Search for Neutrinoless Double-β Decay of $^{100}$Mo in the final NEMO-3 dataset

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University College London

on behalf of the NEMO collaboration

XLIX$^{th}$ Rencontres de Moriond
Electroweak Interactions and Unified Theories
La Thuile, 15$^{th}$-22$^{nd}$ March 2014
Which processes cause double beta decay?

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

\( \eta \) can be due to mass mechanism, V+A, majoron, SUSY, ... with different topology in the final state

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Measuring the Lepton Number Violating parameter

- need to know the Nuclear Matrix Element (NME)
- variation between models and isotopes
- combine measurements from as many isotopes as possible

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

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Abundance (%)</th>
<th>(Q_{\beta\beta}) (MeV)</th>
<th>(G_{\text{0}\nu}^{0\nu}) (10^{-14} y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>48Ca</td>
<td>0.19</td>
<td>4,276</td>
<td>7.15</td>
</tr>
<tr>
<td>76Ge</td>
<td>7.8</td>
<td>2,039</td>
<td>0.71</td>
</tr>
<tr>
<td>82Se</td>
<td>9.2</td>
<td>2,992</td>
<td>3.11</td>
</tr>
<tr>
<td>100Mo</td>
<td>9.6</td>
<td>3,034</td>
<td>5.03</td>
</tr>
<tr>
<td>116Cd</td>
<td>7.5</td>
<td>2,804</td>
<td>5.44</td>
</tr>
<tr>
<td>130Te</td>
<td>34.5</td>
<td>2,529</td>
<td>4.89</td>
</tr>
<tr>
<td>136Xe</td>
<td>8.9</td>
<td>2,467</td>
<td>5.13</td>
</tr>
<tr>
<td>150Nd</td>
<td>5.6</td>
<td>3,368</td>
<td>23.2</td>
</tr>
</tbody>
</table>

m_{\beta\beta} = 50 \text{ meV}

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**NEMO3**

- The particle physicist’s nuclear physics experiment.
- “Smoking gun”: complete event reconstruction for:
  - background rejection
  - signal characterization (discovery!)

**Isotopes**

Large quantities: $^{100}$Mo (7kg) $^{82}$Se (1 kg)
Small quantities: $^{116}$Cd $^{150}$Nd $^{48}$Ca $^{96}$Zr $^{130}$Te
All major isotopes except $^{76}$Ge and $^{136}$Xe
NEMO3

- source distributed on cylindrical surface
- 3D wire drift chamber operated in Geiger mode (6180 cells)
  - He + 4% ethyl alcohol + 1% Ar + 0.1% H$_2$O
- calorimeter made of 1940 plastic scintillators coupled to low radioactivity PMTs
- Magnetic field: 25 Gauss
- Gamma shield: iron
- Neutron shield:
  - 30cm borated water (external wall)
  - 40cm wood (top and bottom)
- Two separate runs:
  - Phase 1, “High” Rn: Feb, 2003 → Sep, 2004
Backgrounds

In addition to $\beta\beta(2\nu)$, $^{214}$Bi and $^{208}$Tl contribution

Internal Background
Backgrounds

External Background

Radio-impurities in material, $\gamma$ from $(n,\gamma)$, $(n,n'\gamma)$ and $\mu$ bremstrahlung

Reduction by a factor at least 100 compared to calorimeters

In addition to $\beta\beta(2\nu)$, $^{214}\text{Bi}$ and $^{208}\text{Tl}$ contribution

Internal Background

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Backgrounds

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External Background

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In addition to $\beta\beta(2\nu)$, $^{214}\text{Bi}$ and $^{208}\text{TI}$ contribution

Internal Background

Radon Background

Radon daughter ($^{214}\text{Bi}$) deposited on the Source foil or near wires

Some of these backgrounds are rejected by $\gamma$, X or delayed $\alpha$ detection
Backgrounds measurements

External background: $e\gamma$-external

Internal $^{214}$Bi : $e\alpha(\gamma)$-events from foil

External background: $e$-crossing events

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Selection of $\beta\beta$ events

Criteria to select $\beta\beta$ events
- 2 tracks with charge < 0
- 2 PMT, each > 200 keV
- PMT-Track association
- Common vertex
- Internal hypothesis (external event rejection)
- No other isolated PMT ($\gamma$ rejection)
- No delayed track ($^{214}\text{Bi}$ rejection)

Run: 3478
Event: 6930
Date: 09/11/2004

$(\Delta\text{vertex}) = 3 \text{ cm}$
0νββ $^{100}$Mo - Final sample

NEMO-3 - $^{100}$Mo - 7 kg, 5 y

$E_{TOT} \in [2.8, 3.2]$ MeV

<table>
<thead>
<tr>
<th>Sample</th>
<th>Entries</th>
</tr>
</thead>
<tbody>
<tr>
<td>External bkgs</td>
<td>$&lt; 0.2$</td>
</tr>
<tr>
<td>$^{214}$Bi from $^{222}$Rn</td>
<td>$5.2 \pm 0.5$</td>
</tr>
<tr>
<td>$^{214}$Bi internal</td>
<td>$1.0 \pm 0.1$</td>
</tr>
<tr>
<td>$^{208}$Tl 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>
</tbody>
</table>

