Search for 0νββ decay and measurement of 2νββ with the NEMO-3 experiment

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NEMO-3 is uniquely suited to provide theorists with many SM measurements:

- $2\nu\beta\beta$ half-lives for various isotopes
- Decays to excited states
- Dynamics of the decay

Well known phase-space factor

Effective neutrino mass

Difficult to calculate Nuclear Matrix Element (NME)

$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu} \left| M_{0\nu} \right|^2 \langle m_{\beta\beta} \rangle^2$

\[ \langle m_\nu \rangle = 50 \text{ meV} \]

\[ T_{1/2}^{0\nu} \]

\[ \text{Vergados et al. 2012} \]
Double Beta Decay

\[ \frac{1}{T^{0\nu}_{1/2}} = G_{0\nu} |M_{0\nu}|^2 \left\langle m_{\beta\beta} \right\rangle^2 \]

Well known phase-space factor

Effective neutrino mass

Difficult to calculate Nuclear Matrix Element (NME)

- NEMO-3 can also probe the underlying 0νββ physics via kinematic decay variables
  - Mass mechanism, right hand currents, majoron emission, SUSY, etc.

mass mechanism right-handed currents

cosθ between electrons

Events

Reconstructed

Theoretical
The NEMO-3 Technique

The multi-isotope, multi-observable $0\nu\beta\beta$ search

- **Heterogenous (source ≠ detector)** vs Homogenous (source = detector)
  - Full decay kinematics reconstruction
    - Individual electron energies ($E_1, E_2$)
    - Timing ($T_1, T_2$)
    - Track lengths ($L_1, L_2$)
    - Curvature (+,-)
    - Opening angle ($\cos\theta$)
    - Emission vertex
  - Identification of $e^-$, $e^+$, $\alpha$, and $\gamma$
  - High degree of background suppression

![Diagram showing decay vertex, charged particle trajectory, modular thin source foil, tracking volume, and segmented calorimeter.]
The NEMO-3 Detector

- Source + Tracking + Calorimetry
  - 7 different isotopes in thin source foils
  - Drift wire cells operating in Geiger mode
  - Plastic scintillator blocks coupled to low radioactivity 3” and 5” PMTs

- 25 Gauss magnetic field aids in PID
- External iron, wood, and borated water shielding for \((\gamma,n)\) flux
- Anti-radon enclosure surrounds detector
  - Phase 1 (pre-enclosure): Feb 2003 – Sep 2004
- Located in the Laboratoire Souterrain de Modane (LSM) at 4800 m.w.e.
The NEMO-3 Detector

- NEMO-3 construction
- Inside a sector, source + tracker + calorimeter
- Installation of anti-radon enclosure
- Decommissioning, no source foils
NEMO-3 Backgrounds

**External Backgrounds:**
- Impurities in detector materials and detector environment

**Internal Backgrounds:**
- Impurities in source foils ($^{208}\text{Tl} - Q_\beta = 5.0 \text{ MeV} \text{ & } ^{214}\text{Bi} - Q_\beta = 3.3 \text{ MeV}$)

**Radon Backgrounds:** ($^{214}\text{Bi}$)
- Radon from surroundings permeates into detector depositing daughters on foil surface, drift wires, etc.
Background Measurements

- NEMO-3 is uniquely suited to measure its own backgrounds

Example: $^{214}$Bi

- Specific topologies indicate various background contributions
- Observables can be fitted to measure and constrain background activities
$^{100}\text{Mo} \ \beta\beta \ \text{Event}$

- **Clear** signature of a $\beta\beta$ event originating in the $^{100}\text{Mo}$ foils
- **Full decay kinematics** captured
- **No other interactions** present
Final Results: $^{100}$Mo

