An Apparatus to Search for Neutrinoless Double Beta Decay

Benton Pahlka
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On behalf of the NEMO Collaboration

Outline:  
◆ Physics motivation for $0\nu\beta\beta$ and practical factors  
◆ The NEMO-3 Experiment  
◆ Results from NEMO-3  
◆ R&D for SuperNEMO  
◆ SuperNEMO status
Phenomenology of Double Beta Decay

- What is the absolute neutrino mass scale?
- What is the neutrino mass ordering (“mass hierarchy”)?
- Are neutrinos Majorana or Dirac particles?

\[(Z, A) \rightarrow (Z, A + 2) + 2e^- + 2\bar{\nu}_e\]

\[\Delta L = 0\]

\[\Delta L = 2\]

\[\nu = \bar{\nu}\]

\[n \rightarrow p\]

Allowed in the Standard Model

Beyond the Standard Model

\[0\nu\beta\beta\] only possible if neutrinos are massive Majorana particles!
NEMO-3 Experimental Technique

Based on Calorimetry and Tracking

Observables of the final state:

**Tracking:**
- Vertex location
- Trajectory of each electron
- Track curvature from magnetic field
- Angular distribution

**Calorimetry:**
- Energy of each electron
- Time coincidence

Background rejection through:
- PID: identify $e^+$, $e^-$, $\gamma$, $\alpha$
- Event topology
- Particle energy
The NEMO-3 Detector

Thin source foils:
10 kg of $\beta\beta$ isotopes
cylindrical, $S = 20 \text{ m}^2$, 60 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 (18 cm)
Neutron shield: borated water
+ Wood

Radon-free air around the detector
Phase One: Feb 2003 – Oct 2004: high radon
Phase Two: Dec 2004 – today: low radon
NEMO-3 Isotopic Sources

- Twenty sectors
- Seven double beta decay isotopes
- Cu and natTe used to study background
The NEMO-3 Detector

NEMO-3 Installation (2001)

PMTs
scintillators
ββ isotope foils

cathode rings, wire chamber
NEMO-3 Kinematics

Goal: Reconstruct two electrons in the final state
Particle Physics – like approach

Candidate $0\nu\beta\beta$ event if:

\[ E_1 + E_2 = Q_{\beta\beta} \]

Deposited energy:
\[ E_1 + E_2 = 2088 \text{ keV} \]
Internal hypothesis:
\[ (\Delta t)_{\text{mes}} - (\Delta t)_{\text{theo}} = 0.22 \text{ ns} \]
Common vertex:
\[ (\Delta \text{vertex})_\perp = 2.1 \text{ mm} \]

Run Number: 2040
Event Number: 9732
Date: 2003-03-20

Vertex emission

Longitudinal view

(\Delta \text{vertex})_\parallel = 5.7 \text{ mm}
$^{130}\text{Te}$, Low radon, 3.49 y, TS10

$^{100}\text{Mo}$, 3.85 years

$^{82}\text{Se}$, 1 kg, Phase 2, 3.49 y

$^{150}\text{Nd}$

$^{96}\text{Zr}$

$^{48}\text{Ca}$

\[ (7.17 \pm 0.01\,\text{(stat)} \pm 0.54\,\text{(syst)}) \times 10^{18}\,\text{y} \]

\[ [9.6 \pm 0.1\,\text{(stat)} \pm 1.0\,\text{(sys)}] \times 10^{19}\,\text{y} \]

\[ [7.0 \,^{+1.0}_{-0.8}\,\text{(stat)} \,^{+1.1}_{-0.9}\,\text{(sys)}] \times 10^{20}\,\text{y} \]

\[ 1221\,\text{days} \]

\[ 948\,\text{days} \]

\[ 100\,\text{Mo} \]

\[ 82\text{Se} \]

\[ 130\text{Te} \]

\[ 150\text{Nd} \]

\[ 96\text{Zr} \]

\[ 48\text{Ca} \]
$0\nu\beta\beta$: $^{100}\text{Mo}$ and $^{82}\text{Se}$ (Phase 1+2)

End-point energy spectrum

$^{100}\text{Mo}$ exposure: $4.51\text{y} \times 6.914\text{ kg} = 31.18\text{ kg}\cdot\text{y}$

$T_{1/2} (0\nu\beta\beta) > 1.0 \times 10^{24}\text{ y} \ @ \ 90\% \ C.L.$

$<m_\nu> < 0.47 - 0.96 \text{ eV}$

$^{82}\text{Se}$ exposure: $4.51\text{y} \times 0.932\text{ kg} = 4.20\text{ kg}\cdot\text{y}$

$T_{1/2} (0\nu\beta\beta) > 3.2 \times 10^{23}\text{ y} \ @ \ 90\% \ C.L.$

$<m_\nu> < 0.9 - 2.5 \text{ eV}$
NEMO-3 Dismantling

June 13, 2011
NEMO-3 Dismantling

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NEMO-3 to SuperNEMO

\[ T_{1/2}^{0\nu}(n_{\sigma}) = \frac{4.16 \times 10^{26} y}{n_{\sigma}} \left( \frac{\varepsilon a}{W} \right) \sqrt{\frac{M t}{b \Delta E}} \]

