Topological detection of $\beta\beta$-decay with NEMO-3 and SuperNEMO

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University College London
Tamura Symposium, Austin (TX)
8 May 2017
Two ways of searching for $\beta\beta$

- $E_{e1} + E_{e2} = Q_{\beta\beta}$ (for $0\nu$)
- Several observables
- Two electrons
- Coincident
- From the same vertex
- Angular distributions between two electrons

**"Calorimeter"**

Background $\gamma$ lines

**"Topological"**

Tracko-Calo, e.g. NEMO3/SuperNEMO
NEMO-3/SuperNEMO Design

**Unique** Detection principle: reconstruct topological signature

- Decay vertex
- Charged particle trajectory
- Particle individual energy and TOF
- Modular thin ββ source foil
- High granularity tracking volume
- Segmented calorimeter
Background Suppression

Powerful **background rejection and characterisation** through topology, timing, particle ID (e+, e-, α, γ)

**Lowest** background index

**NEMO-3**
\[ b = 10^{-3} \text{ cnts kg}^{-1} \text{ keV}^{-1} \text{ yr}^{-1} \] — data!

**SuperNEMO**
\[ b = (0.5-1) \times 10^{-4} \text{ cnts kg}^{-1} \text{ keV}^{-1} \text{ yr}^{-1} \]

**Calorimeter expts (GERDA, CUORE)**
\[ b = 10^{-3} \text{ cnts kg}^{-1} \text{ keV}^{-1} \text{ yr}^{-1} \]
(recent fantastic achievement by GERDA)

But much more modest energy resolution see next slide
Experimental Sensitivity

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

**maximise** efficiency & isotope abundance

**maximise** exposure = mass \( \times \) time

**minimise** background & energy resolution

\[ b \times \Delta E \text{ (in RoI) is what's important (not just FWHM)} \]

E.g.:

SuperNEMO\(^{82}\text{Se}\), FWHM=4%

\[ b \times \Delta E = 5 \times 10^{-5} \times 120\text{keV} = 0.006 \]

Ultimate HPGe, FWHM=0.2%

\[ b \times \Delta E = 0.001 \times 4\text{keV} = 0.004 \]
Topology Reconstruction — open-minded search for any $0\nu\beta\beta$ mechanism

\[
\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q_{\beta\beta}, Z) |M^{0\nu}|^2 \eta^2
\]

$\eta$ can be due to $\langle m_\nu \rangle$, V+A, Majoron, SUSY, $H^-$ or a combination of them.

\[\langle m_\nu \rangle \quad \text{V+A}\]

"Probing new physics models of $0\nu\beta\beta$ with SuperNEMO", EPJ C (2010) 70, pp. 972-943.

Topology can be used to disentangle underlying physics mechanism
NEMO-3 — Neutrino Ettore Majorana Observatory

Data taking: Feb’03 - Jan’11

Laboratoire Souterrain de Modane (LSM)
Modane, France
(Tunnel Frejus, depth of ~4,800 mwe)
NEMO-3 - 20 sectors with ~10 kg of isotopes

25G B-field

Passive shielding + anti-radon shielding

wire chamber

PMTs

Plastic scintillator

ββ isotope foils
Full topology reconstruction = unprecedented understanding of backgrounds

$^{214}$Bi on the surface of the source foil

Delay time of the $\alpha$ track

Pure sample of $^{214}$Bi – $^{214}$Po

$T_{1/2} = 162.9$

Measuring $^{222}$Rn in NEMO-3. 5mBq/m$^3$ in Phase-II
Full topology reconstruction = unprecedented understanding of backgrounds

E.g.: External background

The “Anatomy” of $\beta\beta$ decay with NEMO

NEMO-3 $2\nu\beta\beta$ result for $^{100}$Mo to ground state

Unprecedented statistics — $O(10^6)$ events with $S/B \approx 80$

$$T_{1/2}^{2\nu} = [7.16 \pm 0.01\text{(stat)} \pm 0.54\text{(syst)}] \times 10^{18} \text{ yr}$$
Search for $0\nu\beta\beta$

NEMO-3 - $^{100}$Mo - 7 kg, 4.96 y


$T_{1/2}(0\nu\beta\beta) > 1.1 \times 10^{24}$ yr at 90% CL

$\langle m_\nu \rangle < 0.33 - 0.62$ eV

No events > 3.2 MeV after 5 yr of running! (34.3 kg x yr of $^{100}$Mo)