- $Q_{\beta\beta} = 3.034$ MeV, 6.9 kg
- High background suppression $\rightarrow S/B = 76$
- Mass mechanism limit:
  $$T_{1/2}^{0\nu} > 1.1 \times 10^{24} \text{ y (90\% C.L.)}$$
  $$\langle m_{\beta\beta} \rangle < 0.3 - 0.6 \text{ eV}$$
- No events above 3.2 MeV for full 47 kg·y
  - Background free for high $Q_{\beta\beta}$ isotopes!
- $0\nu\beta\beta$ searched in the [2 - 3.2] MeV region
**Final Results: \(^{82}\text{Se}\)**

- \(Q_{\beta\beta} = 2.995 \text{ MeV}, 0.93 \text{ kg}\)
- SuperNEMO baseline isotope
- Longer \(T_{1/2}^{2\nu}\) reduces contributions to \(0\nu\beta\beta\) search from the irreducible \(2\nu\beta\beta\) tail

\[T_{1/2}^{2\nu} = \left[10.07 \pm 0.14 \text{ (stat.)} \pm 0.54 \text{ (syst.)}\right] \times 10^{19} \text{ y}\]

- More precise than (and consistent with) previous world-average value

\[T_{1/2}^{0\nu} > 2.5 \times 10^{23} \text{ y (90\% C.L.)}\]

\[\langle m_{\beta\beta} \rangle < 1.2 - 3.0 \text{ eV}\]
**Final Results: $^{116}$Cd**

- $Q_{\beta\beta} = 2.804$ MeV, 410 g
- **Opportunity to test single versus higher states dominance** hypotheses (SSD vs HSD)
- Single electron energy used for discriminating these states
  - Results favor SSD but don't exclude HSD

\[ T_{1/2}^{2\nu} = [2.74 \pm 0.04 \text{ (stat.)} \pm 0.18 \text{ (syst.)}] \times 10^{19} \text{ y} \]
Final Results: $^{150}\text{Nd}$

- $Q_{\beta\beta} = 3.368 \text{ MeV}, 36.5$ g
- Full decay kinematics provided by NEMO-3 allows multivariate approach to $0\nu\beta\beta$ search
  - Boosted Decision Tree (BDT) was used with 10 kinematic/detector variables

$T^{2\nu}_{1/2} = \left[ 9.34 \pm 0.22 \text{ (stat.)}^{+0.62}_{-0.60} \text{ (syst.)} \right] \times 10^{18}$ y

- Most precise half-life measurement for this isotope

$T^{0\nu}_{1/2} > 2.0 \times 10^{22}$ y (90% C.L.)

$\langle m_{\beta\beta} \rangle < 1.6 - 5.3$ eV

- Expected (observed) limit is 11% (34%) better than using $E_{\text{TOT}}$ variable alone
Final Results: $^{48}\text{Ca}$

- $Q_{\beta\beta} = 4.276 \text{ MeV} \rightarrow$ Highest decay energy of any candidate isotope
  - Above nearly all backgrounds
- **Most difficult to amass** $\rightarrow$ 6.99 g in NEMO-3 one of world's largest agglomerations!

- Most precise $2\nu\beta\beta$ half-life determination to date: 
  $$T_{1/2}^{2\nu} = [6.4^{+0.7}_{-0.6} \text{ (stat.)} +^{1.2}_{-0.9} \text{ (syst.)}] \times 10^{19} \text{ y}$$
Neutrinoless quadruple beta decay ($0^{\nu}4\beta$) is a proposed process allowing for Dirac neutrinos
- (Heeck & Rodejohann 2013)

Best candidate is $^{150}\text{Nd} \rightarrow ^{150}\text{Gd} + 4\text{e}^-$ due to highest $Q_{4\beta} = 2.08$ MeV

NEMO-3 uniquely suited since it can reconstruct full kinematics in the 4e “golden channel”

Expected half-life: $4.3 \times 10^{21}$ y

$T^{0\nu4\beta}_{1/2} > 2.6 \times 10^{21}$ y (90% C.L.)

