Double Beta Decay as a tool in neutrino physics – experiments NEMO 3, SuperNEMO and TGV

Ivan Štekl
Institute of Experimental and Applied Physics, Czech Technical University in Prague

(1) TGV experiment – measurement of 2νEC/EC decay of $^{106}$Cd

(2) NEMO 3 experiment – measurement of 0ν and 2νββ decay of several isotopes

(3) SuperNEMO – R&D, measurement of 0νββ decay of $^{82}$Se or $^{150}$Nd
Double Beta Decay Signature

1. $2\nu$DBD: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e \rightarrow$ Allowed by SM
2. $0\nu$DBD: $(A,Z) \rightarrow (A,Z+2) + 2e^- \rightarrow$ new physics beyond the SM

Two electrons each with a continuous spectrum and a monochromatic sum energy

2 neutrinos Double Beta Decay continuous spectrum

Neutrinoless Double Beta Decay peak enlarged by the detector energy resolution

sum electron energy / Q
1994-2000: $2\nu\beta\beta^{48}\text{Ca}, T_{1/2} = 4.2 \times 10^{19}$ y

(2000 – ...)

to investigate $\beta\beta$ processes in $^{106}\text{Cd}$ (to focus on $2\nu\text{EC/EC}$ channel)

observables:
2 characteristic X-rays from de-excitation of $^{106}\text{Pd}$ shell

$2\nu\text{EC/EC}$:

$$2e + ^{106}_{48}\text{Cd} \rightarrow ^{106}_{46}\text{Pd} + 2\nu_e + (\gamma, X-rays)$$

$Q_{EC/EC} = 2778$ keV, ROI: $19$ keV $\leq E_X \leq 23$ keV
TGV II (cryostat)

- 32 HPGe planar detectors Ø60 mm x 6 mm (active area 2040 mm$^2$)
- Total mass of samples: 10 - 25 g
- E-threshold: $\approx 10$ keV
- Samples: 12x $^{106}$Cd foils (~10g)
Phase I result

- acquisition with 10g of $^{106}$Cd after 8491 hours:
  - data
  - linear background
  - Cd X-ray multiplet
  - excluded Pd X-ray events

\[ T_{1/2}^{2νEC/EC} \left( ^{106}Cd \right) > 3.0 \cdot 10^{20} \text{ y (90%)} \]
Conclusions, near-term plans

- Main run (1 year duration) with enriched $^{106}\text{Cd}$ completed
- Phase I terminated giving new estimation on $T_{1/2}$ ($2\nu\text{EC/EC, g.s.} \rightarrow \text{g.s.}$) of $^{106}\text{Cd}$

$T_{1/2} = 1.0 \cdot 10^{20} \text{ y (Suhonen)}$

$T_{1/2} > 3.0 \cdot 10^{20} \text{ y (TGV II)}$

$T_{1/2} = 8.7 \cdot 10^{20} \text{ y (Hirsch)}$

$T_{1/2} = 4.4 \cdot 10^{21} \text{ y (Simkovic)}$

Main source of background inside the cryostat localized and removed

Phase II started (December 2007):

- more enriched material available (15g)
- to continue for at least 3 years
- factor 10 of improvement is reasonable
**Plans in 2008:**

1. Continuation of the measurement with enriched $^{106}$Cd (2νEC/EC decay on the level $10^{21}$ yrs.)

2. Conceptual design study (MC, theoretical calculations, background study) –
   a) the possibility to measure 2νEC/EC decay with other isotopes ($^{162}$Er, $^{156}$Dy) V.Ceron, J.Hirsch, arXiv:nucl-th/9911021v1
   b) the study of the possibility to measure 0νEC/EC decay ($^{152}$Gd g.s., $^{112}$Sn exc. state– resonance enhancement of the 0νEC/EC process if $Q - Q_r < 1$ keV)
   Z.Sujkowski, S.Wycech, Phys. Rev. C70, 052501, 2004
   signature – X-rays < 100 keV + γ or $e^-e^+$ or Majoron
   advantage: good value of the rates between 0νEC/EC and 2νEC/EC processes