Background free technique for high $Q_{\beta\beta}$ isotopes

$^{48}$Ca(4.27 MeV), $^{150}$Nd(3.37 MeV)

$^{96}$Zr(3.35 MeV)

Other $0\nu\beta\beta$ results

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$\langle \lambda \rangle$ (1E-6)</th>
<th>$\langle \eta \rangle$ (1E-8)</th>
<th>$\lambda'$111/f (1E-2)</th>
<th>$\langle$gee$\rangle$ (1E-5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo100 (NEMO3)</td>
<td>0.9-1.3</td>
<td>0.5-0.8</td>
<td>4.4-6.0</td>
<td>1.6-3.0</td>
</tr>
<tr>
<td>Te130 (CUORICINO)</td>
<td>1.6-2.4</td>
<td>0.9-5.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xe136 (K-Z)</td>
<td>1.6-2.4</td>
<td>0.9-5.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ge76 (GERDA)</td>
<td>1.1</td>
<td>0.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ge76 (HdM)</td>
<td>1.1</td>
<td>0.64</td>
<td></td>
<td>8.1</td>
</tr>
</tbody>
</table>

V+A

SUSY

Majoron

8-May-2017

R. Saakyan, NEMO-3 and SuperNEMO, Tamura17
Recent 2νbb Results

NEMO-3 - $^{150}\text{Nd}$ - 36.6 g, 5.25 y

Data (327)
- $2\nu\beta$
- $^{208}\text{TI}$ internal
- Other backgrounds

- $\langle m_\nu \rangle$
- $\langle \lambda \rangle$
- $\langle \eta \rangle$
- $\chi^0_{n=1}$

$T_{1/2}^{2\nu} = \left[ 6.4^{+0.7}_{-0.6} \text{(stat)}^{+1.2}_{-0.9} \text{(syst)} \right] \times 10^{19} \text{ yr}$

in tension with Shell Model
Nuclear Matrix Elements Calculations

NEMO-3 - $^{48}\text{Ca}$ - 7 g, 5.25 y

Data (1368 Entries)
- $^{48}\text{Ca}$ $2\nu\beta$
- $^{90}\text{Sr} / 90\text{Y}$
- External
- Radon
- Other $2\nu\beta$
- Other internal

- $\langle m_\nu \rangle$
- $\langle \eta \rangle$
- $\langle \lambda \rangle$
- $\chi^0_{n=1}$

$N_{obs} < 2.68$
$N_{obs} < 2.70$
$N_{obs} < 2.65$
$N_{obs} < 9.35$
## Summary of $2\nu\beta\beta$ Results

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Mass (g)</th>
<th>$Q\beta\beta$ (keV)</th>
<th>$T(2\nu)$ (1E19yrs)</th>
<th>S/B</th>
<th>Comment</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Se82</td>
<td>932</td>
<td>2996</td>
<td>9.6 ± 1.0</td>
<td>4</td>
<td>World’s best</td>
<td>Phys.Rev.Lett. 95(2005) 483</td>
</tr>
<tr>
<td>Cd116</td>
<td>405</td>
<td>2809</td>
<td>2.74 ± 0.18</td>
<td>10</td>
<td>World’s best</td>
<td>Phys. Rev. D 95 (2017) 012007</td>
</tr>
<tr>
<td>Nd150</td>
<td>37</td>
<td>3367</td>
<td>0.93 ± 0.06</td>
<td>2.7</td>
<td>World’s best</td>
<td>Phys. Rev. D 94 (2016) 072003</td>
</tr>
<tr>
<td>Zr96</td>
<td>9.4</td>
<td>3350</td>
<td>2.35 ± 0.21</td>
<td>1</td>
<td>World’s best</td>
<td>Nucl.Phys.A 847(2010) 168</td>
</tr>
<tr>
<td>Ca48</td>
<td>7</td>
<td>4271</td>
<td>6.4 ± 1.2</td>
<td>6.8 (h.e.)</td>
<td>World’s best</td>
<td>Phys. Rev. D 93 (2016) 112008</td>
</tr>
<tr>
<td>Mo100</td>
<td>6914</td>
<td>3034</td>
<td>0.71 ± 0.05</td>
<td>80</td>
<td>World’s best</td>
<td>Phys.Rev.Lett. 95(2005) 483</td>
</tr>
<tr>
<td>Te130</td>
<td>454</td>
<td>2533</td>
<td>70 ± 14</td>
<td>0.5</td>
<td>First direct detection</td>
<td>Phys. Rev. Lett. 107, 062504 (2011)</td>
</tr>
</tbody>
</table>