First ever limit!
**Final Results: Unique Physics**

- NEMO-3 was an observatory running for 7+ years
  - Opportunity to search for new physics → time variation of fundamental constants/processes
- $2\nu\beta\beta$ decay rate of $^{100}\text{Mo}$ → **First search for variations in a 2\textsuperscript{nd}-order weak decay**
- Employing periodogram technique to search for periodicities with a range of frequencies

![Time Series](image)

**Monte Carlo Model**

$T_{\text{TRUE}} = 10$

![Periodogram](image)

$T_{\text{MEAS}} = 1/0.0998 = 10.02$

C.L. = 99.97%

![Decay Rate vs Time](image)

**Blinded $^{100}\text{Mo} 2\nu\beta\beta$ Data**

PRELIMINARY

- Multiple channels available in NEMO-3 dataset
  - $2\nu\beta\beta$ rates in other isotopes
  - Single $\beta$ emitters (backgrounds) for higher statistics
Summary and Outlook

➢ The NEMO-3 advantage
  ➢ No events > 3.2 MeV in 47 kg·y in $^{100}$Mo search $\rightarrow \langle m_{\beta\beta} \rangle < 0.3 - 0.6$ eV
  ➢ Multi-isotope + multi-observables
  ➢ NEMO-3 continues producing a unique spectrum of results
  ➢ World-leading $2\nu\beta\beta$ measurements and probing of $0\nu\beta\beta$ mechanics
  ➢ Varying nuclear decay rates, $0\nu4\beta$ decay, etc.
Backup Slides
Energy Calibrations

- 20 calibration tubes close to foils for sources at 3 vertical positions:
  - reconstruction of the $1e^-$ events from the source to the calorimeter
  - $^{207}$Bi: 482 and 976 keV conversion electrons every 2-3 weeks
  - $^{90}$Sr-$^{90}$Y: $\beta$-decay end-point $Q_\beta = 2280$ MeV
  - $^{207}$Bi: 1682 keV conversion electrons $\rightarrow$ test the energy scale

![Diagram showing energy calibrations with data/MC comparison](image)
Laser Energy Survey

- Light injection into each calorimeter block through optical fibers:
  - linearity better than 1% between 0 and 4 MeV
  - PMT gain and timing survey twice a day (82% PMTs < 5%)

- $^{214}$Bi $\beta$-decay end-point ($Q_\beta = 3.27$ MeV) to validate PMT stability:
  - reconstruction of the BiPo $e^-\alpha_{\text{delayed}}$ events from radon
    (background-free channel)

Phase 1: high radon data

![Graph showing before and after laser survey for high radon data with MC values]

Phase 2: low radon data

![Graph showing before and after laser survey for low radon data with MC values]
Half Life Limits

**maximise** efficiency ($\varepsilon$) & isotope abundance ($a$)  

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

$W = \text{atomic weight}$

**minimise** background ($b$) & energy resolution ($\Delta E$)

- GERDA ($^{76}\text{Ge}$): $b \times \Delta E \sim 0.01 \times 4 \text{ keV} = 0.04$
- SuperNEMO ($^{82}\text{Se}$): $b \times \Delta E \sim 0.0001 \times 120 \text{ keV} = 0.012$

![Graph showing half-life limits vs exposure](image)

**background-free**

- $T_{1/2}^{0\nu} \propto \sqrt{M \times t}$
- $\langle m_\nu \rangle \propto (M \times t)^{-1/4}$
- gets tedious very quickly …
Underground Laboratories

Essential to go deep underground

- Cosmic ray muon flux reduced by $10^{-6}$
- Other important backgrounds are a function of depth and local geology:
  - Neutrons
  - $\gamma$'s
  - Radon

![Graph showing depth and location of underground laboratories](image)

- **LSM**: (Super-)NEMO
- **Snolab**: SNO+, EXO (?)
NEMO-3 at the LSM

Laboratoire Souterrain de Modane (LSM) : 4800 M.W.E.

