NEMO-3 and SuperNEMO
A search for zero neutrino double beta decay

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NOW 2010
Why event reconstruction is useful

$2\nu\beta\beta$
- Allowed by the standard model
- Irreducible background in the search for $0\nu\beta\beta$
- Input into NME calculations

$0\nu\beta\beta$
- Not allowed by the standard model
- Neutrino must be Majorana
- New physics mechanisms may contribute e.g. Majaron
  - arXiv: 1005.1241

- Powerful background rejection tool

- If we observe $0\nu\beta\beta$ then studying the 2e, 1e energy + angular distributions will give information about the production mechanism.
Neutrino Ettore Majorana Observatory
Fréjus Underground Laboratory : 4800 m.w.e.

Source: 10 kg of $\beta\beta$ isotopes
cylindrical, $S = 20 \text{ m}^2$, $d \sim 60 \text{ mg/cm}^2$

Tracking detector:
drift wire chamber operating
in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H$_2$O

Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs

Magnetic field: 25 Gauss
Gamma shield: Pure Iron ($d = 18$ cm)
Neutron shield: 30 cm water (ext. wall)
40 cm wood (top and bottom)
(since march 2004: water + boron)

Particle ID: $e^-$, $e^+$, $\gamma$ and $\alpha$
Event reconstruction

Observables of the final state
- Trajectories of the 2 electrons
- Energies of the 2 electrons
- Time of flight
- Curvature of the tracks in a B-field (+ or -).

Backgrounds are measured using event topology and timing to produce a background model for $\beta\beta$.
$^{100}\text{Mo} \ 2\nu\beta\beta$ updated result

\begin{align*}
T_{1/2}(2\nu) &= [7.17 \pm 0.01(\text{stat}) \pm 0.54(\text{sys})] \times 10^{18} \text{ yr} \Rightarrow \sim 3.5 \text{ yr}, \text{ Phase II (low Rn), } S/B = 76 \\
M^{2\nu}(^{100}\text{Mo}) &= 0.126 \pm 0.006
\end{align*}

This is an update of a previous published result using phase I data

*Phys. Rev. Lett. 95 182302 (2005)*

\begin{align*}
T_{1/2}(2\nu\beta\beta) &= 7.11 \pm 0.02 \ (\text{stat}) \pm 0.54 \ (\text{syst}) \times 10^{18} \text{ years, } S/B = 40
\end{align*}
2νββ results for other isotopes (preliminary)

Many more results available. Excited states, 0ν for different mechanisms and isotopes

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$0\nu\beta\beta$ for $^{100}\text{Mo} (~7\text{kg})$ and $^{82}\text{Se} (~1\text{kg})$

[2.8-3.2] MeV: DATA = 18; MC = 16.4±1.4
$T_{1/2}(0\nu) > 1.0\times10^{24}$ yr at 90%CL
$\langle m_\nu \rangle < (0.47 - 0.96)$ eV

V+A: $T_{1/2}(0\nu) > 5.4\times10^{23}$ yr at 90%CL
Majoron: $T_{1/2}(0\nu) > 2.1\times10^{22}$ yr at 90%CL

[2.6-3.2] MeV: DATA = 14; MC = 10.9±1.3
$T_{1/2}(0\nu) > 3.2\times10^{23}$ yr at 90%CL
$\langle m_\nu \rangle < (0.94 - 2.5)$ eV

$\lambda < 1.4\times10^{-6}$
$g_{ee} < 0.5\times10^{-4}$ World’s best result!
SuperNEMO Collaboration

~ 100 physicists, 10 countries, 27 Institutions

USA
MHC
INL
U Texas

Marocco
Fes U

UK
UCL
U Manchester
Imperial College
Warwick

France
CEN Bordeaux
IRES Strasbourg
LAL ORSAY
LPC Caen
LSCE Gif/Yvette
Marseille

Finland
U Jyvaskula

Russia
JINR Dubna
ITEP Mosow
Kurchatov Institute

Slovakia
(Charles U Praha
IEAP Praha)

Czech Republic
(Charles U Praha
IEAP Praha)