Observed events: 15

Efficiency = 4.7%
Exposure = 34.7 kg·y

0 events observed in the range $E_{TOT} \in [3.2, 10]$ MeV

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0νββ $^{100}$Mo - Limits on the half-life

- modified frequentist analysis
- $E_{TOT} \in [2.0, 3.2]$ MeV
- account for statistical and systematic uncertainties and their correlations

<table>
<thead>
<tr>
<th>0νββ process</th>
<th>Stat. Only</th>
<th>Systematics</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass mechanism</td>
<td>1.1</td>
<td>1.1</td>
<td>1.0 [0.7, 1.4]</td>
</tr>
<tr>
<td>$q_{r.h.} - l_{r.h.}$ coupling $\langle \lambda \rangle$</td>
<td>0.7</td>
<td>0.6</td>
<td>0.5 [0.4, 0.8]</td>
</tr>
<tr>
<td>$q_{r.h.} - l_{l.h.}$ coupling $\langle \eta \rangle$</td>
<td>1.0</td>
<td>1.0</td>
<td>0.9 [0.6, 1.3]</td>
</tr>
<tr>
<td>Majoron</td>
<td>0.050</td>
<td>0.044</td>
<td>0.039 [0.027, 0.059]</td>
</tr>
</tbody>
</table>

Systematics:
- 0νββ reconstruction efficiency: 7%
- 2νββ events in window: 0.7%
- $^{208}$Tl contamination: 10%
- $^{214}$Bi contamination: 10%

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0νββ - Limits @ 90% C.L. on LNV parameters

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

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Exposure (kg·y)</th>
<th>Half life ((10^{25} \text{y})) published</th>
<th>(\langle m_\nu \rangle) (eV) published</th>
<th>(\langle m_\nu \rangle) (eV) calculated</th>
<th>(\langle \lambda \rangle) ((10^{-6})) published</th>
<th>(\langle \eta \rangle) ((10^{-8})) published</th>
<th>(\lambda'_{111}/f) ((10^{-2})) published</th>
<th>(\langle g_{ee} \rangle) ((10^{-5})) published</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{100}\text{Mo}) [1]</td>
<td>34.7</td>
<td>0.1</td>
<td>0.33 - 0.87</td>
<td>0.33 - 0.87</td>
<td>0.9 - 1.3</td>
<td>0.5 - 0.8</td>
<td>4.4 - 6.0</td>
<td>2 - 5</td>
</tr>
<tr>
<td>(^{130}\text{Te}) [2][3]</td>
<td>19.75</td>
<td>0.3</td>
<td>0.31 - 0.71</td>
<td>0.31 - 0.71</td>
<td>1.6 - 2.4</td>
<td>0.9 - 5.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{136}\text{Xe}) [4][5]</td>
<td>89.5</td>
<td>1.9</td>
<td>0.14 - 0.34</td>
<td>0.14 - 0.34</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{136}\text{Xe}) [6]</td>
<td>99.8</td>
<td>1.1</td>
<td>0.19 - 0.45</td>
<td>0.19 - 0.45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{76}\text{Ge}) [7]</td>
<td>21.6</td>
<td>2.1</td>
<td>0.2 - 0.4</td>
<td>0.26 - 0.62</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{76}\text{Ge}) [8]</td>
<td>35.5</td>
<td>1.9</td>
<td>0.4</td>
<td>0.27 - 0.65</td>
<td>1.1</td>
<td>0.6</td>
<td></td>
<td>8.1</td>
</tr>
</tbody>
</table>

- \(\langle m_\nu \rangle\) limits recalculated using updated phase space and NME calculations see refs in [1] hep-ex/1311.5695
- \(f = \left( \frac{M_\tilde{\chi}}{1 \text{TeV}} \right)^2 \left( \frac{M_\tilde{\chi}}{1 \text{TeV}} \right)^{1/2}\)
2νββ $^{100}$Mo Phase 2 data - 7kg x 4 years

- 700000 two-electron events from $^{100}$Mo foils
- $S/B = 76$
- $\varepsilon(2\nu2\beta) = 0.043$
- $T_{1/2}(2\nu2\beta) = [7.16 \pm 0.01\text{(stat)} \pm 0.54\text{(syst)}] \times 10^{18} \text{y} \quad \text{PRELIM.}$

Consistent with the published NEMO-3 result obtained with Phase 1 data:
$T_{1/2} = [7.11 \pm 0.02\text{(stat)} \pm 0.54\text{(syst)}] \times 10^{18} \text{y}$