NEMO-3
The world’s biggest and cleanest Geiger counter
Ran from Feb. 2003 to Jan. 2011
238\textsuperscript{U} and 232\textsuperscript{Th} Chains
NEMO-3 Backgrounds

208TI:
- Internal
- External (e.g. PMTs)
NEMO-3 Backgrounds

External background: eγ-external and e-crossing events

Internal $^{214}$Bi : eα(γ)-events from foil
Radon/Thoron Backgrounds

- Most troublesome are $^{214}\text{Bi}$ and $^{208}\text{Tl} \rightarrow$ High single beta Q values
- Can enter detector from highly diffusive radon gas
- Or can be present in detector and source foil materials
- Background minimization:
  - Material screening and purification
  - Vetoes and active shielding
  - Radon barriers
  - Background identification in situ
NEMO-3 Event Displays

2e⁻ event signal

e⁻ γγγ event measure $^{208}\text{Tl}$

β - α (delay track) event
$^{214}\text{Bi} \rightarrow ^{214}\text{Po} \rightarrow ^{210}\text{Pb}$

e⁺ – e⁻ pair event
B rejection
Source Foil Background Measurement

- HPGe $\gamma$ spectroscopy not sufficient to reach few $\mu$Bq/kg today (factor 50 improvement needed for thin foils)
- Main contaminations for $0\nu 2\beta$ search ($^{214}$Bi and $^{208}$Tl) measured through BiPo processes from natural radioactivity chains:

- $\beta$ and $\alpha$ particles detected by thin radiopure plastic scintillators coupled to light-guides and low radioactivity PMTs:
The BiPo Detector

- 2 modules of $3.0 \times 0.6 \text{ m}^2$ can measure 1.4 kg of $^{82}\text{Se}$ foil (40 mg/cm$^2$)
- 2 mm thick aluminized polystyrene scintillators, PMMA light guides and 5" Hamamatsu low radioactivity PMTs
- PMT pulses digitized by MatAcq boards and dedicated trigger board
- Running since 2012 in Canfranc Underground Lab (LSC, Spain)
- Sensitivity: $^{208}\text{Tl} < 2 \mu\text{Bq/kg}$ and $^{214}\text{Bi} < 10 \mu\text{Bq/kg}$
NEMO-3 $^{100}$Mo $2\nu\beta\beta$ Results

- 6.9 kg of $^{100}$Mo
- $\sim$700 000 $2\nu2\beta$ events collected
- Efficiency $\mathcal{E}_{2\nu} = 4.3 \%$
- Signal to background ratio $S/B = 76$
- Preliminary half-life:
  \[ T_{1/2}^{2\nu} = 7.16 \pm 0.01 \text{ (stat)} \pm 0.54 \text{ (syst)} \times 10^{18} \text{ y} \]
  compatible with previously published [Phys. Rev. Lett. 95, 182302 (2005)]

- 0.7 % systematical uncertainty on the $2\nu2\beta$ efficiency above 2 MeV
NEMO-3 $^{116}$Cd $0\nu\beta\beta$ Limits

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Obs. $T_{1/2}^{0\nu}$ limit</th>
<th>($\times 10^{23}$ yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle m_{\beta\beta} \rangle$</td>
<td>$\geq 1.0$</td>
<td>$&lt; (1.4 - 2.5) \text{ eV}$</td>
</tr>
<tr>
<td>$\chi_{111}$</td>
<td></td>
<td>$&lt; 0.1 \times f$</td>
</tr>
<tr>
<td>$\langle \eta \rangle$</td>
<td>$\geq 1.1$</td>
<td>$&lt; (2.5 - 11.9) \times 10^{-8}$</td>
</tr>
<tr>
<td>$\langle \lambda \rangle$</td>
<td>$\geq 0.6$</td>
<td>$&lt; (3.6 - 43.0) \times 10^{-6}$</td>
</tr>
<tr>
<td>$\langle \tilde{g}_X \rangle$</td>
<td>$\geq 0.085$</td>
<td>$&lt; (5.2 - 9.2) \times 10^{-5}$</td>
</tr>
</tbody>
</table>
NEMO-3 $^{116}$Cd SSD vs HSD Studies

