Search for neutrinoless double beta decay: status of SuperNEMO project

Yu. Shitov, Imperial
Double beta decay basic statements

$\beta\beta 2\nu$: allowed SM process  $T_{1/2} \sim 10^{20} \text{y}$

$\beta\beta 0\nu$: beyond the SM  $T_{1/2} \geq 10^{25} \text{y}$

Massive Majorana neutrinos (particle = antiparticle)

Happiness for theoreticians (many mechanisms proposed to describe the process)
Double beta decay basic equations

\[ A^{0\nu} = (T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q_{\beta\beta}, Z) \left| M^{0\nu} \right|^2 \left\langle m_\nu \right\rangle^2 / m_e^2 \sim Q_{\beta\beta}^7 Z^2 \left| M^{0\nu} \right|^2 \]

- effective neutrino Majorana mass

\[ < m_\nu > = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i \alpha_1} m_2 + |U_{e3}|^2 e^{i \alpha_2} m_3 \]

\( M^{0\nu} \): nuclear matrix element
\( G^{0\nu} \): phase space factor

\[ I^{0\nu}_{1/2}(y) > \frac{\ln 2 \cdot N}{k_{C.L.}} \cdot \frac{\varepsilon}{A} \cdot \sqrt{\frac{M \cdot t}{N_{Bckg} \cdot \Delta E}} \]

\( M \): mass (g)
\( \varepsilon \): efficiency
\( K_{C.L.} \): confidence level
\( N \): Avogadro number
\( t \): exposition time (y)
\( N_{Bckg} \): background events/ (keV/kg/y)
\( \Delta E \): energy resolution (keV)

\( \sim 69 \) stable and \( 28 \alpha\)-unstable \( \beta\beta \) isotopes
Resolution as key point

Avignone, King, Zdesenko, New Journal of Physics 7 (2005) 6
Experimental techniques to observe $\beta\beta$-decay

**Experimental methods**

- **Geochemical & Radiochemical**
  - (A,Z-2)daughter
  - $\beta\beta$-sample (A,Z)

- **Calorimetric**
  - Source $\equiv$ Detector
  - $\beta\beta$-foil
  - TPC

- **Tracko-calo**
  - $E_1$, $E_2$, $\theta$

**Experimental output**

- $\beta\beta$-daughter rate
- $E_1+E_2$ spectrum
- $E_1$, $E_2$, $\theta$
Calorimeter versus tracko-calor/TPC detectors

**Experimental advantages**
- Larger mass
- Better resolution
- High (~100%) efficiency
- Real $\beta\beta$-observation.
- Any $\beta\beta$-source can be measured
- Potentially zero-background exp.
- Test of different $\beta\beta0\nu$ mechanisms in the case of observation

**Experimental drawbacks**
- A few $\beta\beta$-isotopes can be measured $^{76}\text{Ge,}^{130}\text{Te}$ up to now.
- Unavoidable natural background.
- We don’t see electrons, just energy released - no absolute proof, that we see $\beta\beta0\nu$-peak and not something else ($\gamma$-line)!
- Difficult to accept large mass
- Smaller efficiency
- Worth resolution
Neutrino Ettore Majorana Observatory
(Neutrino Experiment on MOlybdenenum – historical name)

~ 80 physicists, 12 countries, 27 laboratories. R&D Program for 02/2006-07/2009 is being carried out. Major contributors: UK, France. Smaller but vital contributions from US, Russia, Czech Republic, Japan.
The NEMO3 detector

Fréjus Underground Laboratory : 4800 m.w.e.

20 sectors

Source: 10 kg of $\beta\beta$ isotopes
cylindrical, $S = 20$ 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 (~30 cm) + Wood (Top/Bottom/Gapes between water tanks)

Able to identify $e^-$, $e^+$, $\gamma$ and $\alpha$–delayed
\[ T_{1/2}(\beta\beta) = 7.11 \pm 0.02 \text{ (stat)} \pm 0.54 \text{ (syst)} \times 10^{18} \text{ years} \]

«\(\beta\beta\) factory» → tool for precision tests
$^{100}$Mo $2
\nu \beta \beta$ single energy spectrum as probe of $2\nu \beta \beta$ mechanism

- **HSD**, higher levels contribute to the decay
- **SSD**, $1^+$ level dominates in the decay


- $^{100}$Mo $2\nu \beta \beta$ single energy distribution in favour of Single State Dominant (SSD) decay

$^{100}$Mo $2\nu \beta \beta$ single energy distribution

\[ T_{1/2} \text{ (stat)} \pm T_{1/2} \text{ (syst)} \times 10^{18} \text{ y} \]

- HSD: $T_{1/2} = 8.61 \pm 0.02 \text{ (stat)} \pm 0.60 \text{ (syst)} \times 10^{18} \text{ y}$
- SSD: $T_{1/2} = 7.72 \pm 0.02 \text{ (stat)} \pm 0.54 \text{ (syst)} \times 10^{18} \text{ y}$
Preliminary results with $^{100}$Mo (7 kg)

