil :} \]
7 kg of $^{82}\text{Se}$ ($d = 53 \text{ mg/cm}^2$)

\[ \text{Calorimeter :} \]
520 x 8” PM + 192 x 5” PM
coupled to polystyrene scintillators
SuperNEMO demonstrator

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$520 \times 8'' \text{ PM} + 192 \times 5'' \text{ PM}$
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Tracking chamber:
2034 wires in Geiger regime
SuperNEMO demonstrator

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\[ \rightarrow \text{Commissioning and data taking by the end of 2016} \]
γ reconstruction algorithms

- Neutrinoless double beta decay
- The SuperNEMO experiment
- γ reconstruction algorithms
- Analysis software development
- Sensitivity studies
- Demonstrator integration and commissioning
Software: simulation and reconstruction

- Use SN@ilWare software developed by and for the SuperNEMO collaboration: relies on GEANT4 and Genbb (event generator).

Visualization of a $0\nu2\beta$ event from the source foil:

$$E = 0.71 \pm 0.03 \text{ MeV}$$
$$t = 1.74 \pm 0.24 \text{ ns}$$

$$E = 1.93 \pm 0.05 \text{ MeV}$$
$$t = 3.44 \pm 0.15 \text{ ns}$$
γ detection and reconstruction in SuperNEMO

- The NEMO experiments are able to look for 0ν2β and to measure the backgrounds thanks to a variety of event topology: 1e−, 2e−, 1e−1e+, 1e−1α, 1eNγ, 2eNγ...

→ Look for $^{208}$Tl and $^{214}$Bi events in the 1eNγ channels

- The γ reconstruction is important for:
  - background identification
  - study of double beta decay towards the excited states of the daughter nucleus.
**Clustering** : Gather the neighbouring calorimeter hits into clusters

**Tracking** : Compute the probability a $\gamma$ flew from one cluster to another based on Time-Of-Flight

Better reconstruction efficiency and fidelity

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**I. Unassociated calorimeter hits**

- $E = 0.12 \pm 0.01$ MeV
  $t = 8.78 \pm 1.19$ ns
- $E = 0.16 \pm 0.01$ MeV
  $t = 8.54 \pm 1.03$ ns
- $E = 0.05 \pm 0.01$ MeV
  $t = 9.83 \pm 1.82$ ns

**II. Clustering**

3 clusters with $\Delta t < 2.5$ ns

- $E = 0.17 \pm 0.01$ MeV
  $t = 12.69 \pm 1.00$ ns
- $E = 0.12 \pm 0.01$ MeV
  $t = 8.78 \pm 1.19$ ns
- $E = 0.16 \pm 0.01$ MeV
  $t = 8.54 \pm 1.03$ ns
- $E = 0.05 \pm 0.01$ MeV
  $t = 9.83 \pm 1.82$ ns

**III. Tracking**

1 hit will not be used ($\sigma_t > 1.5$ ns)

- $E = 0.17 \pm 0.01$ MeV
  $t = 12.69 \pm 1.00$ ns
- $E = 0.31 \pm 0.02$ MeV
  $t = 4.34 \pm 0.74$ ns
- $E = 0.61 \pm 0.03$ MeV
  $t = 2.90 \pm 0.52$ ns

**IV. Tracking**

linking clusters with $P > 4\%$

- $E = 0.17 \pm 0.01$ MeV
  $t = 12.69 \pm 1.00$ ns
- $E = 0.31 \pm 0.02$ MeV
  $t = 4.34 \pm 0.74$ ns
- $E = 0.61 \pm 0.03$ MeV
  $t = 2.90 \pm 0.52$ ns
Analysis software development

- Neutrinoless double beta decay
- The SuperNEMO experiment
- $\gamma$ reconstruction algorithms

- Analysis software development

- Demonstrator integration and commissioning.
Analysis software development

- Implement the end of the event reconstruction chain and provide the analysis tools to the collaboration:
  - Particle identification according to the user definitions
  - Perform relevant topological measurement (energy, vertices separation, TOF probabilities, angle, etc...)
  - Event selection and construction of the final analysis channels
  - Serialize the event model into a more user-friendly and analysis-oriented framework (ROOT TTrees for instance)
Sensitivity studies

- Neutrinoless double beta decay
- The SuperNEMO experiment
- $\gamma$ reconstruction algorithms
- Analysis software development