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**100Mo 2β2ν decay to excited states**

Decays to excited states have several photons in final state

With NEMO3 after 7kg·yr of exposure (Phase1):

\[
T_{1/2}^{2\nu}(0^+ \rightarrow 0^+_1) = 5.7^{+1.3}_{-0.9} \pm 0.8 \, \text{(stat)} \times 10^{20} \, \text{y} \\
T_{1/2}^{0\nu}(0^+ \rightarrow 0^+_1) > 8.9 \times 10^{22} \, \text{y} \, @ \, 90\% \, \text{C.L.} \\
T_{1/2}^{2\nu}(0^+ \rightarrow 2^+_1) > 1.1 \times 10^{21} \, \text{y} \, @ \, 90\% \, \text{C.L.} \\
T_{1/2}^{0\nu}(0^+ \rightarrow 2^+_1) > 1.6 \times 10^{23} \, \text{y} \, @ \, 90\% \, \text{C.L.} \\
\]

### Nuclear Physics A 925 (2014) 25-36
- Measure the γ lines using low background HPGe detector
- 2518g of 100Mo in metallic foils from NEMO3 detector
- Data collected over 2288 hours
- Use 238U, 152Eu and 138La calibrations source: data/MC discrepancy < 7%

\[
T_{1/2}^{2\nu}(0^+ \rightarrow 0^+_1) = 7.5 \pm 0.6 \, \text{(stat)} \pm 0.6 \, \text{(syst)} \times 10^{20} \, \text{y} \\
T_{1/2}^{2\nu}(0^+ \rightarrow 2^+_1) > 2.5 \times 10^{21} \, \text{y} \, @ \, 90\% \, \text{C.L.} \\
\]

**NEW RESULT**

best limits on all other transitions to excited states were set

\[
M_{2\nu}(\text{g.s.})/M_{2\nu}(0^+_1) \sim 1.25 \quad \text{independently on the NME chosen}
\]
## 2νββ Results

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Mass (g)</th>
<th>$Q_{\beta\beta}$ (keV)</th>
<th>$T_{1/2}(2\nu)$ (10^{19} yrs)</th>
<th>S/B</th>
<th>Comment</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>82Se</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) 182302</td>
</tr>
<tr>
<td>116Cd</td>
<td>405</td>
<td>2809</td>
<td>2.8 ± 0.3</td>
<td>10</td>
<td>World’s best!</td>
<td>Phys. Rev. C 80, 032501 (2009)</td>
</tr>
<tr>
<td>150Nd</td>
<td>37</td>
<td>3367</td>
<td>0.90 ± 0.07</td>
<td>2.7</td>
<td>World’s best!</td>
<td>Nucl. Phys. A 847 (2010) 168</td>
</tr>
<tr>
<td>96Zr</td>
<td>9.4</td>
<td>3350</td>
<td>2.35 ± 0.21</td>
<td>1</td>
<td>World’s best!</td>
<td></td>
</tr>
<tr>
<td>48Ca</td>
<td>7</td>
<td>4271</td>
<td>4.4 ± 0.6</td>
<td>6.8 (h.e.)</td>
<td>World’s best!</td>
<td></td>
</tr>
<tr>
<td>100Mo</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) 182302</td>
</tr>
<tr>
<td>130Te</td>
<td>454</td>
<td>2533</td>
<td>70 ± 14</td>
<td>1</td>
<td>First direct detection!!!</td>
<td>Phys. Rev. Lett. 107, 062504 (2011)</td>
</tr>
</tbody>
</table>

First direct observation: $7.7\sigma$ significance

Indirect observations:
- $\sim 2.7 \times 10^{21}$ yrs in $10^9$ yr old rocks
- $\sim 8 \times 10^{20}$ yrs in $10^7$-$10^8$ yr old rocks

Indication from MIBETA Coll in isotopically enriched crystals: $6.1 \pm 1.4$ (st) $+2.9$-$3.5$ (sy) $\times 10^{20}$ yrs
Conclusions

• The unique design of NEMO3 allowed for
  • unique background rejection capabilities
  • measurement of the details of $2\nu\beta\beta$ in several isotopes

• Search of $0\nu\beta\beta$ of $^{100}$Mo in the full data set has lead to the best limit on the half-life of this process
  • limits on the effective Majorana neutrino mass are in the range currently constrained using other isotopes
  • world best limits on several other mechanisms are also provided
Backup
Double-Beta Decay

2-Neutrino Double Beta Decay
- Lepton number conserved.
- Allowed in Standard Model.
- Rate $O(G_F^2)$

0-Neutrino Double Beta Decay
- Lepton number violation:
- Forbidden in Standard Model: $\Delta L = 2$
- Rate($0\nu\beta\beta$) $\ll$ Rate($2\nu\beta\beta$)
Double-Beta Decay : Basic Signature

Measure the summed electron energy and compare to the energy of the transition:

\[ \frac{(E_1 + E_2)}{Q_{\beta\beta}} \in [0, Q_{\beta\beta}] \]

\[ \frac{(E_1 + E_2)}{Q_{\beta\beta}} \approx 1 \]

\[ \otimes \text{ resolution} \]
NEMO3

LSM Modane, France
(Tunnel Frejus, depth of ~4,800 mwe)

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Which Isotopes Can Double-Beta Decay?