### Crucial experimental input for
1) NME calculations
2) Ultimate background characterisation for $0\nu$
3) Sensitive to exotic BSM physics (e.g. Lorentz violation, bosonic neutrinos etc)
Quadruple (!) beta decay — 0ν4β

$\Delta L = 4$ BSM physics with Dirac neutrinos

Only possible with full topological reconstruction of all electrons

<table>
<thead>
<tr>
<th>90%CL limit</th>
<th>Symmetric</th>
<th>Uniform</th>
<th>Semi-symmetric</th>
<th>Anti-symmetric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>$3.2 \times 10^{21}$y</td>
<td>$2.6 \times 10^{21}$y</td>
<td>$1.7 \times 10^{21}$y</td>
<td>$1.1 \times 10^{21}$y</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>$3.7 \times 10^{21}$y</td>
<td>$3.0 \times 10^{21}$y</td>
<td>$2.0 \times 10^{21}$y</td>
<td>$1.3 \times 10^{21}$y</td>
</tr>
</tbody>
</table>

(combined limits for 3 topologies) Preliminary

First experimental limit on this process paper being submitted
The goals of SuperNEMO:

1. Build on the experience of the extremely successful NEMO-3 experiment.

2. Use the power of the tracking-calorimeter approach to identify and suppress backgrounds aiming at a zero-background experiment in the first (Demonstrator Module) phase.

3. Prove that a 100 kg scale experiment can probe the inverted mass hierarchy (~50 meV) domain. Explore feasibility of scaling up topological technique beyond 100kg.

4. In the event of a discovery by any of the next-generation experiments, use the tracking-calorimeter approach to provide “smoking gun” evidence, measure multiple isotopes and attempt to characterise the mechanism of $0\nu\beta\beta$ decay.
From NEMO-3 to SuperNEMO

NEMO-3

- **$^{100}$Mo**
- **7 kg**
- **$^{208}$Tl**: $\sim 100$ μBq/kg
- **$^{214}$Bi**: $< 300$ μBq/kg
- **Rn**: 5 mBq/m³
- **8% @ 3MeV**
- **$T_{1/2} (\beta\beta0\nu) > 1.1 \times 10^{24}$ y**
- **$<m_\nu> < 0.3 - 0.6$ eV**

SuperNEMO

- **$^{82}$Se (or $^{150}$Nd or $^{48}$Ca)**
- **100+ kg**
- **$^{208}$Tl**: $\leq 2$ μBq/kg
- **$^{214}$Bi**: $\leq 10$ μBq/kg
- **Rn**: $\leq 0.15$ mBq/m³
- **4% @ 3 MeV**
- **$T_{1/2} (\beta\beta0\nu) > 1 \times 10^{26}$ y**
- **$<m_\nu> < 0.04 - 0.1$ eV**

R&D since 2006

- **Isotope**
- **Isotope mass $M$**
- **Contaminations in the $\beta\beta$ foil**
- **Rn in the tracker**
- **Calorimeter energy resolution (FWHM)**
- **Sensitivity**
SuperNEMO Demonstrator

- **Location:** LSM
- **ββ Source** (40-50mg/cm² foil)
  - Baseline: $^{82}\text{Se}$ (high Q$_{ββ}$, long T$_{1/2}$ (2ν))
  - Possibility to add $^{150}\text{Nd}$, $^{48}\text{Ca}$ almost any isotope possible
- **Tracker**
  - drift chamber (95% He + 4%C$_2$H$_5$OH + 1%Ar) ~2000 cells in Geiger mode
- **Calorimeter**
  - 550 PMTs + scintillators + endcap + veto
- **25G B-field**
- **Passive shielding:** iron + water
- **Anti-Rn system**

Full baseline SuperNEMO:

15-20 Demonstrator-like modules with 5-7kg of isotope = 100kg

Straightforward extrapolation due to modular design!
### SuperNEMO Demonstrator Goals