- \( n_{\sigma} \): number of std. dev. for a given C.L.
- \( a \): isotopic abundance
- \( \varepsilon \): detection efficiency
- \( W \): molecular weight of the source
- \( M \): total mass of the source (kg)
- \( t \): time of data collection (y)
- \( b \): background rate in counts (keV \cdot kg \cdot y)
- \( \Delta E \): energy resolution (keV)

<table>
<thead>
<tr>
<th>NEMO-3</th>
<th>R&amp;D since 2005</th>
<th>SuperNEMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{100}\text{Mo})</td>
<td>isotope</td>
<td>(^{82}\text{Se}) (maybe also (^{150}\text{Nd}) or (^{48}\text{Ca}))</td>
</tr>
<tr>
<td>7 kg</td>
<td>mass</td>
<td>100 kg</td>
</tr>
<tr>
<td>(A(^{208}\text{TI}) &lt; 20 \mu\text{Bq/kg})</td>
<td>Radio-purity of the foil</td>
<td>(A(^{208}\text{TI}) &lt; 2 \mu\text{Bq/kg})</td>
</tr>
<tr>
<td>(A(^{214}\text{Bi}) &lt; 300 \mu\text{Bq/kg})</td>
<td>Radon in the tracker</td>
<td>(A(^{214}\text{Bi}) &lt; 10 \mu\text{Bq/kg})</td>
</tr>
<tr>
<td>(\text{Rn} \sim 5-6 \text{mBq/m}^3)</td>
<td></td>
<td>(\text{Rn} &lt; 0.1 \text{mBq/m}^3)</td>
</tr>
<tr>
<td>18%</td>
<td>efficiency</td>
<td>30%</td>
</tr>
<tr>
<td>8% FWHM @ 3 MeV</td>
<td>Energy resolution</td>
<td>4% FWHM @ 3 MeV</td>
</tr>
<tr>
<td>(T_{1/2}(0\nu\beta\beta) &gt; 1.4 \times 10^{24} \text{ y}) (&lt;m_n&gt; &lt; 390 – 810 \text{ meV})</td>
<td>sensitivity</td>
<td>(T_{1/2}(0\nu\beta\beta) &gt; 2 \times 10^{26} \text{ y}) (&lt;m_n&gt; &lt; 40 – 140 \text{ meV})</td>
</tr>
<tr>
<td>1 module</td>
<td>modularity</td>
<td>&gt;20 modules (new lab)</td>
</tr>
</tbody>
</table>

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SuperNEMO Demonstrator Module

20 modules for 100 kg

Source: ~ 6.3 kg Se (40 mg/cm², 12m²)
Tracking: ~ 2,100 drift cells
Calorimeter: ~ 600 blocks
Demonstrator in LSM

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SuperNEMO Calorimeter R&D

Measurements of hexagonal blocks give excellent energy resolution

8” Hamamatsu R5912-MOD Super-Bialkali PMT with 276 mm Ø block

ΔE/E ~ 7.2% (FWHM) at 1 MeV

Courtesy of: J.FORGET & C.BOURGEOIS (SuperNEMO Collaboration)
SuperNEMO Calorimeter R&D

Measurements of wall blocks: Small degradation in resolution with tapering

**Cubic Side Wall Block**

- $R = 9.0\%$ (FWHM)

**Cubic Tapered Side Wall Block**

- $R = 9.5\%$ (FWHM)

Optical simulations predict $+0.7\%$ degradation. Compare to $+0.5\%$
SuperNEMO Tracker R&D

- Optimize length, wire material and diameter, read-out, gas mixture
- Several 1-cell and two 9-cell prototypes built and tested
- 90-cell prototype:

90-cell prototype in Manchester
SuperNEMO Tracker R&D: Wiring Robot

Provide automation of tracker cell wiring: uniform tension and repeatability

Cathode feed mechanism

Complete wiring robot setup

Most modules complete. The rest will be ready this month.
BiPo R&D for Source Purity

Measure $^{208}\text{Tl} < 2 \text{ mBq/kg}$ & $^{214}\text{Bi} < 10 \text{ mBq/kg}$ in $\beta\beta$ source foil

![Diagram of BiPo detector with isotopes and decay schemes]

Sensitivity of the BiPo detector

![Graph showing sensitivity versus duration of measurement in months]

$^{238}\text{U}$

$^{214}\text{Bi}$ (19.9 mn)

$^{210}\text{Tl}$ (1.3 mn)

0.021%

$^{232}\text{Th}$

$^{214}\text{Po}$ (164 μs)

$^{210}\text{Pb}$ (22.3 y)

$^{212}\text{Bi}$ (60.5 mn)

36%

$^{212}\text{Po}$ (300 ns)

$^{208}\text{Pb}$ (stable)

$^{208}\text{Tl}$ (3.1 mn)
Comparison of measurement and simulation for a NEMO-3 external wall block.

