Investigating $\beta\beta$ decay with NEMO-3 and SuperNEMO

Summer Blot, on behalf of the NEMO-3 and SuperNEMO experiments

7 September 2015

Outline

Review of double $\beta$ decay

The NEMO technique

Recent results from NEMO-3

Status of SuperNEMO

Summary
Neutrinoless double-beta (0νββ) decay

- BSM process that violates lepton number conservation by 2 units
- Can be mediated by: Light Majorana neutrino exchange, (V+A) current, SUSY, ...
- Not yet observed, current limits at $T_{1/2} > 10^{24}$ y

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

NEMO detection principle

- Reconstruct the full topology and kinematics of final states
- Measure backgrounds *in situ* and reject from signal channel
- Can disentangle underlying $0\nu\beta\beta$ mechanisms

\[ B \cos \theta \]

\[ E_1 \quad t_1 \quad l_1 \quad \cos \theta \quad l_2 \quad E_2 \quad t_2 \]

Source ≠ Active detector

The NEMO-3/SuperNEMO collaboration

LAL (Orsay), IPHC (Strasbourg), INL (Idaho Falls), ITEP (Moscow), JINR (Dubna), LPC (Caen), CENBG (Bordeaux), UCL (London), U. of Manchester, Tokushima U., LAPP (Annecy), Comenius U. (Bratislava), Osaka U., IEAP CTU (Prague), Saga U., Imperial College (London), Mount Holyoke Coll. (South Hadley), Fukui U., INR (Kiev), CPPM (Marseilles), U of Warwick, U. of Texas at Austin

22 Universities & Institutions
9 different countries

Aussois, 2015
The NEMO-3 detector

- ~10 kg of ββ-decay isotopes
  - $^{100}$Mo, $^{82}$Se, $^{130}$Te, $^{116}$Cd, $^{150}$Nd, $^{96}$Zr and $^{48}$Ca
  - Produced as thin foils 30-60mg/cm²
  - Typically 2.5m in height, 63-65 mm wide

- Tracking chamber (both sides of foil)
  - 6180 Geiger cells operating in gas mixture of 95% He, 4% alcohol, 1% Ar and 0.1% H₂O
  - Vertex resolution $\sigma_{XY} \sim 3$ mm, $\sigma_Z \sim 10$mm

- Calorimeter (top, bottom, in and out)
  - 1940 optical modules
  - 3” and 5” PMTs + plastic scintillator blocks
  - FWHM 14-17%, $\sigma_t \sim 250$ ps for electrons @1MeV

Largest mass/exposure with $^{100}$Mo (6.9 kg) and $^{82}$Se (0.93 kg)
The NEMO-3 detector

- Operated from Feb 2003–Jan 2011
- Modane Underground Laboratory (LSM)
- Cylindrical geometry (R, \( \phi \), z)
- 7 different isotopes simultaneously

- Separate tracker-calorimeter systems + B Field
- Enables the reconstruction of full kinematics of final state
Backgrounds to $0\nu\beta\beta$

- External backgrounds from neutron capture, producing high energy $\gamma$-rays
  - e.g. Pair production $e^+e^-$
- Radon induced backgrounds
- Internal background decays
  - Impurities in the foil
  - e.g. Single $\beta$-decay + Møller scattering
- $2\nu\beta\beta$ decay

Use background topology to measure expected rates
Background channels

- External background channels identified by distinct time sequence $(t_i << t_j)$

- Measure internal background rates using single $\beta$-decay channel
Latest NEMO-3 Results – $^{100}$Mo

- 34.7 kgy of $^{100}$Mo
- No excess of data in region of interest:
  \[ E_{\text{TOT}} = [2.8-3.2] \text{ MeV} \]

\[ T_{1/2}^{0v} > 1.1 \times 10^{24} \text{ y} \]

\[ <m_{\beta\beta}> < 0.33-0.62 \text{ eV} \]