**Aiming at zero background**

<table>
<thead>
<tr>
<th>Events in window $E_{\text{sum}} \in [2.8, 3.2]$ MeV</th>
<th>NEMO-3 Phase 2 (29 kg.yr)</th>
<th>Demonstrator Module (29 kg.yr)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Bkgnd</td>
<td>$&lt;0.16$</td>
<td>$&lt;0.16$</td>
<td>(conservative)</td>
</tr>
<tr>
<td>Bi$^{214}$ from Rn$^{222}$</td>
<td>$2.5 \pm 0.2$</td>
<td>$0.07$</td>
<td>radon reduction</td>
</tr>
<tr>
<td>Bi$^{214}$ internal</td>
<td>$0.80 \pm 0.08$</td>
<td>$0.07$</td>
<td>internal contamination reduction</td>
</tr>
<tr>
<td>Ti$^{208}$ internal</td>
<td>$2.7 \pm 0.2$</td>
<td>$0.05$</td>
<td></td>
</tr>
<tr>
<td>2νββ</td>
<td>$7.16 \pm 0.05$</td>
<td>$0.20$</td>
<td>Mo$^{100}$ to Se$^{82}$ 8% to 4% resolution</td>
</tr>
<tr>
<td>Total expected</td>
<td>$13.1 \pm 0.3$</td>
<td>$0.39$</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>12</td>
<td>N/A (yet)</td>
<td></td>
</tr>
</tbody>
</table>

- **Demonstrator** 17.5 kg.yr (~2.5 yr of running)
  - $T_{1/2} > 6.5 \times 10^{24}$ yr, $\langle m_\nu \rangle < 0.16 — 0.40$ eV (90%CL)
- **Straightforward extrapolation** to full SuperNEMO (20 modules)
- **Full SuperNEMO**
  - $T_{1/2} > 1 \times 10^{26}$ yr, $\langle m_\nu \rangle < 0.04 — 0.10$ eV (90%CL)

NEMO-3 sensitivity in 4.5 months!
SuperNEMO Low Background Program

SuperNEMO **Strategy**: Background **Reduction** (U, Th, Rn assays) and **Rejection** (topology, timing etc)

- **SuperNEMO Demonstrator Module**
  - 20 tons

1kg of bananas = 100 Bq

Dedicated facilities developed, built and commissioned

**Rn removal** from gas with cold charcoal trap:

- **He**: $10^{10}$(!) suppression, complete removal
- **N$_2$**: $\sim$$x20$ suppression purification down to 20µB/m$^3$ (measured!)

**Rn Concentration Line** (RnCL)

<table>
<thead>
<tr>
<th>Minimum Detectable Activity / µBq/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
</tr>
<tr>
<td>35</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>25</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>15</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

**SN $^{222}$Rn Concentration Line**

- CL = 90%
- $A_{\text{Trap}} = 0.23$ mBq
- $A_{\text{Det}} = 0.29$ mBq
- $f = 10.0$ lpm
- $\epsilon_{\text{Det}} = 35\%$
- $\epsilon_{\text{Trap}} = 92\%$

$2.4 \, ^{222}\text{Rn atoms/m}^3$ of N$_2$/He/Ar/etc. or 1 part in $10^{25}$ !!!
SuperNEMO Low Background Program

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 Feb’13 @LSC (Canfranc)

+ low background HPGe facilities at LSM, Bordeaux and Boulby
Tracker Cell Production (completed)
2034 cells, ~13,000 wires
Tracker Assembly and Commissioning (completed)

4 C-shaped tracker modules
Rn emanation from fully assembled tracker
Target (150 μBq/m³) reached!

Commissioning with cosmic rays
Quarter-tracker zoomed view
All 4 quarter-tracker modules delivered to LSM
How the particle that led Bohr to think energy might not be conserved could lead the next revolution in physics

Neutrinos are ubiquitous, but mysterious. A Nobel prize was awarded this year for the discovery that they have mass, and undergo quantum oscillations as they travel - discoveries that fundamentally changed our understanding of physics and cosmology. A rare nuclear decay, being searched for now, might lead to a similar revolution.
Calorimeter Production

\[ \frac{\sigma}{E} = 1.8\% @ 3 \text{ MeV} \]

Major Breakthrough!