SSD

<table>
<thead>
<tr>
<th>Observable</th>
<th>KS Test</th>
<th>$\chi^2/ndf$ Test</th>
<th>$P(\chi^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{Tot}$</td>
<td>0.949</td>
<td>0.53</td>
<td>0.992</td>
</tr>
<tr>
<td>$E$</td>
<td>0.999</td>
<td>0.79</td>
<td>0.784</td>
</tr>
<tr>
<td>$E_{Min}$</td>
<td>0.974</td>
<td>0.70</td>
<td>0.767</td>
</tr>
<tr>
<td>$E_{Max}$</td>
<td>0.893</td>
<td>0.72</td>
<td>0.878</td>
</tr>
</tbody>
</table>

HSD

<table>
<thead>
<tr>
<th>Observable</th>
<th>KS Test</th>
<th>$\chi^2/ndf$ Test</th>
<th>$P(\chi^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{Tot}$</td>
<td>0.871</td>
<td>0.59</td>
<td>0.976</td>
</tr>
<tr>
<td>$E$</td>
<td>0.691</td>
<td>1.27</td>
<td>0.140</td>
</tr>
<tr>
<td>$E_{Min}$</td>
<td>0.262</td>
<td>0.92</td>
<td>0.534</td>
</tr>
<tr>
<td>$E_{Max}$</td>
<td>0.376</td>
<td>1.13</td>
<td>0.279</td>
</tr>
</tbody>
</table>
# NEMO-3 2νββ Results

<table>
<thead>
<tr>
<th>Isotope</th>
<th>mass, g</th>
<th>$Q_{ββ}$ (keV)</th>
<th>$T_{1/2}$ (10$^{19}$ yrs)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{100}$Mo</td>
<td>6914</td>
<td>3034</td>
<td>0.71 ± 0.05</td>
<td>World’s Best !</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>932</td>
<td>2996</td>
<td>10.07 ± 0.56</td>
<td>World’s Best !</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>9.4</td>
<td>3350</td>
<td>2.35 ± 0.21</td>
<td>World’s First (N2) &amp; Best !</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>7</td>
<td>4272</td>
<td>6.4 ± 1.4</td>
<td>World’s Best !</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>410</td>
<td>2814</td>
<td>2.74 ± 0.18</td>
<td>World’s Best !</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>454</td>
<td>2528</td>
<td>70 ± 14</td>
<td>World’s Best &amp; First (Direct) !</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>37</td>
<td>3371</td>
<td>0.934 ± 0.066</td>
<td>World’s Best !</td>
</tr>
</tbody>
</table>
NEMO-3 Previous Results

$^{82}\text{Se}$

$\tau_{1/2} = 9.6 \pm 1.0 \times 10^{19}$ y
PRL 95, 182302 (2005)

$^{130}\text{Te}$

$\tau_{1/2} = 7.0 \pm 1.4 \times 10^{20}$ y
PRL 107, 062504 (2011)