693 days of data
Phase I + Phase II

$^{82}$Se

693 days of data
Phase I + Phase II

Expected 2009 sensitivity:
$T_{1/2}(\beta\beta0\nu) \sim 1-2 \times 10^{24}$ (90 % CL)
$\langle m_\nu \rangle < 0.3 - 1.3$ eV

$T_{1/2} > 5.8 \times 10^{23}$ y @ 90% C.L.
$\langle m_\nu \rangle < (0.8 - 1.3)$ eV [1-3]

$T_{1/2} > 2.1 \times 10^{23}$ y @ 90% C.L.
$\langle m_\nu \rangle < (1.4 - 2.2)$ eV [1-3]
# From NEMO to SuperNEMO

## NEMO-3

<table>
<thead>
<tr>
<th>7 kg $^{100}$Mo</th>
<th>Mass of isotope</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{1/2}(\beta\beta2\nu) = 7 \times 10^{18}$ y</td>
<td>$T_{1/2}(\beta\beta2\nu) = 10^{20} \parallel 10^{19}$ y</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FWHM ~ 12% at 3 MeV (dominated by calorimeter ~ 8%)</th>
<th>Energy resolution (FWHM of the $\beta\beta0\nu$ ray)</th>
<th>Total: FWHM $\leq 7%$ at 1 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon(\beta\beta0\nu) = 18%$</td>
<td>$\varepsilon(\beta\beta0\nu) \sim 30%$</td>
<td>Calorimeter: $\leq 4%$ at 3 MeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$^{214}$Bi $&lt; 300 \mu$Bq/kg</th>
<th>Internal contaminations in the source foils in $^{208}$Tl and $^{214}$Bi (If $^{82}$Se) $^{214}$Bi $&lt; 10 \mu$Bq/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{208}$Tl $&lt; 20 \mu$Bq/kg</td>
<td>$^{208}$Tl $&lt; 2 \mu$Bq/kg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\beta\beta2\nu \sim 2$ cts / 7 kg / y</th>
<th>Background</th>
<th>$\beta\beta2\nu=1$, $^{208}$Tl =0.5 $^{214}$Bi=0.5 cts/100 kg/y</th>
</tr>
</thead>
<tbody>
<tr>
<td>($^{208}$Tl, $^{214}$Bi) $\sim 0.5$ cts/7 kg/y</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$T_{1/2}(\beta\beta0\nu) &gt; 2 \times 10^{24}$ y</th>
<th>Sensitivity</th>
<th>$T_{1/2}(\beta\beta0\nu) &gt; (1-2) \times 10^{26}$ y</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;m_{\nu}&gt; &lt; 0.3 – 1.3$ eV</td>
<td></td>
<td>$&lt;m_{\nu}&gt; &lt; 40 – 110$ meV</td>
</tr>
</tbody>
</table>

NEMO-3 successful experience shows us that technique can be extrapolated for larger mass next generation detector to reach new sensitivity level.

**SUPERNEMO R&D is in progress since 2006**
Plane geometry

Source (40 mg/cm²) 12m², tracking volume (~3000 channels) and calorimeter

Modular (~5 kg of enriched isotope/module)

100 kg: 20 modules
- ~ 60 000 channels for drift chamber
- ~ 12 000/20 000 channels for 5”/8” PMT

SuperNEMO basic design
Alternative SuperNEMO sandwich bar design

SC bars double sided with PM. Only ~ 3000 relatively cheap (3”||5”) PM (~12000 8” PM in basic design). More compact, cheaper, less background from PM, but worse resolution (~10-11%).
Baseline design detecting cell with required parameters has been designed.
SuperNEMO tracker (major UK responsibility) has been developed including all accessories required (mechanics, electronics, wiring robot, etc.) 90-cell prototype has been built and testing now.
SuperNEMO collaboration has 6 kg of $^{\text{82}}$Se with technology in hand for full chain of source production: enrichment -> purification -> foil preparation

**Enrichment**

**Purification**

**Source foil preparation**

Chemical purification at INL (US)
Prototype of setup for measurement of extra low levels (a few μBq/kg) of radio impurities in SuperNEMO source foils (BiPo) has been developed and successively tested.
SuperNEMO SoftWare (SNSW) package has been developed and large scale simulations (GRID-based) is in progress.
Pre-production prototype (demonstrator module)

SuperNEMO UK proposal has been submitted in April 2009. The main goals of demonstrator (2009-2011) are:

• To demonstrate the feasibility of large scale detector component production with required performance parameters (e.g. calorimeter energy and time resolution, tracker efficiency and purity).

• To measure background contributions from the detector components.

• To finalize the detector design.