Spain
U Valencia
U Saragossa
U Barcelona

Japan
U Saga
KEK
U Osaka
## Objectives of the 4 year R&D programme

<table>
<thead>
<tr>
<th>NEMO-3</th>
<th>SuperNEMO</th>
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<tbody>
<tr>
<td><strong>${^{100}\text{Mo}}$</strong></td>
<td><strong>$^{82}\text{Se}$ or other</strong></td>
</tr>
<tr>
<td><strong>7 kg</strong></td>
<td><strong>100+ kg</strong></td>
</tr>
<tr>
<td><strong>18 %</strong></td>
<td><strong>$\sim 30%$</strong></td>
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<tr>
<td><strong>$^{208}\text{Tl}$: $\sim 100\ \mu\text{Bq/kg}$</strong></td>
<td><strong>$^{208}\text{Tl} \leq 2\ \mu\text{Bq/kg}$</strong></td>
</tr>
<tr>
<td><strong>$^{214}\text{Bi}$: $&lt; 300\ \mu\text{Bq/kg}$</strong></td>
<td><strong>if $^{82}\text{Se}$: $^{214}\text{Bi} \leq 10\ \mu\text{Bq/kg}$</strong></td>
</tr>
<tr>
<td><strong>Rn: 5 mBq/m$^3$</strong></td>
<td><strong>Rn \leq 0.15 mBq/m$^3$</strong></td>
</tr>
<tr>
<td><strong>8% @ 3 MeV</strong></td>
<td><strong>4% @ 3 MeV</strong></td>
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$T_{1/2}(\beta\beta0\nu) > 2 \times 10^{24}\ \text{y}$

$\langle m_\nu \rangle < 0.3 - 0.9\ \text{eV}$

$T_{1/2}(\beta\beta0\nu) > 1 \times 10^{26}\ \text{y}$

$\langle m_\nu \rangle < 0.04 - 0.11\ \text{eV}$

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Calorimeter R&D to improve energy and time resolution

Each module will have 550 PMTs + scintillator blocks

Scintillator

- Material
- Shape
- Size
- Coating

PMT

- QE
- Uniformity
- Collection efficiency
- Radiopurity

Required resolution demonstrated with 28cm Hex block (≥10cm thick) directly coupled to 8” PMT

FWHM = 4% @ \( Q_{\beta\beta} = 3 \text{ MeV} \)
Tracker R&D
Optimise: length, diameter, readout and gas mixture

• Constructed several prototype single cells of differing lengths and diameters.
• Then progressed to a 9-cell to look at the configuration of the fields and cross-talk.
• From this work a 90-cell prototype was constructed.

Cosmic muon used for testing of reconstruction algorithm

Transverse 0.7mm, longitudinal 1cm
Overall cell efficiency of >98%
Wiring robot

For the full 20 modules in excess of 0.5M wires will need to be strung.

A wiring robot is being developed at the Mullard Space Science Laboratory.

The wiring will be carried out in a clean-room environment with as little human intervention as possible.

Protoype robot being developed at MSSL

90-cell opened up
Production of the $\beta\beta$ Source Foil

• Preferred candidate for the source is $^{82}$Se (others being investigated).
• Enrichment of 100 kg by centrifugation is possible.
• The density on the foil is 40-50 mg/cm$^2$.
• Radio-purity: $^{208}$Tl < 2 µBq/kg, $^{214}$Bi < 10 µBq/kg
• Chemical and physical purification methods

Dedicated BiPo detector to measure low radio-purity levels
Using a GEANT-4 based model of the detector combined with NEMO-3 experience.

5 yrs with 100 kg $^{82}$Se: $T_{1/2}(\beta\beta0\nu) > 1 \times 10^{26}$ y
$<m_\nu> < 0.05 - 0.1$ eV
A SuperNEMO module

• 20 modules having a Planar design.
• Each module will have 5kg of enriched isotope.
• Making a total of 100 kg.
• Drift chamber ~2000 cells in Geiger mode.
• 550 PMTs + scintillator blocks.
1st SuperNEMO module - Demonstrator

- Demonstrate that mass production is possible.
- Study the backgrounds with an emphasise on radon emanation.
- Make a competitive physics measurement

0.3 expected bkg events in 2.8 - 3.2 MeV with 7kg of $^{82}$Se in 2 yr

Sensitivity by 2015: $6.5 \cdot 10^{24}$ yr (90% CL)

Equivalent to $3 \cdot 10^{25}$ yr for $^{76}$Ge (using phase space ratio only)

or ~4 expected “golden events” if KK claim is correct
Integration of the sub-systems

The sub-systems are being produced in many labs; UK, France, Russia …..

Several of these require a clean room and will be integrated in a laboratory at MSSL.

We will commission the sub-systems.

It will then be transported to Modane for full integration.
LSM Extension

Schedule

• Safety tunnel construction start - Sep 2009
• Safety tunnel, end of civil construction - End 2011
• Detailed study of LSM extension (ULISSE) - 2010
• Deadline for final decision/money commitment - May 2011
• Excavation of new Lab completed - mid-2012
• Outfitting completed, Lab ready to host experiments - 2013

Minimal scenario: 45,000m³ (100m long), 12M€ excavation + 3M€ outfitting

2nd ULISSE workshop in October. 11 LOIs received.
SuperNEMO schedule highlights

- NEMO-3 decommissioning - early 2011
- Demonstrator construction - 2010-2012
- Demonstrator physics run start-up - 2013
- Full detector construction start-up - 2014
- Target sensitivity (~0.05 eV) - 2019

KK claim to be verified with Demonstrator by 2015
BACKUP
$\beta\beta$ decay isotopes in NEMO-3 detector