Results: 14.4% FWHM @ 1 MeV simulation
13.8% FWHM @ 1 MeV measurement

See poster #18 by B. Pahlka

(Published NIM A (625) 2011, 20-28)
SuperNEMO Optical Simulations

Simulations of SuperNEMO prototype blocks agree with measurements
Summary

◆ NEMO-3 finished running at the end of 2010
◆ NEMO-3 established a low background technique (with strong BG rejection)
◆ NEMO-3 allows measurement of many observables
  ➢ Energy
  ➢ Topology
  ➢ Timing
◆ SuperNEMO is a next generation experiment based on NEMO-3 success
◆ SuperNEMO further improves the technique
◆ SuperNEMO extends the half-life sensitivity by a factor of 100

Stay tuned for news from the SuperNEMO Demonstrator!
NEMO-3 and SuperNEMO Collaboration

LAL (Orsay), IPHC (Strasbourg), INL (Idaho Falls), ITEP (Moscow), JINR (Dubna), LPC (Caen), CENBG (Bordeaux), UCL (London), U. of Manchester, Tokushima U., Cornelius U. (Bratislava), Osaka, IEAP & Charles U. (Prague), UAB (Barcelona), Saga U., Imperial College (London), Mount Holyoke Coll. (South Hadley), Fukui U., INR (Kiev), CPPM (Marseilles), U. Warwick, Texas (Austin)
Backup Slides
Future Prospects

◆ NEMO-3 finalized running at the end of 2010
◆ Analyzing data now, should expect improved results

◆ A next generation experiment, SuperNEMO is being developed
◆ $^{82}$Se sensitivity $T_{1/2}(0\nu) = (1-2) \times 10^{26}$ y (500 kg\*y exposure) $<m_\nu> \leq 40 – 140$ meV (NME uncertainty)
Optical Photon Model Ingredients

◆ Emission and absorption spectra
  – base scintillator
  – primary and secondary fluors
  – Stokes shifting and fluorescent quantum yield
◆ Spectral reflectivity of all relevant materials
◆ Spectral indices of refraction
◆ Spectral QE of photodetector

GEANT4 + ROOT framework

Example input data for optical simulations:
SuperNEMO Design

20 modules for 100 kg

Source: ~5kg (40 mg/cm², 12m²)
Tracking: ~2,100 drift cells.
Calorimeter: ~600 blocks

Courtesy of: J.FORGET & C.BOURGEOIS (SuperNEMO Collaboration)
Simulations of a large hexagonal prototype block coupled to an 8” PMT to be used for SuperNEMO. Measurements of $7.5 \pm 0.5\%$ FWHM @ 1 MeV have recently been obtained.
NEMO-3 Optical Simulations

Polystyrene scintillator absorption

Refractive indices

Reflection coefficients

SuperNEMO

PMMA absorption
PS absorption
PS nTP + POPOP absorption

borosilicate glass
PST
PMMA

NEMO-3 Optical Simulations

Polystyrene / scintillator absorption

refractive indices

reflection coefficients

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Background Signatures

Candidate $^{208}$Tl decay

Candidate $^{40}$K decay

Candidate $^{214}$Bi decay

Candidate external event

$e^- - \gamma\gamma\gamma$

(produced in foil)

$e^- + e^+$

$e^- \alpha - N\gamma$

delayed alpha

Single crossing electron

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Fréjus Tunnel: 4800 m.w.e.

Altitudes:
- 1228 m FRANCE
- 1263 m ITALIE
- 1298 m

Distances:
- 0 m
- 6210 m
- 12868 m

Houses:
- NEMO-3 and other experiments
- High Purity Germanium (HPGe) Detectors
Double Beta Decay Half-life

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

\[ \text{Phase Space factor} \quad \text{Nuclear matrix element (NME)} \]

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

\[ \text{Phase Space factor} \quad \text{Nuclear matrix element (NME)} \]

\[ \langle m_{\beta\beta} \rangle = \sum_k m_k |U_{ek}^2| e^{i\alpha_k} \]

\[ U_{ek} = \text{PMNS matrix elements} \quad e^{i\alpha_k} = \text{Majorana CP violating phases} \]

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Some Aspects of Neutrino Mass

- Neutrino oscillations can probe the $\Delta m^2$ mass splittings
- Cannot probe the absolute neutrino mass scale

Mass eigenstates $(\nu_1, \nu_2, \nu_3)$

$|\nu_i\rangle = \sum_{\alpha=e,\mu,\tau} U_{\alpha i} |\nu_{\alpha}\rangle$

$U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}$

Pontecorvo-Maki-Nakagawa-Sakata mixing matrix

flavor eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$

Normal hierarchy $(m_3)^2 >> (m_2)^2 \sim (m_1)^2$

Inverted hierarchy $(m_2)^2 \sim (m_1)^2 >> (m_3)^2$
Phenomenology of Double Beta Decay

- Nucleon pairing in even-even nuclei more bound than odd-odd
- $^{116}\text{Cd}$ stable against $\beta$ decay but unstable against $\beta\beta$ decay

![Diagram showing the decay process from $^{116}\text{Cd}$ to $^{116}\text{In}$, with levels and energies indicated.]