3. Pixel detectors (Si or Ge) in EC/EC decay – thickness between 300 μm-1 mm (coincidence measurement, position of detection, energy of X-ray, particles recognition, measurement of background)
Future plans

**Instrumentation**

- Planar pixellated detector (Si, GaAs, CdTe, thickness: 300/700/1000 μm, Ge ~500 μm)
- Bump-bonded to Medipix readout chip containing amplifier, double discriminator, and counter or ADC (TimePix) in each pixel cell

**Medipix2 and TimePix**
- Pixels: 256 x 256
- Pixel size: 55 x 55 μm²
- Area: 1.5 x 1.5 cm²

**Medipix2 Quad**
- Pixels: 512 x 512
- Pixel size: 55 x 55 μm²
- Area: 3 x 3 cm²

How about to use a pixellated detector for EC/EC measurements? (coincidences, position, X-ray energy, recognition of particle type)
• to investigate EC/EC processes in $^{106}\text{Cd}$ (to focus on g.s. to g.s. channel) using Timepix detectors in coincidence mode
• observables:
  2 characteristic X-rays from de-excitation of $^{106}\text{Pd}$ shell

Advantages:
- better efficiency comparing with TGV II (factor 2)
- information about energy + position of registrated X-ray
- track recognition (background vs. signal)
- much less material needed (lower background)
- measurement under room temperature (easy access)
Phase II of the TGV experiment

Measurement with TGV II detector:
- start in Modane December 2007
- planned for 3-4 years
- more enriched material (15 gr.)
- suppression of background.

\[
T_{1/2}^{EC/EC} (^{106}Cd) > 2 - 3 \cdot 10^{21} \text{ y (90\%)}
\]

R&D with Timepix detector:
- measurement of background in IEAP CTU lab with 1 Timepix detector
- measurement of background in Modane underground lab with 1 Timepix detector
- development of coincidence mode with 2 Timepix detectors
- measurement of background in Modane underground lab using coincidence mode

\[
T_{1/2}^{EC/EC} (^{106}Cd) > 4 - 6 \cdot 10^{21} \text{ y (90\%)}
\]
NEMO 3: Neutrino Ettore Majorana Observatory
(France, UK, Spain, Russia, USA, Japan, Czech Republic, Ukraine, Finland)

Tracking detector: drift chamber (6180 Geiger cell)
\[ \sigma_t = 5 \text{ mm}, \sigma_z = 1 \text{ cm} \text{ (vertex) } \]

Calorimeter (1940 plastic scintillators – Low radioactive PMTs)
Energy Resolution FWHM=14\% (1 MeV)

Shieldings against gammas and neutrons
Magnetic field for charge identification
High radiopurity materials

Identification e\-, e\+, \gamma, \alpha

Efficiency: 8\% in the 2.7 – 3.2 windows energy region

Running at Modane underground laboratory since 2003

Unique feature: measurement of all kinematic parameters: individual energies and angular distribution
$^{100}\text{Mo}$ $2\beta2\nu$ result


**Sum Energy Spectrum**

- NEMO-3
- $^{100}\text{Mo}$
- 219 000 events
- 6914 g
- 389 days
- S/B = 40

**Angular Distribution**

- NEMO-3
- $^{100}\text{Mo}$
- 219 000 events
- 6914 g
- 389 days
- S/B = 40

$T_{1/2} = 7.11 \pm 0.02 \text{ (stat)} \pm 0.54 \text{ (syst)} \times 10^{18} \text{ y}$

\[ \beta\beta 2\nu \text{ results with other nuclei} \]