- $^{100}$Mo $6.914 \text{ kg}$
  - $Q_{\beta\beta} = 3034 \text{ keV}$

- $^{82}$Se $0.932 \text{ kg}$
  - $Q_{\beta\beta} = 2995 \text{ keV}$

- $^{116}$Cd $405 \text{ g}$
  - $Q_{\beta\beta} = 2805 \text{ keV}$

- $^{96}$Zr $9.4 \text{ g}$
  - $Q_{\beta\beta} = 3350 \text{ keV}$

- $^{150}$Nd $37.0 \text{ g}$
  - $Q_{\beta\beta} = 3367 \text{ keV}$

- $^{48}$Ca $7.0 \text{ g}$
  - $Q_{\beta\beta} = 4272 \text{ keV}$

- $^{130}$Te $454 \text{ g}$
  - $Q_{\beta\beta} = 2529 \text{ keV}$

- nat$^{130}$Te $491 \text{ g}$

- Cu $621 \text{ g}$

(Enriched isotopes produced by centrifugation in Russia)

$\beta\beta$0ν search

$\beta\beta$2ν measurement

External bkg measurement

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NEMO-3 Backgrounds for $\beta\beta$

- **External $\gamma$** (if the $\gamma$ is not detected in the scintillators)
  
  Origin: natural radioactivity of the detector or neutrons
  
  Main bkg for $\beta\beta2\nu$ but negligible for $\beta\beta0\nu$
  
  $(^{100}\text{Mo and } ^{82}\text{Se } Q_{\beta\beta} \sim 3 \text{ MeV} > E\gamma(^{208}\text{Tl}) \sim 2.6 \text{ MeV})$

- **$^{232}\text{Th (}^{208}\text{Tl)}$ 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

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Example: Radon inside the tracking detector

$^{214}\text{Bi} \rightarrow ^{214}\text{Po} \rightarrow ^{210}\text{Pb}$ (164 $\mu$s)

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

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

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

Monitoring of the Radon bkg every day

- Phase 1: Feb. 2003 $\rightarrow$ Sept. 2004
  Radon Contamination
- Phase 2: Dec. 2004 $\rightarrow$ Today
  $A$ (Radon) $\approx 5$ mBq/m$^3$

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Radon trapping facility
(First developed for SuperKamiokande)

Phase I: February 2003 – September 2004 (radon background in data)
~ 1 0νββ-like event/ν/kg with 2.8 < E₁+E₂ < 3.2 MeV

Phase II: since October 2004 (radon level reduced by a factor of 6)

1 ton of charcoal @ -50°C, 9 bars
air flux = 150 m³/h
Input: A(²²²Rn) 15 Bq/m³

Output: A(²²²Rn) < 15 mBq/m³ !!!
reduction factor of 1000

Inside the NEMO 3 tent: factor of 100 – 300
Inside NEMO 3: almost factor of 10 A(²²²Rn) ≈ 6 mBq/m³

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Neutrinos are massive and they mix

What else do we want to know?

- Number of neutrinos: Are there sterile neutrinos?

- $\theta_{13}$, Precision values of mixing angles and $\Delta m^2$'s

- Absolute neutrino mass value. Only limits so far.
  Tritium: $m_{\nu_e} < 2.3$ eV
  Cosmology: $\sum m_{\nu} < 1$ eV

- Neutrino mass spectrum: Normal ($m_1 < m_2 < m_3$)
  Inverted ($m_3 < m_1 < m_2$) or Quasi-degenerate ($m_1 \approx m_2 \approx m_3$)?

- Origin of matter-antimatter asymmetry.
  CP-violation in lepton sector: $\delta \neq 0,\pi$ and/or $\alpha,\beta \neq 0,\pi$?

- Nature of Neutrinos: Majorana ($\nu = \text{anti-}\nu$) or Dirac ($\nu \neq \text{anti-}\nu$)?
  Full lepton number violation (required in most Grand Unification Theories).
Physics Studies

Full chain of GEANT-4 based software + detector effects + NEMO3 experience

$^{82}$Se

Exposure 500 kg y

$T_{1/2} > 10^{26}$ yr, $<m_\nu> < 50-100$ meV at 90%CL with target detector parameters

Much more than 1 result!
- Other mechanisms: V+A, Majoron, etc
- Disentangling $<m_\nu>$ and V+A:
  - arXiv: 1005.1241
- $\beta\beta 0\nu$ (and 2\nu) to excited states
Open-minded search for any 0νββ mechanism

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

η can be due to \( \langle m_\nu \rangle \), V+A, Majoron, SUSY, H⁻ or a combination of them

\[ \langle m_\nu \rangle \]

**V+A**

\[ \theta - \text{angle between } e_1 \text{ and } e_2 \]

\[ E_1 - \text{single } e^- \text{ energy, keV} \]

Topography can be used to disentangle underlying physics mechanism

**V+A**

\[ \langle m_\nu \rangle \]

**Majoron**

Topology detection is a more sensitive method for phenomena with continuous spectra, e.g. 2νββ, 0νβββ (Majoron)