• To produce a competitive physics measurement with $^{82}$Se covering the region of the Klapdor group claim (1yr of data taking with 6kg of $^{82}$Se in the demonstrator module will have a similar sensitivity to GERDA Phase-I).
Baseline design of demonstrator in LSM

Selected pure iron bored water tanks

5.4 m 5.9 m 4 m

0.2 m NEMO3 steel plates

0.3 m Wood

100t 100t 32tx2
Selected pure iron bored water tanks

Radonless air

Alternative bar design of demonstrator in LSM

2.8 m
5.9 m
0.2 m NEMO3 steel plates
0.3 m Wood

2.45 m
4.4 m
1.5 m
# World leading double beta-decay projects

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Isotope</th>
<th>kg</th>
<th>$T_{1/2}$ yr, 90% CL</th>
<th>$m_\nu^*$, meV</th>
<th>Start-up timescale</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>HM</td>
<td>$^{76}$Ge</td>
<td>15</td>
<td>$&gt;1.9 \times 10^{25}$</td>
<td>230-560</td>
<td>1990</td>
<td>finished</td>
</tr>
<tr>
<td>KDHK claim</td>
<td>$^{76}$Ge</td>
<td>15</td>
<td>$(0.7-4.2) \times 10^{25}$ (3σ)</td>
<td>150-920</td>
<td>1990</td>
<td>finished</td>
</tr>
<tr>
<td>CUORICINO</td>
<td>$^{130}$Te</td>
<td>11</td>
<td>$&gt;2.4 \times 10^{24}$</td>
<td>200-900</td>
<td>2002</td>
<td>finished</td>
</tr>
<tr>
<td>NEMO 3</td>
<td>$^{100}$Mo</td>
<td>7</td>
<td>$2 \times 10^{24}$ (expect. 2009)</td>
<td>300-1300</td>
<td>2003</td>
<td>running</td>
</tr>
<tr>
<td>CUORE</td>
<td>$^{130}$Te</td>
<td>210</td>
<td>$1.3 \times 10^{26}$</td>
<td>40-92</td>
<td>2011</td>
<td>approved</td>
</tr>
<tr>
<td>GERDA, Phase I</td>
<td>$^{76}$Ge</td>
<td>15</td>
<td>$3 \times 10^{25}$</td>
<td>180-440</td>
<td>2009</td>
<td>approved</td>
</tr>
<tr>
<td>Phase II</td>
<td>$^{76}$Ge</td>
<td>~31</td>
<td>$2 \times 10^{26}$</td>
<td>70-170</td>
<td>2011</td>
<td>approved</td>
</tr>
<tr>
<td>EXO 200</td>
<td>$^{136}$Xe</td>
<td>160</td>
<td>$6.4 \times 10^{25}$</td>
<td>270-380</td>
<td>2008</td>
<td>approved</td>
</tr>
<tr>
<td>EXO 1t</td>
<td>$^{136}$Xe</td>
<td>800</td>
<td>$2 \times 10^{27}$</td>
<td>50-68</td>
<td>2015</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>SuperNEMO</td>
<td>$^{82}$Se/$^{150}$Nd</td>
<td>100+</td>
<td>$(1-2) \times 10^{26}$</td>
<td>40-110</td>
<td>2011</td>
<td>R&amp;D</td>
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<tr>
<td>COBRA</td>
<td>$^{116}$Cd</td>
<td>151</td>
<td>$1.5 \times 10^{26}$</td>
<td>38-96</td>
<td>?</td>
<td>R&amp;D</td>
</tr>
</tbody>
</table>

* Matrix elements from MEDEX’07 or provided by experiments
Roadmap for double beta-decay projects

CUORICINO, EXO-200

CUORE, EXO

NEMO 3
HM Claim
GERDA
SuperNEMO

2015-2020, 1t experiments (1 or 2)
>2020, >10t experiment

S. Pascoli, S.T.P., 2006
The $0\nu\beta\beta$–decay is a test of physics beyond the Standard Model by the search of the leptonic number violation and would determine the nature of the neutrino (Majorana), absolute neutrino mass scale and neutrino hierarchy.

Several experiments are needed to measure different sources with several techniques.

NEMO-3 technique can be extrapolated at ~100 kg to be sensitive to $(1-2)\times10^{26}$ y. Only tracko-calor (SuperNEMO) and gas TPC can directly register $0\nu\beta\beta$-decay. In the case of discovery only direct methods will allow to determine the process leading to $\beta\beta(0\nu)$: light neutrino exchange, right-handed current, supersymmetry, etc.

3-year SuperNEMO R&D program is carrying out and it is in good shape. Key challenges are calorimeter resolution, isotope choice, and radio purity. Based on design study results full proposal for 100+ kg detector in 2009. “Last minute” isotope change possible. E.g. CUORE sees the signal in $^{130}$Te.

First module - 2011
All 20 modules ~2013

Target SuperNEMO sensitivity: 20-110 meV by 2016, which is competitive with the other next generation $0\nu\beta\beta$-experiments.