- $^{82}\text{Se}$: $T_{1/2} = 9.6 \pm 0.3 \text{ (stat)} \pm 1.0 \text{ (syst)} \times 10^{19} \text{ y}$
- $^{116}\text{Cd}$: $T_{1/2} = 2.8 \pm 0.1 \text{ (stat)} \pm 0.3 \text{ (syst)} \times 10^{19} \text{ y}$
- $^{150}\text{Nd}$: $T_{1/2} = 9.7 \pm 0.7 \text{ (stat)} \pm 1.0 \text{ (syst)} \times 10^{18} \text{ y}$
- $^{96}\text{Zr}$: $T_{1/2} = 2.0 \pm 0.3 \text{ (stat)} \pm 0.2 \text{ (syst)} \times 10^{19} \text{ y}$
- $^{48}\text{Ca}$: $T_{1/2} = 3.9 \pm 0.7 \text{ (stat)} \pm 0.6 \text{ (syst)} \times 10^{19} \text{ y}$
- $^{130}\text{Te}$: $T_{1/2} = 7.6 \pm 1.5 \text{ (stat)} \pm 0.8 \text{ (syst)} \times 10^{20} \text{ y}$ (new!)
- $^{100}\text{Mo-}$
- $^{100}\text{Ru}(0^+)$: $T_{1/2} = 5.7^{+1.3}_{-0.9} \text{ (stat)} \pm 0.8 \text{ (syst)} \times 10^{20} \text{ y}$

NEMO-3 is $2\beta(2\nu)$-decay factory!!!
**ββ0ν search (ΔL = 2)**

**100Mo**, Phase I + II, 693 days

\[ T_{1/2}^{\beta\beta0\nu} > 5.8 \times 10^{23} \text{ (90 \% CL)} \]

\[ <m_\nu> < 0.8 - 1.3 \text{ eV} \]

Expected in 2009:

\[ T_{1/2}^{\beta\beta0\nu} > 2 \times 10^{24} \text{ (90 \% CL)} \]

\[ <m_\nu> < 0.4 - 0.7 \text{ eV} \]

**82Se**, Phase I + II, 693 days

\[ T_{1/2}^{\beta\beta0\nu} > 2.1 \times 10^{23} \text{ (90 \% CL)} \]

\[ <m_\nu> < 1.4 - 2.2 \text{ eV} \]

\[ T_{1/2}^{\beta\beta0\nu} > 8 \times 10^{23} \text{ (90 \% CL)} \]

\[ <m_\nu> < 0.7 - 1.1 \text{ eV} \]

- Collaboration decided to perform blind analysis with mock data
- Plan to open the box and update the results ~ summer 2008
  - and once again at the end of the experiment ~ early 2010.
SuperNEMO project

(France, UK, Russia, Spain, USA, Japan, Czech Republic, Ukraine, Finland)

Tracko-calor with 100 kg of $^{82}$Se or $^{150}$Nd
(possibility to produce $^{150}$Nd with the French AVLIS facility)

$T_{1/2} > 2 \times 10^{26}$ yr

$\langle m_\nu \rangle < 0.05 - 0.09$ eV

Modules based on the NEMO3 principle
Measurements of energy sum, angular distribution and individual electron energy

3 years R&D program: improvement of energy resolution
Increase of efficiency
Background reduction

......

R&D funded by France, UK, Spain, Russia, Czech Republic

2009: TDR
2011: commissioning and data taking of first modules in Canfranc (Spain)
2013: Full detector running
<table>
<thead>
<tr>
<th>NEMO-3</th>
<th>SuperNEMO</th>
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<tbody>
<tr>
<td><strong>100</strong>Mo</td>
<td><strong>150</strong>Nd or <strong>82</strong>Se</td>
</tr>
<tr>
<td>7 kg</td>
<td>100-200 kg</td>
</tr>
<tr>
<td><strong>8% @3MeV</strong></td>
<td><strong>4% @ 3MeV</strong></td>
</tr>
<tr>
<td><strong>8 %</strong></td>
<td>Efficiency <strong>ε(ββ0ν)</strong></td>
</tr>
<tr>
<td><strong>208</strong>Tl &lt; 20 µBq/kg</td>
<td><strong>208</strong>Tl &lt; 2 µBq/kg</td>
</tr>
<tr>
<td><strong>214</strong>Bi &lt; 300 µBq/kg</td>
<td><em>(If <strong>82</strong>Se: <strong>214</strong>Bi &lt; 10 µBq/kg)</em></td>
</tr>
</tbody>
</table>