- No events > 3.2 MeV
- Reached background expectations

<table>
<thead>
<tr>
<th>Mass mechanism</th>
<th>$T_{1/2} &gt; 1.1 \times 10^{24} \text{ y}$</th>
<th>$m_{\beta\beta} &lt; 0.33-0.62 \text{ eV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH current $&lt;\lambda&gt;$</td>
<td>$T_{1/2} &gt; 0.7 \times 10^{24} \text{ y}$</td>
<td>$&lt;\lambda&gt; &lt; (0.9-1.3)\times10^{-6}$</td>
</tr>
<tr>
<td>RH current $&lt;\eta&gt;$</td>
<td>$T_{1/2} &gt; 1.0 \times 10^{24} \text{ y}$</td>
<td>$&lt;\eta&gt; &lt; (0.5-0.8)\times10^{-8}$</td>
</tr>
<tr>
<td>Majoron ($\chi^0_{n=1}$)</td>
<td>$T_{1/2} &gt; 0.05 \times 10^{24} \text{ y}$</td>
<td>$&lt;g_{ee}&gt; &lt; 1.6-3.0 \times10^{-5}$</td>
</tr>
</tbody>
</table>

Other results from NEMO-3

- World best $T_{\frac{1}{2}}^{2\nu\beta\beta}$ measurements for all 7 isotopes investigated
- Best $T_{\frac{1}{2}}^{0\nu\beta\beta}$ decay limits for most

Updated results with full exposure coming soon...

$T_{\frac{1}{2}}^{2\nu\beta\beta}(^{100}\text{Mo}) = 7.16 \pm 0.01_{\text{stat}} \pm 0.54_{\text{syst}}$
The SuperNEMO detector

- 20 identical Modules with 100 kg total isotope mass
- Demonstrator module (1/20) will house 7kg of $^{82}$Se and with 2.5y reach sensitivity of $<m_{\beta\beta}> < 0.2 - 0.4$ eV
- Full SuperNEMO to reach sensitivity of $<m_{\beta\beta}> < 0.04 - 0.1$ eV

Thin $\beta\beta$-decay source foils
- 7kg of $^{82}$Se in demonstrator module
- Factor of x10 decrease in $^{208}$Tl contamination and x30 decrease in $^{214}$Bi

Calorimeter walls
- 5” & 8” PMTs coupled to scintillator blocks
- FWHM 4% for electrons @3MeV ($Q_{\beta\beta}$ value)

Tracking chambers
- Wire chambers in Geiger mode
SuperNEMO demonstrator status – source foils

- 25% of source foil produced for demonstrator ($^{82}\text{Se}$)
- Radio-purity measurements underway using the dedicated BiPo detector
SuperNEMO demonstrator status – tracker

- First half of tracker complete
- First quarter (aka C0) commissioned, ready for shipment from UK to LSM
  - 98.4% of cells fully operational! (504 total)
- Radon tests for C1 underway, commissioning to follow

Commissioning with cosmics
SuperNEMO demonstrator status – calorimeter

- Production and testing of optical modules is well underway (40% complete)
- Energy resolution meeting design specifications (FWHM 4% @ Q_{ββ})
SuperNEMO demonstrator status – radiopurity

- All materials screened for radiopurity with HPGe detectors and radon emanation chamber
- Radon (Rn) concentration line measures Rn in tracker gas (Target < 0.15 mBq/m³)
- Radon trap will be installed to remove Rn from air
- Preliminary measurements of radon in tracker sections are very promising!!
From demonstrator to full SuperNEMO

Full SuperNEMO to reach sensitivity of $T_{1/2} > 1 \times 10^{26}$ y corresponding to $<m_{\beta\beta}> < 0.04 - 0.1$ eV with 500 kg x y
Summary

- NEMO-3/SuperNEMO experiments can reconstruct multiple final state topologies and event kinematics.
- Offers a unique way to search for $0\nu\beta\beta$ decay and disentangle underlying mechanisms.
- Analysis of full data set from NEMO-3 is ongoing.
  - Best limit with $34.7 \text{ kg}_{\text{xy}}$ of $^{100}\text{Mo}$ is $T_{1/2} > 1.1 \times 10^{24} \text{ y}$
    
    $$<m_{\beta\beta}> < 0.33 - 0.62 \text{ eV}$$

- Construction of SuperNEMO demonstrator is underway.
  - 7kg of $^{82}\text{Se}$
  - With 2.5 kg$_{\text{xy}}$, will reach $<m_{\beta\beta}> < 0.2 - 0.4 \text{ eV}$