35 $\beta^-\beta^-$ emitters
6 $\beta^+\beta^+$ emitters
Choice of Isotope

Choice of isotope:

◆ $Q_{\beta\beta}$
◆ Isotopic abundance
◆ Phase space factor ($G_{0\nu}$)
◆ Nuclear matrix elements ($M_{0\nu}$)
◆ Background at the $Q_{\beta\beta}$ value

$$\frac{1}{T_{1/2}^0} = G_{0\nu}(Q_{\beta\beta}^5, Z) \cdot |M_{0\nu}^{GT}|^2 \cdot \left\langle m_{\beta\beta} \right\rangle^2$$

$$\left\langle m_{\beta\beta} \right\rangle = \sum_k m_k |U_{ek}|^2 e^{i\alpha_k}$$

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$Q_{\beta\beta}$ (MeV)</th>
<th>Isotopic Abundance (%)</th>
<th>$G_{0\nu} \times 10^{-25}$ (y$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>4.271</td>
<td>0.187</td>
<td>2.44</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>2.040</td>
<td>7.8</td>
<td>0.24</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>2.995</td>
<td>9.2</td>
<td>1.08</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>3.350</td>
<td>2.8</td>
<td>2.24</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>3.034</td>
<td>9.6</td>
<td>1.75</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>2.804</td>
<td>7.5</td>
<td>1.89</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>2.528</td>
<td>33.8</td>
<td>1.70</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>2.479</td>
<td>8.9</td>
<td>1.81</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>3.367</td>
<td>5.6</td>
<td>8.00</td>
</tr>
</tbody>
</table>
Choice of Isotope (2)

Choice of isotope:

- $Q_{\beta\beta}$
- Isotopic abundance
- Phase space factor ($G$)
- Nuclear matrix elements ($M$)
- Background at the $Q$ value

Calculating NMEs is a complex task:

- Heavy open shell nuclei have complicated nuclear structure
- Must have complete set of states for intermediate nucleus
- Many-body problem requires good approximations

\[ \frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q_{\beta\beta}, Z) \cdot \left| M_{0\nu}^{GT} \right|^2 \cdot \left\langle m_{\beta\beta} \right\rangle^2 \]
Choice of Isotope (3)

Choice of isotope:

- $Q_{\beta\beta}$
- Isotopic abundance
- Phase space factor ($G$)
- Nuclear matrix elements ($M$)
- Background at the $Q$ value

- $^{40}\text{K}$, $^{60}\text{Co}$, $^{137}\text{Cs}$
- $^{214}\text{Bi}$ and other radon progeny
- $^{208}\text{TI}$ (2.6 MeV gamma line) and other thorium progeny
- $\gamma$ from (n,$\gamma$) reaction and cosmic ray muon bremsstrahlung

+ tail of $2\nu\beta\beta$ distribution
Experimental Techniques

0νββ half-life sensitivity

\[ T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16 \times 10^{26} y}{n_\sigma} \left( \frac{\varepsilon a}{W} \right) \sqrt{\frac{Mt}{b\Delta E}} \]

\( n_\sigma \) – number of std. dev. for a given C.L.
\( a \) – isotopic abundance
\( \varepsilon \) – detection efficiency
\( W \) – molecular weight of the source
\( M \) – total mass of the source (kg)
\( t \) – time of data collection (y)
\( b \) – background rate in counts (keV \cdot kg \cdot y)
\( \Delta E \) – energy resolution (keV)

Different technologies exploit different physical parameters

<table>
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<tr>
<th>Experiments</th>
<th>Isotopes</th>
<th>Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEMO3</td>
<td>(^{100})Mo, (^{82})Se</td>
<td>Tracking + calorimeter</td>
</tr>
<tr>
<td>Cuoricino</td>
<td>(^{130})Te</td>
<td>Bolometers</td>
</tr>
<tr>
<td>GERDA</td>
<td>(^{76})Ge</td>
<td>Ge diodes</td>
</tr>
<tr>
<td>COBRA</td>
<td>(^{130})Te, (^{116})Cd</td>
<td>ZnCdTe semi-conductors</td>
</tr>
<tr>
<td>CANDLES</td>
<td>(^{48})Ca</td>
<td>CaF(_2) scintillating crystals</td>
</tr>
<tr>
<td>SNO++</td>
<td>(^{150})Nd</td>
<td>Nd loaded liquid scintillator</td>
</tr>
</tbody>
</table>

Strengths: Efficiency, Resolution, mass

Tracking-calorimetry

Source ≠ detector

\( N_{\text{Bckg}} \), isotope choice flexibility
Background Considerations

Backgrounds contribute to the $2\nu\beta\beta$ and $0\nu\beta\beta$ energy spectra

- $^{210}\text{Bi}$ and $^{90}\text{Y}$ are pure beta emitters
- $^{214}\text{Bi}$, $^{208}\text{Tl}$ and others emit betas and gammas
- Plots show gamma rays and beta rays together

Simulated energy spectra for several isotopes showing gamma ray spikes overlayed on top of continuous beta spectra.
Processes that mimic $\beta\beta$-decay

Internal Backgrounds from:
- impurities in isotopic foil
- $2\nu\beta\beta$ background of $0\nu\beta\beta$

External Backgrounds from:
- PMTs (glass, shielding)
- iron / water shielding
- tracking chamber wires
- copper support structure
- outside the detector
Steps Towards a $\beta\beta$ Analysis

Key is identifying ALL background contaminations

NEMO-3 Advantage: Backgrounds are measured *in situ*!