- Sensitivity studies

- Demonstrator integration and commissioning.
Analysis overview

- Simulate and reconstruct Monte-Carlo datasets for signal and backgrounds (several years of CPU hours)
- Select $\beta$-$\beta$-like events
- Perform cuts to optimize the signal selection and background rejection (machine learning tools like Boosted Decision Trees...)
- Evaluate the demonstrator sensitivity for the neutrinoless double beta decay search, assuming the target background contributions
Demonstrator performance

- Should reach the NEMO3 sensitivity in less than a year.
- Less than one background count in total in the energy region of interest in the demonstrator.
- Demonstrator with 17.5 kg.y should reach $\langle m_{\beta\beta} \rangle < 0.2 - 0.4$ eV

![](image-url)
Demonstrator integration and commissioning

- The demonstrator is under construction in Laboratoire Souterrain de Modane, in the Frejus tunnel under the Alps.
Demonstrator integration and commissioning

- Mechanical structure and clean tent in LSM
Demonstrator integration and commissioning

- Integration and commissioning of the calorimeter
The end

Thank you for your attention!
Backup

BACKUP
Experimental challenges

- Find a peak at the end of the $2\nu 2\beta$ spectrum
- $2\nu 2\beta$ irreducible background → improve energy resolution
- High $Q_{\beta\beta}$ isotope to rise above natural radioactivity
- Radiopure source and materials

Internal (source contamination, Radon on source surface, ...)

External (PMT glass, ...)

= radioisotope; $\beta$ = electron from $\beta$-decay; IC = internal conversion
## Comparison NEMO3 SuperNEMO

<table>
<thead>
<tr>
<th></th>
<th>NEMO3</th>
<th>SuperNEMO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mass</strong></td>
<td>7 kg</td>
<td>100 kg</td>
</tr>
<tr>
<td><strong>Isotopes</strong></td>
<td>$^{100}$Mo</td>
<td>$^{82}$Se, $^{150}$Nd</td>
</tr>
<tr>
<td></td>
<td>7 isotopes</td>
<td></td>
</tr>
<tr>
<td><strong>Energy resolution @3MeV</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FWHM - $\sigma$</td>
<td>8 % - 3.4 %</td>
<td>4 % - 1.7 %</td>
</tr>
<tr>
<td><strong>Source contaminations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A(^{208}\text{Tl})$</td>
<td>$\sim 100$ µBq/kg</td>
<td>$\leq 2$ µBq/kg</td>
</tr>
<tr>
<td>$A(^{214}\text{Bi})$</td>
<td>$\sim 300$ µBq/kg</td>
<td>$\leq 10$ µBq/kg</td>
</tr>
<tr>
<td><strong>Radon in tracker</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A(^{222}\text{Rn})$</td>
<td>$\sim 5$ mBq/m³</td>
<td>$\leq 0.15$ mBq/m³</td>
</tr>
<tr>
<td><strong>0ν efficiency</strong></td>
<td>18 %</td>
<td>30 %</td>
</tr>
<tr>
<td><strong>Exposure</strong></td>
<td>35 kg.y</td>
<td>500 kg.y</td>
</tr>
<tr>
<td><strong>Sensitivity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T^{0\nu2\beta}_{1/2}$ (90% C.L.)</td>
<td>$&gt; 1.1 \times 10^{24}$</td>
<td>$&gt; 1 \times 10^{26}$</td>
</tr>
<tr>
<td>$\langle m_{\beta\beta} \rangle$</td>
<td>$&lt; 0.33 - 0.87$ eV</td>
<td>$&lt; 0.04 - 0.1$ eV</td>
</tr>
</tbody>
</table>

**Sensitivity** :

$$T^{0\nu2\beta}_{1/2} \propto \left\{ \begin{array}{ll} \epsilon m t & \text{without background.} \\ \epsilon \sqrt{\frac{m t}{b \Delta E}} & \text{with background.} \end{array} \right.$$ 

$$(T^{0\nu2\beta}_{1/2})^{-1} = G^{0\nu} |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2 \text{ (for Mass Mechanism)}$$

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NEMO-3 results

NEMO3 results for the $0\nu2\beta$ search in $^{100}\text{Mo}$ (Phys. Rev. D 92, 072011):