**Internal radiopurity**

**208**Tl and **214**Bi in the ββ foils

**SENSITIVITY**

<table>
<thead>
<tr>
<th><strong>T_{1/2}(ββ0ν)</strong> &gt; 2.10^{24} y</th>
<th><strong>&lt;m_ν&gt;</strong> &lt; 0.3 – 1.3 eV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T_{1/2}(ββ0ν)</strong> &gt; (1-2)-10^{26} y</td>
<td><strong>&lt;m_ν&gt;</strong> ~ 40-140 meV</td>
</tr>
</tbody>
</table>
Schedule / cost

- 2007: R&D SuperNEMO
- 2008: NEMO3 Running
- 2009: SuperNEMO 1st module construction
- 2010: Preparation of the site
- 2011: Construction of 20 modules
- 2012: 6 SuperNEMO modules running @ Canfranc
- 2013: Final SuperNEMO modules installation

Cost estimate (preliminary)
- Isotope: (10 M€) if 82Se, 20 M€ if 150Nd (AVLIS)
- Detector: 20 M€

Grand Total: 40 - 50 M€
Examples of practical activities of the IEAP staff in NEMO:
1) *anti-radon setup* - removes Rn from the air, 150 m$^3$/h, A < 10 mBq/m$^3$. Financed partly by czech side.

2) *Production of neutron shielding of NEMO detector* - stainless steel tanks filled by borated water. Financed by czech side.

3) *Production of supporting frame* – low background steel. Financed by czech side.
Activities of the IEAP staff - plans for 2008:

1) *Rn measurements* - measurement of Rn diffusion, apparatus for measurement of Rn emanation.

2) *Ultra low background facility based on high volume HPGe* (600 cm³) - will be installed in LSM as IEAP CTU contribution. Financed by IEAP and JINR.

3) *Testing facility of scintillating detectors* – in IEAP, to test resolution.

4) *Data processing for NEMO 3* (*¹⁰⁰Mo excited states, *¹¹⁶Cd*) and *TGV*

5) *Activities with pixel detectors for ββ decay* – fully done in IEAP inside Medipix collaboration.
Back-up slides
**Half-life for 0νββ:**

\[ T_{1/2} = \frac{\varepsilon}{W} F_a \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} \]

- Isotopical enrichment
- Source mass
- Exposure time
- Detection efficiency
- Energy resolution
- Molecular weight
- Background rate in c/(keV.kg.y)
- source = enriched material (\(F_a\))
- big mass of the source (M)
- long time of measurement (t)
- “best” energetical resolution of the detector (\(\Delta E\))
- background as low as possible (B)
Background Sources

- **Natural radioactivity of materials** (source itself, surrounding structures)
  - Neutrons
  - Cosmogenic induced activity (long living)
  - $^2\nu$ Double Beta Decay

- **Neutrons**
  - Activity in the rock and in surrounding materials
    - $(\alpha, n)$ processes $\rightarrow$ [0, 10] MeV spectrum
  - Choice of materials

- **Cosmogenic induced**
  - High-energy $\mu$-induced complicated problem
    - Depth
    - Appropriate shielding / coincidence techniques
    - Reliable simulations
    - "Ad hoc" experiments at muon accelerators could be useful

- **Storage of materials underground**
  - Partial or full detector realization underground (Ge diodes)
    - Reliable simulations
    - "Ad hoc" experiments at muon accelerators could be useful