- Measure single $\beta$-emitters in $^{116}$Cd source foil:
  - $^{40}$K, $^{234m}$Pa, $^{210}$Bi

Recent publication in NIM A606 (2009) 449-465

- all external backgrounds
- internal backgrounds from $^{214}$Bi and $^{208}$Tl

- Measure single $\beta$-emitters with gamma transition in $^{116}$Cd source foil:
  - confirm $^{214}$Bi measurement

Must still identify additional contamination in the $^{116}$Cd source

- Other backgrounds measured with:
  - High Purity Germanium detectors
  - single electron ejection with alpha emission (e-α)
  - electrons originating in tracking chamber that interact with the foil

- Use activity model to study $2\nu\beta\beta$ and $0\nu\beta\beta$ half-lives
Single Electron Selection Criteria

To select single electron events in the foil, we require:

1) TRACKING REQUIREMENTS
   - One track with “negative” curvature
   - At least one of the first two Geiger planes near the foil are fired
   - At least one of the first two Geiger planes near the wall are fired
   - Electron track length > 50 cm

2) CALORIMETER REQUIREMENTS
   - Only one isolated scintillator to be fired
   - The track is associated to the scintillator
   - Minimum electron energy > 200 keV

3) FOIL VERTEX REQUIREMENTS
   - Track is reconstructed in cadmium foil
   - No alpha particles in event
Results

Data: 7636 ± 87
Background: 674 ± 15
Signal: 6949 ± 88
Total time: 1471 days
Mass: 410.4 grams
Efficiency: 3.6%

\[ T_{1/2}^{2\beta2\nu} = (2.88 \pm 0.04 \text{ stat} \pm 0.16 \text{ syst}) \times 10^{19} \text{ y} \]

**116Cd 0νββ Results (V-A)**

\[ T_{1/2}^{0ν\beta\beta} > 1.29 \times 10^{23} \text{ y (90\% C.L.)} \]

\[ T_{1/2}^{0ν\beta\beta} > 1.7 \times 10^{23} \text{ y (90\% C.L.)} \]


\[ G = 1.89 \times 10^{-25} \text{ y}^{-1} \quad M = 1.83 - 2.93 \text{ eV}^{-1} \quad \langle m_{\beta\beta} \rangle < 2.2 - 3.5 \text{ eV} \]
$^{116}$Cd $2\nu\beta\beta$ Results

Other Observables

**E$_{\text{min}}$ and E$_{\text{max}}$ together**

**Cos $\theta$**

**Internal TOF probability**

**Vertex position within sector**

---

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$^{116}\text{Cd} \, 0\nu\beta\beta$ Results (V+A)

Models exist that contain neutrino couplings to right-handed leptons (V+A)

- Combined Results
  - Data: 7636
  - Exp. Background: 7623
  - Exp. 0$\nu$\beta$\beta$ Signal: < 5.98
  - 0$\nu$\beta$\beta$ efficiency: 6.92%

$T_{1/2}^{0\nu\beta\beta} > 6.88 \times 10^{22} \text{ y (90\% C.L.)}$

$T_{1/2}^{0\nu\beta\beta} > 1.2 \times 10^{21} \text{ y (90\% C.L.)}$

0νββ-decay (Majoron Emission)

Models exist where the global baryon-lepton symmetry is broken predicting a boson (Majoron) which can couple to the neutrino.

Spectral index $n$ is related to $G ~ (Q_{ββ} - T)^n$

$n = 1$

$\frac{T_{1/2}}{0νββχ^0} > 1.3 \times 10^{22}$ y
$\frac{T_{1/2}}{0νββχ^0} > 0.8 \times 10^{22}$ y

$n = 2$

$\frac{T_{1/2}}{0νββχ^0} > 5.4 \times 10^{21}$ y
$\frac{T_{1/2}}{0νββχ^0} > 1.7 \times 10^{21}$ y

$n = 3$

$\frac{T_{1/2}}{0νββχ^0} > 3.0 \times 10^{21}$ y
$\frac{T_{1/2}}{0νββχ^0} > 0.8 \times 10^{21}$ y

$n = 7$

$\frac{T_{1/2}}{0νββχ^0} > 8.4 \times 10^{20}$ y
$\frac{T_{1/2}}{0νββχ^0} > 4.1 \times 10^{19}$ y

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Technology and Instrumentation in Particle Physics