Candidate isotopes:

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<th>$Q_{\beta\beta}$ (MeV)</th>
<th>Abundance (%)</th>
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<td>9.2</td>
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<tr>
<td>$^{96}$Zr</td>
<td>3.348</td>
<td>2.800</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>3.034</td>
<td>9.6</td>
</tr>
<tr>
<td>$^{110}$Pd</td>
<td>2.004</td>
<td>11.800</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>2.804</td>
<td>7.5</td>
</tr>
<tr>
<td>$^{124}$Sn</td>
<td>2.530</td>
<td>5.600</td>
</tr>
<tr>
<td>$^{130}$Te</td>
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<td>$^{150}$Nd</td>
<td>3.368</td>
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</tr>
</tbody>
</table>

$^{106}$Cd is a double-EC candidate!

More energetic decay: easier to separate from background. Enrichment often possible, always expensive!
Calibrations

- $^{207}$Bi sources
  - position of 1682 keV peak used for energy scale uncertainty
  - data-MC discrepancy < 0.2%
  - energy scale known @ 2% or PMT is removed
  - systematics on $2e^-$ reconstruction efficiency: 7%
- $^{232}$U sources: systematics on the reconstruction of $^{208}$Tl in the foil: 10%
- gain variations are monitored during the day using light injection system, PMT showing large fluctuations are rejected

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Background: Rn activity

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

Fraction of non-$\alpha$ events: 0.59±1.33%

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

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

Internal background from $\gamma$-emitters($^{208}$Tl,$^{207}$Bi,...): (e$\gamma$,e$\gamma\gamma$,e$\gamma\gamma\gamma$)-events

Internal background from $\beta$-emitters($^{234m}$Pa,$^{40}$K,$^{90}$Y,...): 1e-events
Search for $0\nu\beta\beta$ with $^{82}\text{Se}$

$^{82}\text{Se}$, Phase 1, 1.0 year

$^{82}\text{Se}$, Phase 2, 3.5 years

$[2.6, 3.2]$ MeV:

$\varepsilon(0\nu) = 0.105$
Tot MC= $3.8 \pm 0.5$ , Data: 4 events
MC $2\nu\beta\beta = 0.4 \pm 0.1$
MC radon = $2.4 \pm 0.4$
MC int bkg=$1.0 \pm 0.2$ ($^{214}\text{Bi}=0.55, ^{208}\text{Tl}=0.42$)

$[2.6, 3.2]$ MeV in 4.5 years 14 events observed, 11.1$\pm$1.3 expected

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$^{100}\text{Mo}$ $2\beta 2\nu$ decay to excited states

Event topology:

- $0^+_1$: $2e^- + 2g$ in time & energy and TOF cuts
- $2^+_1$: $2e^- + 1g$ in time & energy and TOF cuts

$T_{1/2}^{2\nu}(0^+ \rightarrow 0^+_1) = 5.7^{+1.3}_{-0.9} \text{(stat)} \pm 0.8 \text{(syst)} \times 10^{20}$ y

$T_{1/2}^{0\nu}(0^+ \rightarrow 0^+_1) < 8.9 \times 10^{22}$ y @ 90% C.L.

$T_{1/2}^{2\nu}(0^+ \rightarrow 2^+_1) > 1.1 \times 10^{21}$ y @ 90% C.L.

$T_{1/2}^{0\nu}(0^+ \rightarrow 2^+_1) > 1.6 \times 10^{23}$ y @ 90% C.L.

SSD/HSD $2\nu\beta\beta$ ($^{100}$Mo)

HSD, higher levels contribute to the decay

SSD, $1^+$ level dominates in the decay

(Abad et al., 1984, *Ann. Fis.* A 80, 9)

$\chi^2/\text{ndf} = 254 / 42$

$k_g E_1 + E_2 > 2\text{ MeV}$

Real data

Electron energy distribution in $2\beta2\nu$ decay of $^{100}$Mo is in favour of Single State Dominance (SSD)

$5.01 \text{ kg} \cdot \gamma$

$E_1 + E_2 > 2\text{ MeV}$

Real data

Single electron spectrum different between SSD and HSD


$\chi^2/\text{ndf} = 42,3 / 42$

$k_g E_1 + E_2 > 2\text{ MeV}$

Real data