- Commissioning to begin at the end of next year! (2016)

Thank you for your attention!
**2νββ decay**
- Occurs if β-decay is forbidden or highly suppressed (35 isotopes)
- 2\textsuperscript{nd} order weak process in the Standard Model (SM) ($T_{1/2} \sim 10^{18-21}$ yrs)
- Detect 2 electrons with continuous \( \Sigma E_{TOT} \) (\( \bar{\nu}_e \)'s escape detection)

**0νββ decay**
- BSM process that violates ΔL conversation by 2 units
- Can be mediated by: Light Majorana ν, (V+A) current, SUSY
- Observed final state identical to 2νββ
Dirac vs Majorana

Schechter-Valle theorem

Image from Neutrino Physics, Kai Zuber, IoP Publishing 2004
Experimental considerations for $0\nu\beta\beta$

- **Choice of isotope**
  - Large $G^{0\nu}$ and $M^{0\nu}$ for shorter $T_{1/2}$
  - Large $Q_{\beta\beta}$ for background rejection
  - Large mass of isotope of interest
    - Enrichment, purification, abundance

- **Detector design**
  - Good energy resolution
  - Radio-pure materials
  - Active or passive

- **Choice of location**
  - Experiments underground and protected by many layers of passive and active shielding to protect from cosmic muon spallation, uranium fission, etc
The NEMO-3 detector – $\beta\beta$-decay sources

- Only technique that can measure multiple isotopes at the same time
- Largest mass with $^{100}\text{Mo}$ (6.9 kg) and $^{82}\text{Se}$ (0.93 kg)
NEMO-3 tracker

- Wire tracking chamber with 6180 cells operating in Geiger mode
  - 95% He, 4% alcohol, 1% Ar, 0.1% H₂O
- Vertex resolution: σ_{XY} \sim 3 \text{ mm}, \sigma_z \sim 10 \text{ mm}
- 25 G magnetic field for discrimination between e^+/e^−
NEMO-3 calorimeter

- 1940 optical modules
- 3” and 5” low-radioactivity PMTs coupled to large (10x10x10) scintillator blocks
- ~15% / $\sqrt{E}$ @ 1 MeV
- Dedicated studies for PMT monitoring to ensure high quality modules used in analysis
NEMO-3 calibrations

- Monthly absolute calibration runs with $^{207}$Bi sources + runs with $^{90}$Sr source for calibrating up to 3 MeV
- Check PMT stability with daily laser survey (82% of PMTs stable for entire lifetime of experiment)

![Laser survey validation](image)

- Before laser survey: EXP: 1502644 ev; E>3.4MeV 8 ev
  MC: E>3.4MeV 2.32 +/- 0.28 ev
- After laser survey: EXP: 1037896 ev; E>3.4MeV 2 ev
  MC: E>3.4MeV 1.72 +/- 0.28 ev

![Laser survey validation](image)

- $^{207}$Bi C.E. peaks
- $^{90}$Sr (90Y) endpoint
Measuring backgrounds: $^{214}$Bi-$^{214}$Po cascade

- Electronics store Geiger hits information up to 700$\mu$s after event trigger
- Tag $^{214}$Bi-$^{214}$Po cascades with one electron and one cluster of delayed Geiger hits ($\alpha$)

$^{214}$Po half-life is 164.3$\mu$s

arxiv:1506.05825
Measuring backgrounds: Crossing electrons

- High energy external γ-flux can produce $e^+e^-$ pairs in foil
- Use passive shielding to reject most events (slide 9)
- Use calo timing information to tag and characterize external events

*NIM A 606: 449-465, 2009*
Measuring backgrounds: electron + gammas

- Many internal background decay to excited states of their daughter isotopes
- Tag γ rays emitted in de-excitation to identify these backgrounds
- Channel selects one electron and N scintillator hits without tracks pointing to them

![Graph showing data points and MC background]

- **208Tl**
  - \( Q_\beta = 4999.0 \text{ keV} \)
  - \( T_{1/2} = 3.053 \text{ min} \)
  - \( \beta^- : 100\% \)
- Table of energies and half-lives:
  - Energy (keV):
    - 510.8
    - 860.6
    - 583.2
    - 2614.5
  - T_{1/2}:
    - < 100 ps
    - 4 ps
    - 294 ps
    - STABLE