June 13, 2011
## Overview of the Field

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<tr>
<td>SuperNEMO</td>
<td>$^{82}\text{Se}$, $^{150}\text{Nd}$</td>
<td>Tracking + calorimeter</td>
<td>Bckg rejection, isotope choice</td>
</tr>
<tr>
<td>Cuoricino</td>
<td>$^{130}\text{Te}$</td>
<td>Bolometers</td>
<td>Energy resolution, efficiency</td>
</tr>
<tr>
<td>CUORE</td>
<td>$^{130}\text{Te}$</td>
<td>Bolometers</td>
<td>Energy resolution, efficiency</td>
</tr>
<tr>
<td>GERDA</td>
<td>$^{76}\text{Ge}$</td>
<td>Ge diodes</td>
<td>Energy resolution, efficiency</td>
</tr>
<tr>
<td>Majorana</td>
<td>$^{76}\text{Ge}$</td>
<td>Ge diodes</td>
<td>Energy resolution, efficiency</td>
</tr>
<tr>
<td>COBRA</td>
<td>$^{130}\text{Te}$, $^{116}\text{Cd}$</td>
<td>ZnCdTe semi-conductors</td>
<td>Energy resolution, efficiency</td>
</tr>
<tr>
<td>EXO</td>
<td>$^{136}\text{Xe}$</td>
<td>TPC ionisation + scintillation</td>
<td>Mass, efficiency, final state signature</td>
</tr>
<tr>
<td>MOON</td>
<td>$^{100}\text{Mo}$</td>
<td>Tracking + calorimeter</td>
<td>Compactness, Bckg rejection</td>
</tr>
<tr>
<td>CANDLES</td>
<td>$^{48}\text{Ca}$</td>
<td>CaF$_2$ scintillating crystals</td>
<td>Efficiency, Background</td>
</tr>
<tr>
<td>SNO++</td>
<td>$^{150}\text{Nd}$</td>
<td>Nd loaded liquid scintillator</td>
<td>Mass, efficiency</td>
</tr>
<tr>
<td>XMASS</td>
<td>$^{136}\text{Xe}$</td>
<td>Liquid Xe</td>
<td>Mass, efficiency</td>
</tr>
<tr>
<td>CARVEL</td>
<td>$^{48}\text{Ca}$</td>
<td>CaWO$_4$ scintillating crystals</td>
<td>Mass, efficiency</td>
</tr>
<tr>
<td>Yangyang</td>
<td>$^{124}\text{Sn}$</td>
<td>Sn loaded liquid scintillator</td>
<td>Mass, efficiency</td>
</tr>
<tr>
<td>DCBA</td>
<td>$^{150}\text{Nd}$</td>
<td>Gaseous TPC</td>
<td>Bckg rejection, efficiency</td>
</tr>
</tbody>
</table>
Higher States Dominance

**E_{\text{total}}**

**Min Electron Energy**

**Max Electron Energy**

**Single Electron Energy**

**Combined Results**

<table>
<thead>
<tr>
<th>Data</th>
<th>7636 ± 87</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>674 ± 15</td>
</tr>
<tr>
<td>Signal</td>
<td>6944 ± 89</td>
</tr>
<tr>
<td>S/B</td>
<td>10.3</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.036</td>
</tr>
<tr>
<td>T1/2 (2b2n)</td>
<td>3.08 ± 0.04 x 10^{19} y</td>
</tr>
</tbody>
</table>
SSD vs HSD

Monte Carlo distributions for the total energy, maximum electron energy and the cosine of the angle show no difference between SSD and HSD.

- Total Energy (MeV)
  - Mean: 1.215
  - RMS: 0.354

- Maximum Electron Energy (MeV)
  - Mean: 0.786
  - RMS: 0.279

- Cosine of the angle
  - Mean: -0.234
  - RMS: 0.615
Final 2e Selection Criteria

1) TRACKING REQUIREMENTS
   - Only two tracks identified and reconstructed
   - Each track corresponds to a particle with negative charge
   - The first Geiger plane near the foil are fired (layer 0)
   - Reject petal scintillator near foils
   - For petal events near the wall, there must be a Geiger hit in layer 5 or 6
   - At least one of the first two Geiger planes near the scintillator are fired (7 or 8)
   - Sum of electron tracks > 60 cm
   - Less than 2 (no more than one) fast Geiger hits, not associated to any track
     with distance to event vertex in XY plane < 15 cm
   - If both tracks belong to one part of the detector, there are no fast GG hits
     on the other part with distance to event vertex in XY plane < 15 cm

2) CALORIMETER REQUIREMENTS
   - Only two isolated scintillators to be fired
   - Scintillator and track to be associated (track/scintillator correlation)
   - gain < 6 and account for dead PMTs in data/MC
   - $E_{\text{min}} > 200 \text{ keV}$ and $E_{\text{tot}} > 400 \text{ keV}$

3) FOIL REQUIREMENTS
   - Event must be reconstructed in cadmium foil
   - Distance between track/foil vertices in XY plane < 2 cm
   - Distance between track/foil vertices in Z plane < 4 cm

4) TIME OF FLIGHT REQUIREMENTS
   - Internal TOF probability > 1%
   - External TOF probability < 1%
Latest NEMO-3 Results

- No evidence for non conservation of lepton number as of June 2010
- Current limits on $0\nu\beta\beta$ (at 90% C.L.):

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Exposure (kg·y)</th>
<th>$T_{1/2}(0\nu\beta\beta)$, y</th>
<th>$\langle m_\nu \rangle$, eV [NME ref.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{100}$Mo</td>
<td>26.6</td>
<td>$&gt; 1.0 \cdot 10^{24}$</td>
<td>$&lt; 0.47 – 0.96$ [1-3]</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>3.6</td>
<td>$&gt; 3.6 \cdot 10^{23}$</td>
<td>$&lt; 0.94 – 1.6$ [1-3]; $&lt; 2.5$ [7]</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>0.095</td>
<td>$&gt; 1.8 \cdot 10^{22}$</td>
<td>$&lt; 1.7 – 2.4$ [4,5]; $&lt; 4.8 – 7.6$ [6]</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>1.4</td>
<td>$&gt; 9.8 \cdot 10^{22}$</td>
<td>$&lt; 1.6 – 3.1$ [2,3]</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>0.031</td>
<td>$&gt; 9.2 \cdot 10^{21}$</td>
<td>$&lt; 7.2 – 19.5$ [2,3]</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>0.017</td>
<td>$&gt; 1.3 \cdot 10^{22}$</td>
<td>$&lt; 29.6$ [7]</td>
</tr>
</tbody>
</table>

- NME references:
Electron-gamma: $E_{\text{total}} > 2.0$ MeV

All background activities are fixed except $^{214}\text{Bi}$ in the foil. We measure the activity of $^{214}\text{Bi}$ in the foil using Phase Two data in the medium activity region:

- $^{214}\text{Bi}$ (e-gamma) Activity: $0.65 \pm 0.36$ mBq
- $^{214}\text{Bi}$ (e-alpha) Activity: $0.39 \pm 0.04$ mBq

This analysis is not sensitive enough to provide precise values.
SSD and HSD Monte Carlo Distributions

Monte Carlo distributions for the minimum electron energy and the single electron energy show very slight difference between SSD and HSD.