$^{150}\text{Nd}$

$\tau_{1/2} = 9.1 \pm 0.7 \times 10^{18}$ y

$^{96}\text{Zr}$

$\tau_{1/2} = 2.35 \pm 0.21 \times 10^{19}$ y

$^{116}\text{Cd}$

$\tau_{1/2} = 2.9 \pm 0.3 \times 10^{19}$ y
To be published

$^{48}\text{Ca}$

$\tau_{1/2} = 4.4 \pm 0.6 \times 10^{19}$ y
Systematics under study
**NEMO-3 $^{150}\text{Nd} \ 0\nu4\beta$**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$Q_{0\nu4\beta}$</th>
<th>$\tau_{2\nu2\beta}^{1/2}$</th>
<th>$\tau_{1\nu2\beta}^{1/2}$</th>
<th>NA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{96}<em>{40}\text{Zr} \rightarrow ^{96}</em>{44}\text{Ru}$</td>
<td>0.629</td>
<td>$2 \times 10^{19}$</td>
<td></td>
<td>2.8</td>
</tr>
<tr>
<td>$^{136}<em>{54}\text{Xe} \rightarrow ^{136}</em>{58}\text{Ce}$</td>
<td>0.044</td>
<td>$2 \times 10^{21}$</td>
<td></td>
<td>8.9</td>
</tr>
<tr>
<td>$^{150}<em>{60}\text{Nd} \rightarrow ^{150}</em>{64}\text{Gd}$</td>
<td>2.079</td>
<td>$7 \times 10^{18}$</td>
<td></td>
<td>5.6</td>
</tr>
</tbody>
</table>

- NEMO-3 contains both $^{150}\text{Nd}$ & $^{96}\text{Zr}$
- Only $^{150}\text{Nd}$ has a significant $Q_{4\beta}$ value
- 4$\nu4\beta$? → suppressed by phase space needed for 8-particle decay
- 0$\nu4\beta$ model postulates $\nu$'s are Dirac particles and 0$\nu2\beta$ is forbidden

ArXiv:1306.0580v2
- Increase sensitivity by looking in 3-electron channel:

- Lifetime estimate:
  \[ \frac{\tau_{0\nu4\beta}}{\tau_{2\nu2\beta}} \approx 10^{46} \left( \frac{\Lambda}{\text{TeV}} \right)^4 \]

- But:
  - Very uncertain.
  - Little phenomenology yet in the literature.
Nuclear Decay Rate Variations

- Variations in nuclear decay rates have been claimed previously
  - Decay of $^{32}$Si and $^{226}$Ra from BNL and PTB respectively
  - Postulated to correlate with solar activity and the Earth-Sun distance

The Periodogram Approach

- Is a common technique for detecting periodic signals hidden in noise
  - It has very well known statistical behavior
  - It’s equivalent to least squares fitting of sinusoids to data
  - It’s time translation invariant
- Consider an arbitrary time series:
- The Discrete Fourier Transform (DFT) is then:

\[
X(t_i), i=1,2,\ldots N
\]

- The \textbf{classical} periodogram is then defined by:

\[
FT_X(\omega) = \sum_{j=1}^{N} X(t_j) \exp(-i \omega t_j)
\]

\[
P_X(\omega) = \frac{1}{N} |FT_X(\omega)|^2
\]

\[
= \frac{1}{N} \left[ \left( \sum_j X_j \cos(\omega t_j) \right)^2 + \left( \sum_j X_j \sin(\omega t_j) \right)^2 \right]
\]

If \(X(t)\) contains a sinusoidal component of frequency \(\omega_0\) then at \(\omega=\omega_0\), the \(X(t)\) and \(\exp(-i\omega t)\) are in phase and make a large contribution to the sum \(\rightarrow\) large power \(P(\omega)\)
The Generalized Lomb-Scargle Periodogram

- Extends the periodogram technique:
  - Can be used on unevenly sample data ($\Delta t \neq \text{const.}$ Or presence of gaps)
  - Accounts for data weights and offset
- Power calculation is replaced by →

$$P_{GLS}(\omega) = \frac{1}{\sum w_i(X_i - \bar{X})^2} \left\{ \frac{\left[ \sum w_i(X_j - \bar{X}) \cos(\omega(t_j - \tau)) \right]^2}{\sum w_i \cos^2(\omega(t_j - \tau)) - \left[ \sum w_i \cos(\omega(t - \tau)) \right]^2} + \frac{\left[ \sum w_i(X_j - \bar{X}) \sin(\omega(t_j - \tau)) \right]^2}{\sum w_i \sin^2(\omega(t_j - \tau)) - \left[ \sum w_i \sin(\omega(t - \tau)) \right]^2} \right\}$$

$$\tan(2\omega \tau) = \frac{\sum w_i \sin(2\omega t_j) - 2 \sum w_i \cos(\omega t_j) \sum w_i \sin(\omega t_j)}{\sum w_i \cos(2\omega t_j) - \left[ (\sum w_i \cos(\omega t_j))^2 - (\sum w_i \sin(\omega t_j))^2 \right]}$$