- 8” PMTs with large blocks (440 modules)
- 5” PMTs in outer rows/columns, endcaps and veto
- Every block characterised
- Production completed — performance on target!
  - Paper submitted to NIM A
Calorimeter Construction

- Both calorimeter walls are assembled and installed at LSM
- Light Injection calibration system to monitor gain drift within 1%
Calorimeter Integration at LSM
Detector integration at LSM
Half of detector (calorimeter + tracker) fully integrated
First events from half-detector commissioning! Mar’17
ββ Source Module and Calibration Sources Deployment System

- Calibration sources: $^{207}$Bi + $^{60}$Co + others
  - “Rn-free” deployment system

- 7kg $^{82}$Se produced and purified
- R&D on $^{150}$Nd and $^{48}$Ca
- Source foil installation this summer

$^{82}$Se foil production at ITEP

$^{82}$Se foil production at LAPP
Electronics, Slow Control and DAQ

- **Electronic architecture (demonstrator):**
  - 52 Calorimeter FEB (712 Channels).
  - 57 Tracker FEB (6102 channels).
  - 6 Control and Readout Board.
  - 1 Trigger board.

- **Tracker rack** (3 crates)
- **Calorimeter rack** (3 crates)

**SN_CalFEB**

**SN_Trigger**

**SN_Tracker_FEB**

**SN_CROB**

**SN_FEB**

- **Data**
- **Trigger and data path**

**SN_TRIGGER**

- **Trigger Primitives (TP)**
- **12 SerDes link**
- **18 bit@40Mhz**
- **720Mbps (92LV18)**

**Hub**

**CMS**

**DAQ**

**Tracker FEB**
SuperNEMO Demonstrator Schedule

- Source installation complete by Aug’17
- Integration, commissioning, passive shielding by end 2017
  - first physics data without shielding (external backgrounds)
- Start running for physics early 2018
- Measure target levels of $^{214}$Bi in foil and $^{222}$Rn within couple of months
- $^{208}$Tl ~ 1 year
- Target sensitivity ($6.5 \times 10^{24}$ yr) in 2.5 yr
- Critical input to future tracko-calco and other $\beta\beta$ experiments — unique ability to constrain and characterise backgrounds
Full SuperNEMO — 15-20 modules, 100kg of isotope(s)

- Distributed location in different underground labs possible/beneficial
- Construction can proceed in parallel with data taking
- Can provide superior sensitivity with high $Q_{\beta\beta}$ isotopes ($^{150}\text{Nd}$, $^{48}\text{Ca}$, $^{96}\text{Zr}$)
- Cost range: €2.5M/module
- Expensive to extrapolate >100kg

Is it possible to reduce footprint and cost? In particular, is it possible to achieve detector cost $\leq$ isotope cost?
SuperNEMO Design with scintillator bars

- Fewer much cheaper PMTs (with less radioactivity)
- Compact design
- Very high (close to ~100%) efficiency of $\gamma$ tagging
- No B-field. Tagging e+ with 511 keV $\gamma$'s $\Rightarrow$ better efficiency

$\sigma_E/E (3 \text{ MeV}) = 2.3\%$ (c.f. 1.9% for baseline design)

Disclaimer: One of ideas being discussed within collaboration rather than agreed direction of travel.
SuperNEMO Design with scintillator bars

Background suppression with bars. Top View.

- 14mx14mx2.5m sufficient to accommodate 100kg of isotope*
- Detector cost estimate: ~€50k per kg of isotope (c.f. >€250k/kg for baseline design),
- i.e. detector cost ~ isotope cost

* Can fit in new hall at Boulby lab

Input from Demonstrator (background, resolutions and their interplay) crucial!

- Further optimisation possible/needed
  - Fewer tracker cells, perhaps 3-4 hits enough?
  - Shorter distance between foil and calorimeter — more compact, higher efficiency
- Readout
- ....

scalability
Scalability of topological technique

All ~tonne detectors will be background limited

- Hard to model
- many unknown backgrounds
- systematic becomes dominant factor

- Can achieve 2νββ only background in principle.
- Can be constrained with minimum systematics (>10^7 events)!
Topological approach to bb detection is unique

- Smoking gun signature and comprehensive background characterisation
- Isotope flexibility
- Sensitive to different 0νββ mechanisms
- Rich physics potential outside 0νββ, both BSM (Lorentz violation, 0ν4β, bosonic neutrino) and nuclear models (e.g. Single State Dominance vs Higher State Dominance) as demonstrated by NEMO-3

Unlike most other approaches can in principle eliminate all backgrounds apart from 2νββ.

If radioactive backgrounds and cost (detector~isotope) are brought under control — topological technique can be in principle scalable to tonnes.