![Graph showing the results of the $0\nu2\beta$ search in $^{100}\text{Mo}$]
Isotope choice

\[(T_{1/2}^{0\nu 2\beta})^{-1} = G^{0\nu} |M_{0\nu}|^2 \langle m_{\beta\beta}\rangle^2 \text{ (for Mass Mechanism)}\]

<table>
<thead>
<tr>
<th>(2\beta)</th>
<th>(Q_{\beta\beta} [\text{MeV}])</th>
<th>(G_{0\nu} [10^{-14} \text{ y}^{-1}])</th>
<th>(T_{1/2}^{2\nu} [\text{y}])</th>
<th>(NA [%])</th>
</tr>
</thead>
<tbody>
<tr>
<td>48 Ca</td>
<td>4.274</td>
<td>6.35</td>
<td>4.3 \times 10^{19}</td>
<td>0.187</td>
</tr>
<tr>
<td>76 Ge</td>
<td>2.039</td>
<td>0.62</td>
<td>1.3 \times 10^{21}</td>
<td>7.61</td>
</tr>
<tr>
<td>82 Se</td>
<td>2.996</td>
<td>2.70</td>
<td>9.2 \times 10^{19}</td>
<td>8.73</td>
</tr>
<tr>
<td>96 Zr</td>
<td>3.348</td>
<td>5.63</td>
<td>2.0 \times 10^{19}</td>
<td>2.8</td>
</tr>
<tr>
<td>100 Mo</td>
<td>3.035</td>
<td>4.36</td>
<td>7.0 \times 10^{18}</td>
<td>9.63</td>
</tr>
<tr>
<td>116 Cd</td>
<td>2.805</td>
<td>4.62</td>
<td>3.0 \times 10^{19}</td>
<td>7.49</td>
</tr>
<tr>
<td>130 Te</td>
<td>2.530</td>
<td>4.09</td>
<td>6.1 \times 10^{20}</td>
<td>34.1</td>
</tr>
<tr>
<td>136 Xe</td>
<td>2.462</td>
<td>4.31</td>
<td>2.1 \times 10^{21}</td>
<td>8.9</td>
</tr>
<tr>
<td>150 Nd</td>
<td>3.368</td>
<td>19.2</td>
<td>7.9 \times 10^{18}</td>
<td>5.6</td>
</tr>
</tbody>
</table>
Nuclear matrix elements
Underlying mechanisms

(a) Mass Mechanism
Events

(b) Right Handed Current
Events

(c) Mass Mechanism
Events

(d) Right Handed Current
Events
Current experiments sensitivities

$\beta\beta$ experiments current sensitivities

![Graph showing $T_{1/2}$ and $m_{\beta\beta}$ limits for various experiments and isotopes.](image)
Underground laboratory
Time-of-Flight probability

TOF and internal probability

\[ \chi^2_{int} = \left( \frac{(t_2^{exp} - t_1^{exp}) - \left( \frac{l_2}{\beta_2 c} - \frac{l_1}{\beta_1 c} \right)}{\sigma_{t_1}^2 + \sigma_{t_2}^2} \right)^2 \]

\[ \sigma_{t_i}^2 = \left( \frac{\partial t_{int}}{\partial t_{i,meas}} \right)^2 \sigma_{t_{i,meas}}^2 + \left( \frac{\partial t_{int}}{\partial E_i} \right)^2 \sigma_{E_i}^2 \]

with \( \sigma_{t_{i,meas}} = 400 \text{ ps} \) and energy FWHM = 8% (at 1 MeV). For two electrons, the track length uncertainty is negligible.

Then,

\[ P(\chi^2_{int}) = 1 - \frac{1}{\sqrt{2\pi}} \int_0^{\chi^2_{int}} x^{-\frac{1}{2}} e^{-\frac{x}{2}} \, dx \]
Energy spectra

- Simulate and select $\beta\beta$-like events:
  - $0\nu$: signal
  - $2\nu$: irreducible background
  - $^{208}\text{Tl}$ and $^{214}\text{Bi}$: source contamination
  - Radon: gas in tracker

$\beta\beta$-like events energy distribution

- $Q_{\beta\beta}^{(82}\text{Se}) = 2.996$ Mev
- $Q_{\beta}^{(214}\text{Bi}) = 3.272$ Mev
- $Q_{\beta}^{(208}\text{Tl}) = 5.001$ Mev