![Graph showing Monte Carlo distributions for minimum electron energy and single electron energy for SSD and HSD.]
0νββ-decay with Majoron Emission

Calculate the results for the neutrino-Majoron coupling constant $<g_{ee}>$:

- Phase space factor and NME are known for $n =$1, 3, and 7

<table>
<thead>
<tr>
<th>Spectral Index $n$</th>
<th>Phase Space Factor</th>
<th>NME</th>
<th>This work $T_{1/2} (2\nu\beta\beta\chi^0)$ (y)</th>
<th>Best Previous Limit $T_{1/2} (2\nu\beta\beta\chi^0)$ (y)</th>
<th>This work $&lt;g_{ee}&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n = 1$</td>
<td>$1.75 \times 10^{-15}$</td>
<td>3.29</td>
<td>$&gt; 1.3 \times 10^{22}$</td>
<td>$&gt; 0.8 \times 10^{22}$ [1,3]</td>
<td>$&lt; 6.4 \times 10^{-5}$</td>
</tr>
<tr>
<td>$n = 2$</td>
<td></td>
<td></td>
<td>$&gt; 5.4 \times 10^{21}$</td>
<td>$&gt; 1.7 \times 10^{21}$ [3]</td>
<td></td>
</tr>
<tr>
<td>$n = 3$</td>
<td>$6.95 \times 10^{-18}$</td>
<td>3.29</td>
<td>$&gt; 3.0 \times 10^{21}$</td>
<td>$&gt; 3.5 \times 10^{20}$ [2]</td>
<td>$&lt; 2.1 \times 10^{-3}$</td>
</tr>
<tr>
<td>$n = 7$</td>
<td>$1.03 \times 10^{-16}$</td>
<td>3.29</td>
<td>$&gt; 8.4 \times 10^{20}$</td>
<td>$&gt; 4.1 \times 10^{19}$ [2]</td>
<td>$&lt; 3.2 \times 10^{-2}$</td>
</tr>
</tbody>
</table>
Electron-Gamma Analysis

Analysis details:
• Phase Two data used (runs 3395 – 7920)
• Try to measure internal $^{214}$Bi with events containing electrons and gammas
• Second attempt with $E_e > 0.5$ MeV and $E_\gamma > 0.5$ MeV

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Activity (mBq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{214}$Bi internal</td>
<td>$0.63 \pm 0.14$</td>
</tr>
</tbody>
</table>

Initial activity values:

Can we measure $^{214}$Bi with better precision than this?

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Medium Activity Region Activity (mBq)</th>
<th>Low Activity Region Activity (mBq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{214}$Bi internal</td>
<td>$0.153 \pm 0.040$</td>
<td>$0.062 \pm 0.014$</td>
</tr>
<tr>
<td>$^{214}$Bi mylar (HPGe)</td>
<td>$&lt; 0.24$</td>
<td>$&lt; 0.10$</td>
</tr>
<tr>
<td>$^{214}$Bi (int + mylar)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Electron-gamma Selection Criteria

1) TRACKING REQUIREMENTS
   - One track with “negative” curvature
   - At least one of the first and last two Geiger planes near the foil are fired
   - Less than 2 fast Geiger hits, not associated to any track
     with distance to event vertex in XY plane < 15 cm
   - If track belong to one part of the detector, there are no fast GG hits on the
     other part with distance to event vertex in XY plane < 15 cm
   - Electron track length > 50 cm

2) CALORIMETER REQUIREMENTS
   - Two isolated scintillators registered
   - Scintillator and track are associated
   - $E_e > 500$ keV and $E_\gamma > 500$ keV
   - $E_{\text{total}} > 1000$ keV

3) FOIL REQUIREMENTS
   - Track is reconstructed in cadmium foil
   - High activity region rejected
   - No alpha particles in event

4) TIME OF FLIGHT REQUIREMENTS
   - TOF probability for internal decay > 4%
   - TOF probability for external OCE < 1%
Medium activity region modeled better. Radon in tail represented well.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Activity (mBq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}$K</td>
<td>$7.98 \pm 0.11$</td>
</tr>
<tr>
<td>$^{234m}$Pa</td>
<td>$0.89 \pm 0.02$</td>
</tr>
<tr>
<td>$^{210}$Bi (surf)</td>
<td>$1810 \pm 20$</td>
</tr>
</tbody>
</table>
Single Electron Analysis
Low Activity Region

Low activity region modeled better. Radon in tail represented well.

\[ \chi^2 = 183/156 \]