- **Two main sources**
  - Activity in the rock and in surrounding materials
  - $^2\nu$ Double Beta Decay
Three neutrino mass and mixing

$$
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}_L =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
$$

$$U_{MNS} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
e^{i\alpha_1/2} & 0 & 0 \\
0 & e^{i\alpha_2/2} & 0 \\
0 & 0 & 1
\end{pmatrix}
$$

Oscillation phase: $\delta$
Majorana phases: $\alpha_1, \alpha_2$

3 masses + 3 angles + 1(3) phase(s) = 7(9) new parameters for SM
Neutrino mass squared splittings and angles

<table>
<thead>
<tr>
<th>parameter</th>
<th>best fit</th>
<th>3σ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2_{21}$ [10^{-5} eV^2]</td>
<td>7.9</td>
<td>7.1–8.9</td>
</tr>
<tr>
<td>$\Delta m^2_{31}$ [10^{-3} eV^2]</td>
<td>2.6</td>
<td>2.0–3.2</td>
</tr>
</tbody>
</table>

Valle et al

$\theta_{12} = 33^\circ \pm 5^\circ$

$\theta_{23} = 45^\circ \pm 10^\circ$

$\theta_{13} < 13^\circ$

3σ errors

Absolute neutrino mass scale?
Phase II preparation (1)

238keV area distribution along the cryostat:
Phase II preparation (4)

- test measurement with modified endcap – 1 month acquisition:

  Spectrum before and after endcap modification

  238keV area reduction:
  - whole cryostat: 5x
  - four central detector pairs: 13x
Track of muon
Track of electron
SuperNEMO preliminary design

Planar geometry

Source \((40 \text{ mg/cm}^2) \times 12 \text{ m}^2\), tracking volume \((\sim 3000 \text{ channels})\) and calorimeter \((\sim 1000 \text{ PMT})\)

Modular \((\sim 5 \text{ kg of enriched isotope/module})\)

100 kg: 20 modules

\(~ 60,000 \text{ channels for drift chamber}\)

\(~ 20,000 \text{ PMT (2000 if scintillator bars)}\)

Top view

Side view
In case of dominant mass mechanism:

**neutrinoless Double Beta Decay rate**

\[
\frac{1}{\tau} = G(Q,Z) \left| M_{\text{nucl}} \right|^2 \langle M_{\beta\beta} \rangle^2
\]

\[
\langle M_{\beta\beta} \rangle = \left| U_{e1} \right|^2 M_1 + e^{i\alpha_1} \left| U_{e2} \right|^2 M_2 + e^{i\alpha_2} \left| U_{e3} \right|^2 M_3
\]

*what the experimentalists try to measure*

*what the nuclear theorists try to calculate*

*Phase space*

*Nuclear matrix elements*

*parameter containing the physics*

*Effective Majorana mass*
TGV II (predictions, measurements)

- **Theoretical predictions:**
  - \( T_{1/2} = 1.0 \cdot 10^{20} \text{ y} \) (Suhonen)
  - \( 8.7 \cdot 10^{20} \text{ y} \) (Hirsch)
  - \( 4.4 \cdot 10^{21} \text{ y} \) (Simkovic)

- **Experimental results:** (mostly to excited states of \(^{106}\text{Pd}\))
  - \( T_{1/2} > 6.2 \cdot 10^{18} \text{ y} \) (Barabash, HPGe detector + Cd foil, Modane)
  - \( T_{1/2} > 7.3 \cdot 10^{19} \text{ y} \) (Belli, NaI(Tl), geometry similar to TGV, Gran Sasso)
  - \( T_{1/2} (\text{g.s} \rightarrow \text{g.s.}) > 5.8 \cdot 10^{17} \text{ y} \) (Georgadze, measurement with \(^{116}\text{CdWO}_4\) scintillators, Solotvina)