- **100Mo** \( 1e2\gamma \text{ & } 1e3\gamma \)

- **208Pb**
  - STABLE

*arxiv:1506.05825*
# Results from NEMO-3

![NEMO-3 Data](image)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Mass (g)</th>
<th>$2\nu\beta\beta$ $T_{1/2}$ ($\times 10^{19}$ y)</th>
<th>$0\nu\beta\beta$ $T_{1/2}$ (90% CL)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{82}$Se</td>
<td>932</td>
<td>$9.6 \pm 0.1_{\text{stat}} \pm 1.0_{\text{syst}}$</td>
<td>$&gt; 3.2 \times 10^{23}$</td>
<td>PhysRevLett 95 (2005) 182302</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>37.0</td>
<td>$0.91^{+0.025}<em>{-0.022}</em>{\text{stat}} \pm 0.063_{\text{syst}}$</td>
<td>$&gt; 1.8 \times 10^{22}$</td>
<td>PhysRevC 80 (2009) 032501</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>9.4</td>
<td>$2.35 \pm 0.14_{\text{stat}} \pm 0.16_{\text{syst}}$</td>
<td>$&gt; 9.2 \times 10^{21}$</td>
<td>Nucl.Phys.A847 (2010) 168</td>
</tr>
<tr>
<td>$^{130}$Tl</td>
<td>454</td>
<td>$70 \pm 9_{\text{stat}} \pm 11_{\text{syst}}$</td>
<td>$&gt; 1.3 \times 10^{22}$</td>
<td>PhysRevLett 107 (2011) 062504</td>
</tr>
</tbody>
</table>

New results soon for $^{150}$Nd, $^{48}$Ca, $^{116}$Cd, $^{96}$Zr and $^{82}$Se for full exposure!
**$^{100}\text{Mo}$ $0\nu\beta\beta$ result**

- Event break-down
- Dominant systematic is absolute normalization on $0\nu\beta\beta$ efficiency

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<table>
<thead>
<tr>
<th>Contribution</th>
<th>$N_{2e}$ events $E_{TOT} = [2.8-3.2]$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>External background</td>
<td>$&lt; 0.2$</td>
</tr>
<tr>
<td>$^{214}\text{Bi}$ from radon</td>
<td>$5.2 \pm 0.5$</td>
</tr>
<tr>
<td>$^{214}\text{Bi}$ internal</td>
<td>$1.0 \pm 0.1$</td>
</tr>
<tr>
<td>$^{208}\text{TI}$ internal</td>
<td>$3.3 \pm 0.3$</td>
</tr>
<tr>
<td>$2\nu\beta\beta$</td>
<td>$8.45 \pm 0.05$</td>
</tr>
<tr>
<td>Total Expected</td>
<td>$18.0 \pm 0.6$</td>
</tr>
<tr>
<td>Data</td>
<td>15</td>
</tr>
</tbody>
</table>

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**Systematics**

<table>
<thead>
<tr>
<th>Systematics</th>
<th>%</th>
<th>Estimation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0\nu\beta\beta$</td>
<td>7.0</td>
<td>Activity of $^{207}\text{Bi}$ calibration sources HPGe v NEMO</td>
</tr>
<tr>
<td>$2\nu\beta\beta$</td>
<td>0.7</td>
<td>$2\nu\beta\beta$ total energy spectrum fit $&gt; 2$ MeV</td>
</tr>
<tr>
<td>$^{214}\text{Bi}$ internal</td>
<td>10.0</td>
<td>Variation of activity between bkg. channels</td>
</tr>
<tr>
<td>$^{208}\text{TI}$ internal</td>
<td>10.0</td>
<td>Activity of $^{232}\text{U}$ calibration sources HPGe v NEMO</td>
</tr>
</tbody>
</table>

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Comparison to other isotopes

- See [arxiv:1506.05825] for references to other isotope results.
Moving towards SuperNEMO