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Activity (mBq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}$K</td>
<td>3.66 ± 0.10</td>
</tr>
<tr>
<td>$^{234m}$Pa</td>
<td>0.26 ± 0.01</td>
</tr>
<tr>
<td>$^{210}$Bi (surf)</td>
<td>454 ± 5</td>
</tr>
</tbody>
</table>
Electron-gamma Analysis
Low Activity Region

Require $E_e > 0.5$ MeV, $E_\gamma > 0.5$ MeV, and $E_{\text{total}} > 1.0$ MeV:

- $\chi^2 = 16/26$
- $\chi^2 = 27/22$
- $\chi^2 = 13/20$
- $\chi^2 = 34/50$
Event Reconstruction and Analysis

**Goal:** Select data events characteristic of a given topology

- **RAW data/MC (ADC and TDC)**
  - ~ 3 TB

- **RECO data/MC (event tracks)**
  - ~ 5 TB
  - Trigger rate ~ 7 Hz
  - $\beta\beta$ rate ~ 1 event / 2.5 minutes

- **SKIMMED data/MC**
  - ~ 500 MB
  - topology skimming and calibration

- **FINAL data/MC**
  - ~ 5 MB
  - final selection criteria

**MC** = Monte Carlo simulated data generated using **DECAY0** (e.g. backgrounds, $2\nu\beta\beta$, etc)
Single Electron Analysis
Medium and Low Activity Regions

MEDIUM ACTIVITY REGION

LOW ACTIVITY REGION

Benton Pahlka
Technology and Instrumentation in Particle Physics
June 13, 2011
$^{116}\text{Cd}$ 2νββ Results
Minimum and Maximum Energies

Minimum Electron Energy (MeV)

Counts

Maximum Electron Energy (MeV)

Counts

Benton Pahlka
Technology and Instrumentation in Particle Physics
June 13, 2011
**Event Reconstruction Chain**

**Goal:** Select data events characteristic of a given topology

RAW data (ADC and TDC)

~ 3 TB

-track reconstruction

RECO data (event tracks)

~ 5 TB

-topology skimming and calibration

SKIMMED data

~ 500 MB

-final selection criteria

FINAL data set

~ 5 MB

Trigger rate ~ 7 Hz

ββ rate ~ 1 event / 2.5 minutes

June 13, 2011
Fitting the Signal

Compare data to Monte Carlo with known activity estimates

- Fix backgrounds to measured activities
- Subtract background
- Fit data to one (or more) signals to get activity

Example

Two isotope signals to fit

Known backgrounds

Example

After background subtraction, fit data to two signals
Single Electron Results

Arrangement of foil segments. Two types of enrichment are used, (I) and (II). 93.2% enrichment (chemical/gas centrifuge).

Results of selecting single electron events in the cadmium foil. The two different types of enriched cadmium and the contaminated clips are visible.
# Results

## 2νββ Results

<table>
<thead>
<tr>
<th>SSD</th>
<th>This work</th>
<th>Best Previous Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_{1/2} (2νββ) (y)$</td>
<td>$T_{1/2} (2νββ) (y)$</td>
</tr>
<tr>
<td></td>
<td>$2.88 \pm 0.04 \text{ (stat)} \pm 0.16 \text{ (syst)} \times 10^{19} y$</td>
<td>$2.9 \pm 0.06 \text{ (stat)} + 0.4 -0.3 \text{ (syst)} \times 10^{19} y$</td>
</tr>
</tbody>
</table>

| HSD | $3.08 \pm 0.04 \text{ (stat)} \pm 0.16 \text{ (syst)} \times 10^{19} y$ |

## 0νββ Results

<table>
<thead>
<tr>
<th>Light Majorana exchange (V-A)</th>
<th>This work</th>
<th>Best Previous Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_{1/2} (0νββ) (y)$</td>
<td>$T_{1/2} (0νββ) (y)$</td>
</tr>
<tr>
<td></td>
<td>$&gt; 1.29 \times 10^{23}$</td>
<td>$&gt; 1.7 \times 10^{23}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Right-handed current (V+A)</th>
<th>This work</th>
<th>Best Previous Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$&lt; m_{ββ} \text{ (eV)}$</td>
<td>$&lt; m_{ββ} \text{ (eV)}$</td>
</tr>
<tr>
<td></td>
<td>$&gt; 6.88 \times 10^{22}$</td>
<td>$&gt; 1.2 \times 10^{21}$</td>
</tr>
</tbody>
</table>

## Spectral Index $n$

<table>
<thead>
<tr>
<th>Spectral Index $n$</th>
<th>This work</th>
<th>Best Previous Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_{1/2} (0νββ\chi^0) (y)$</td>
<td>$T_{1/2} (0νββ\chi^0) (y)$</td>
</tr>
<tr>
<td>$n = 1$</td>
<td>$&gt; 1.3 \times 10^{22}$</td>
<td>$&gt; 0.8 \times 10^{22} [1,3]$</td>
</tr>
<tr>
<td>$n = 2$</td>
<td>$&gt; 5.4 \times 10^{21}$</td>
<td>$&gt; 1.7 \times 10^{21}[3]$</td>
</tr>
<tr>
<td>$n = 3$</td>
<td>$&gt; 3.0 \times 10^{21}$</td>
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<tr>
<td>$n = 7$</td>
<td>$&gt; 8.4 \times 10^{20}$</td>
<td>$&gt; 4.1 \times 10^{19} [2]$</td>
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</tbody>
</table>

$< g_{ee} >$

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