- Powers follow exponential distribution → easily calculable false alarm probability on C.L.s

$$\text{Prob}\{P_{LS} > p\} = 1 - (1 - e^{-P_{LS}})^N$$

$$C.L. = 100 \times (1 - e^{-P_{LS}})^N$$
The Generalized Lomb-Scargle Periodogram

- Example application of the technique to pure noise and modulated data

1. Randomly generated Gaussian noise time series

2. Lomb power $P_{LS}$ is calculated at each sample frequency

3. Powers follow exponential distribution allowing for simple calculation of false alarm probability and C.L. No significant powers detected in pure noise
The Generalized Lomb-Scargle Periodogram

- Example application of the technique to pure noise and modulated data

1. Modulation is applied:
   \[ X'(t_i) = X(t_i) \times (1 + A \sin(2\pi f t_i)) \]
   with \( f = 0.03 \)

2. Large Lomb power \( P_{LS} \) appears at the corresponding value of \( f \)

3. Correspondingly large C.L. for that peak
Rate Modulation Sensitivity

- Pseudo-data MC is generated to mimic NEMO-3 decay rate data
- Data is then modulated with sinwave of different parameters (amplitude, freq)
- Periodogram technique applied to each data set $\rightarrow$ largest peak/C.L. are output
Periodogram Applications

- Has been used to probe for variations on other experiments

SNO Neutrino Flux Analysis

SuperKamiokande Neutrino Flux Analysis

arXiv:0910.2433
arXiv:hep-ex/0307070
# NEMO-3 to SuperNEMO

<table>
<thead>
<tr>
<th></th>
<th>NEMO-3</th>
<th>SuperNEMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>6.9 kg</td>
<td>100 kg</td>
</tr>
<tr>
<td><strong>Isotopes</strong></td>
<td>100(^{100})Mo</td>
<td>82(^{150})Se, 48(^{48})Ca</td>
</tr>
<tr>
<td></td>
<td>7 isotopes</td>
<td></td>
</tr>
<tr>
<td>Energy resolution ((\sigma \mid \text{FWHM}))</td>
<td>@ 3 MeV 3.4</td>
<td>8 %</td>
</tr>
<tr>
<td>Radon in tracker</td>
<td>5.0 mBq/m(^3)</td>
<td>0.15 mBq/m(^3)</td>
</tr>
<tr>
<td>Sources contaminations</td>
<td>(\mathcal{A}(^{208}\text{Tl})) (\approx 100 \mu\text{Bq/kg})</td>
<td>(&lt; 2 \mu\text{Bq/kg})</td>
</tr>
<tr>
<td></td>
<td>(\mathcal{A}(^{214}\text{Bi})) (60 - 300 \mu\text{Bq/kg})</td>
<td>(&lt; 10 \mu\text{Bq/kg})</td>
</tr>
<tr>
<td>Total background</td>
<td>cts·keV(^{-1})·kg(^{-1})·y(^{-1})</td>
<td>1.3 \times 10(^{-3})</td>
</tr>
<tr>
<td>Sensitivity (90 % CL)</td>
<td>(T_{1/2}^{0\nu}) (&gt; 1.1 \times 10^{24} \text{y})</td>
<td>(&gt; 1 \times 10^{26} \text{y})</td>
</tr>
<tr>
<td></td>
<td>(\langle m_\nu \rangle) (&lt; 0.33 - 0.87 \text{eV})</td>
<td>(&lt; 0.04 - 0.10 \text{eV})</td>
</tr>
</tbody>
</table>