Even better if enrichment of high Qββ isotopes becomes feasible

In case of discovery — best way for full characterisation of 0νββ
BACKUP
New Underground Lab at Boulby

- Large Experimental Hall: 45m(L) x 7m(W) x 6.5m(H). Class < 10,000 cleanroom throughout.
- Low background screening laboratory: < 1,000 cleanroom
- 10T lifting capacity
- Transportation capacity: 2m x 2.1m x 2.1m in manshaft cage. Up to 8m long items with a week notice. Larger than in SNO and Homestake
- Uninterrupted Power Supply, 100-1000 Mbps internet
- Low natural Rn, 2.5 Bq/m³
- Essentially ready for beneficial occupancy
Background: The Enemy and how to fight it

- **External** $\gamma$ (if the $\gamma$ is not detected in the scintillators)
  
  Origin: natural radioactivity of the detector or neutrons
  
  Major bkg for $2\nu\beta\beta$ but small for $0\nu\beta\beta$
  
  $^{100}\text{Mo}$ and $^{82}\text{Se}$ $Q_{\beta\beta} \sim 3 \text{ MeV} > E_{\gamma}(^{208}\text{TI}) \sim 2.6 \text{ MeV}$

- $^{232}\text{Th}$ ($^{208}\text{TI}$) and $^{238}\text{U}$ ($^{214}\text{Bi}$) contamination inside the $\beta\beta$ source foil

- **Radon** ($^{214}\text{Bi}$) inside the tracking detector
  - deposits on the wire near the $\beta\beta$ foil
  - deposits on the surface of the $\beta\beta$ foil

Each bkg is measured using the NEMO-3 data
NEMO-3 Event Display

$1e1\alpha \ (^{214}{\text{Bi}} \rightarrow ^{214}{\text{Po}})$

External $\gamma$
Crossing electron (external BG)
Anti-radon “factory” - trapping Rn in cooled charcoal. A must for a low-background lab.

Measurements of $^{222}$Rn activity in the gas of tracker (mBq/m$^3$)

- **Phase 1**: Feb’03 → Sep’04
  - $A_{(Radon)} \approx 40 \text{ mBq/m}^3$

- **Phase 2**: Dec. 2004 → Jan’11
  - $A_{(Radon)} \approx 5 \text{ mBq/m}^3$

Anti-Rn factory: Input=15Bq/m$^3$ → Output 15mBq/m$^3$

Inside the detector:
- **Phase 1**: Feb’03 → Sep’04
  - $A_{(Radon)} \approx 40 \text{ mBq/m}^3$

- **Phase 2**: Dec. 2004 → Jan’11
  - $A_{(Radon)} \approx 5 \text{ mBq/m}^3$

**Pure sample of $^{214}$Bi – $^{214}$Po events**

$T_{1/2}=162.9 \mu$s

Delay time of the $\alpha$ track ($\mu$s)

"Handbook" on backgrounds for $\beta\beta$ experiments:
NEMO3: 100Mo decay to excited states

$2\nu2\beta$ to excited states of $^{100}$Mo:
$\tau^{2\nu}_{1/2}(0^+ \rightarrow 0^+_1) = 5.7^{+1.3}_{-0.9} \text{ (stat)} \pm 0.8 \text{ (stat)} \times 10^{20}$ y
$\tau^{2\nu}_{1/2}(0^+ \rightarrow 2^+_1) > 1.1 \times 10^{21}$ y @ 90% CL

$0\nu2\beta$ to excited states of $^{100}$Mo:
$\tau^{0\nu}_{1/2}(0^+ \rightarrow 0^+_1) > 8.9 \times 10^{22}$ y @ 90% CL
$\tau^{0\nu}_{1/2}(0^+ \rightarrow 2^+_1) > 1.6 \times 10^{23}$ y @ 90% CL


Other results coming soon on $^{150}$Nd and $^{96}$Zr

\[ \lambda \approx \left( \frac{M_{W_L}}{M_{W_R}} \right)^2 \sqrt{\frac{m_v}{M_R}} \]
Radon activity measurement

Requirement: Rn activity inside tracker < 150 µBq/m³

Radon Concentration Line (RnCL)

- RnCL sensitivity (90%CL)
  - C-tracker < 50 µBq/m³
  - Large gas volume < 5 µBq/m³

- Measurements of Rn emanation from materials
- Rn permeability measurements through membranes/seals
Gas Flow Rate Study

\[ S = \frac{1}{(\phi \tau / V) + 1} \]

- The tracker works at high flow rates: a possible solution for suppressing radon.