- SuperNEMO shares the same detector design principles as NEMO-3
- Modular in design → first module (of 20 total) is the demonstrator
- Demonstrator will house 7kg of $^{82}\text{Se}$ and with 2.5y will reach sensitivity of $<m_{\beta\beta}> \sim 0.2 - 0.4$ eV

<table>
<thead>
<tr>
<th>Feature</th>
<th>NEMO-3</th>
<th>SuperNEMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotope</td>
<td>$^{100}\text{Mo}$</td>
<td>$^{82}\text{Se}$ ($^{48}\text{Ca},^{150}\text{Nd}$)</td>
</tr>
<tr>
<td>Mass</td>
<td>7 kg</td>
<td>100 kg</td>
</tr>
<tr>
<td>Radiopurity</td>
<td>$A(^{208}\text{Tl}) &lt; 20 \mu\text{Bq/kg}$</td>
<td>$A(^{208}\text{Tl}) &lt; 2 \mu\text{Bq/kg}$</td>
</tr>
<tr>
<td>(activity)</td>
<td>$A(^{214}\text{Bi}) &lt; 300 \mu\text{Bq/kg}$</td>
<td>$A(^{214}\text{Bi}) &lt; 10 \mu\text{Bq/kg}$</td>
</tr>
<tr>
<td></td>
<td>$A(\text{Rn}) &lt; 5 \text{mBq/m}^3$</td>
<td>$A(\text{Rn}) &lt; 0.15 \text{mBq/m}^3$</td>
</tr>
<tr>
<td>Efficiency</td>
<td>18%</td>
<td>30%</td>
</tr>
<tr>
<td>$\sigma_E$ (FWHM@3MeV)</td>
<td>8%</td>
<td>4%</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>$T_{1/2}^{0v} &gt; 1 \times 10^{24}$</td>
<td>$T_{1/2}^{0v} &gt; 1 \times 10^{26}$</td>
</tr>
<tr>
<td></td>
<td>$m_{\beta\beta} &lt; 0.3 - 0.8$ eV</td>
<td>$m_{\beta\beta} &lt; 0.04 - 0.1$ eV</td>
</tr>
</tbody>
</table>

*Values in table correspond to the full 20 modules of SuperNEMO* 

Full SuperNEMO: $m_{\beta\beta} \sim 0.04-0.1$ eV
Considerations for $0\nu\beta\beta$ sensitivity

- Maximizing exposure ($M \times t$) is important
- Minimizing background counts and improving energy resolution have equivalent effects

\[ T_{1/2}^{0\nu} > \frac{4.16 \times 10^{26} y}{n_\sigma} \left( \frac{\epsilon a}{Z} \right) \frac{\sqrt{M \times t}}{b \times \Delta E} \quad \text{with background} \]

\[ T_{1/2}^{0\nu} > \frac{4.16 \times 10^{26} y}{n_\sigma} \left( \frac{\epsilon a}{Z} \right) M \times t \quad \text{No background} \]

- $n_\sigma$ – number of standard deviations for a given CL
- $\epsilon$ – detection efficiency
- $a$ – isotopic abundance in source mass
- $Z$ – Molecular weight of source isotope
- $M$ – exposure in kg y
- $b$ – background rate in kg$^{-1}$ keV$^{-1}$ y$^{-1}$
- $\Delta E$ – energy resolution in $0\nu\beta\beta$ signal region in keV
- $Z$ – Molecular weight of source isotope
SuperNEMO demonstrator - integration

Support frame installed at LSM

Tracker section ready for transport to LSM

SuperNEMO Demonstrator starting to take shape

Optical module production underway

Commissioning by 2016
Sensitivity of next generation $0\nu\beta\beta$ experiments

Current best limit at $m_{\beta\beta} < 130 - 310$ meV (90% CL)

$<m_{\beta\beta}> = m_{1}^{2}|U_{e1}|^{2} + m_{2}^{2}|U_{e2}|^{2} + m_{3}^{2}|U_{e3}|^{2}\bar{e}^{i\alpha} + m_{3}^{2}|U_{e3}|^{2}\bar{e}^{i\beta}$

SNO+ ungraded, nEXO, Super-KamLAND-Zen

Assumes 3 neutrino mixing model


*See talk P. Guzowski’s talk later in this session*