Recent Results from NEMO 3 Experiment

Typical 2νββ events
~ every 1.5 minutes

Search for 0νββ events
Study neutrino mass

H. Ohsumi (Saga U.) @ US-Japan Seminar, September 16-20, 2005, Maui, Hawaii
NEMO3 Collaboration

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• Introduction

• NEMO3
  ➢ description, performances
  ➢ results 2β2ν
  ➢ results 2β0ν : data phase 1  1.08 year
  ➢ fight against radon

• SuperNEMO (if I have time …a little bit)

• Concluding Remarks
Philosophy of NEMO experiment

- **Neutrinoless Double Beta Decays (0νββ)**
  - Majorana ν and effective mass $<m_\nu>$ ? or new physics (SUSY) ?

- **Measure several isotopes (0νββ, 2νββ)**
  - $^{100}$Mo($\sim$7kg), $^{82}$Se($\sim$1kg), $^{130}$Te, $^{116}$Cd, $^{96}$Zr, $^{48}$Ca, $^{150}$Nd

- **Tag and measure all the BG events**
  - $e^-, e^+, \gamma, \alpha, \text{neutron}$

  **Tracking chamber+Calorimeter+\overline{B}-field+Shields**

“zero background” experiment

**2νββ**

$2\nu\beta\beta : 2n \rightarrow 2p+2e^-+2\nu$

(Standard Process)

$0\nu\beta\beta : 2n \rightarrow 2p+2e^-$

($\Delta L = 2$ Process)

(Beyond Standard Model)

$\nu_M$
Expected values of $<m_\nu>$ from neutrinos oscillations parameters

Pascoli and Petcov, hep-ph/0310003 (best fit $\nu_{atm} + \nu_{sol}$)

Quasi-Degenerate (QD): $<m_\nu> > 50$ meV

Inverted Hierarchy (IH): $15$ meV < $<m_\nu>$ < 50 meV

Normal Hierarchy (NH): $<m_\nu>$ < 5 meV

$2\beta$ could give the absolute neutrino mass

(hep-ph/0503246 A.Strumia and F.Vissani)
The Location of the NEMO3

NEMO 3 is here!

Frejus Underground Laboratory
Laboratoire Souterraine de Modane (LSM)
(4800 m.w.e.)

Italy France
The NEMO3 detector

Fréjus Underground Laboratory : 4800 m.w.e.

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

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 ($e = 18\text{cm}$)
Neutron shield:
30 cm water (ext. wall)
40 cm wood (top and bottom)
(since March 2004: water + boron)

Able to identify $e^-$, $e^+$, $\gamma$ and $\alpha$
scintillators

Cathodic rings
Wire chamber

Calibration tube

Calibration Source

$^{207}$Bi
2$e^-$ (IC) lines
~0.5 ,~1 MeV

$^{90}$Sr

$^{60}$Co
How detect signals and tag the background?

**Identification of e, γ, α**

- **Tracking** (Identification e/others)
  - Delayed (<700µs) α track
- **Calorimeter** ε(γ)~50% (@0.5MeV)
  - Possible for tagging eγ, eγγ, eγγγ, ...
- **Time of flight** σt~300ps(@1MeV)
  - External Background rejection
- **Magnetic Field** (Identification e-/e+)
  - 3~5% e-/e+ confusion @ 1~7MeV

**Study of Background Process**

- **214Bi** Tagged by e(γ)α (~164µs)
  - (214Bi->214Po->210Pb)
- **208Tl** eγ, eγγ, eγγγ, with γ (2.6MeV)
  - or Taggd by e(γ) α (~300ns)
  - (212Bi->212Po->208Pb)
- **Neutron** Crossing e (4~8MeV)
\(\beta\beta\) decay isotopes in NEMO-3 detector

\(\beta\beta\) decay isotopes:

- **116\(^{\text{Cd}}\)** 405 g
  \(Q_{\beta\beta} = 2805\) keV

- **96\(^{\text{Zr}}\)** 9.4 g
  \(Q_{\beta\beta} = 3350\) keV

- **150\(^{\text{Nd}}\)** 37.0 g
  \(Q_{\beta\beta} = 3367\) keV

- **48\(^{\text{Ca}}\)** 7.0 g
  \(Q_{\beta\beta} = 4272\) keV

- **130\(^{\text{Te}}\)** 454 g
  \(Q_{\beta\beta} = 2529\) keV

- **nat\(^{\text{Te}}\)** 491 g
  \(Q_{\beta\beta} = 2995\) keV

- **Cu** 621 g

**\(\beta\beta\)\(_{2\nu}\) measurement**

**\(\beta\beta\)\(_{0\nu}\) search**

(All the enriched isotopes produced in Russia)
Sources preparation
Iron shield

Start taking data 14 February 2003

Water tank

wood

coil

Iron shield
Typical $\beta\beta$ event observed from $^{100}$Mo

**Deposited energy:**

$E_1 + E_2 = 2088$ keV

**Internal hypothesis:**

$(\Delta t)_{\text{mes}} - (\Delta t)_{\text{theo}} = 0.22$ ns

**Common vertex:**

$(\Delta \text{vertex})_{\perp} = 2.1$ mm

**Vertex emission:**

$(\Delta \text{vertex})_{\parallel} = \ldots$

**Trigger:**

1 PMT $> 150$ keV

3 Geiger hits (2 neighbour layers + 1)

Trigger rate $= 7$ Hz

$\beta\beta$ events: 1 event every 1.5 minutes
**Background events observed by NEMO-3...**

- Electron crossing $> 4$ MeV
- Neutron capture

- Electron + $\alpha$ delay track (164 $\mu$s) \[ ^{214}\text{Bi} \rightarrow ^{214}\text{Po} \rightarrow ^{210}\text{Pb} \]

- Electron + N $\gamma$'s \[ ^{208}\text{Tl} \ (E_\gamma = 2.6 \text{ MeV}) \]

- Electron – positron pair $\bar{B}$ rejection
**Performance of the detector**

**Tracking Detector:**
- 99.5% Geiger cells ON
- Vertex resolution:
  2 e⁻ channels (482 and 976 keV) using $^{207}$Bi sources at 3 well known positions in each sector
  
  $\sigma_\perp (\Delta\text{Vertex}) = 0.6 \text{ cm}$
  $\sigma_\parallel (\Delta\text{Vertex}) = 1.3 \text{ cm}$ (Z=0)
  
- e⁺/e⁻ separation with a magnetic field of 25 G
- ~ 3% confusion at 1 MeV

**Time Of Flight:**
- Time Resolution ($\beta\beta$ channel) $\approx 250$ ps at 1 MeV
  
  ToF (external crossing e⁻) $> 3$ ns
  external crossing e⁻ totally rejected

**Calorimeter:**
- 97% of the PMTs+scintillators are ON
- Energy Resolution:
  calibration runs (every ~ 40 days) with $^{207}$Bi sources
  
  | | Ext. Wall 5'' PMTs | Int. Wall 3'' PMTs |
  | FWHM (1 MeV) | 14% | 17% |

- Daily Laser Survey to control gain stability of each PM

**Expected Performance of the detector has been reached**
$2\beta 2\nu$ decay results in NEMO-3
$^{100}$Mo $2\beta 2\nu$ preliminary results


**Sum Energy Spectrum**

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

**Angular Distribution**

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

- Data
- $2\beta 2\nu$ Monte Carlo
- Background subtracted

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

7.37 kg.y
2\(\beta\)2\(\nu\) preliminary results for other nuclei

\[ 82^{\text{Se}} \quad T_{1/2} = 9.6 \pm 0.3 \text{ (stat)} \pm 1.0 \text{ (syst)} \times 10^{19} \text{ y} \]

\[ 116^{\text{Cd}} \quad T_{1/2} = 2.8 \pm 0.1 \text{ (stat)} \pm 0.3 \text{ (syst)} \times 10^{19} \text{ y} \]

\[ 150^{\text{Nd}} \quad T_{1/2} = 9.7 \pm 0.7 \text{ (stat)} \pm 1.0 \text{ (syst)} \times 10^{18} \text{ y} \]

\[ 96^{\text{Zr}} \quad T_{1/2} = 2.0 \pm 0.3 \text{ (stat)} \pm 0.2 \text{ (syst)} \times 10^{19} \text{ y} \]
**100Mo 2β2ν Single Energy Distribution**

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

**Single electron spectrum different between SSD and HSD**

**Data**

- **HSD**: $T_{1/2} = 8.61 \pm 0.02$ (stat) $\pm 0.60$ (syst) $\times 10^{18}$ y
- **SSD**: $T_{1/2} = 7.72 \pm 0.02$ (stat) $\pm 0.54$ (syst) $\times 10^{18}$ y

**100Mo 2β2ν single energy distribution in favour of Single State Dominant (SSD) decay**
Search for $2\beta^0\nu$ decay in NEMO-3
Limit on the effective mass of the Majorana neutrino
Phase 1 (Feb. 2003 – Sept. 2004: 1.08 y of data) with radon bkg
(limits @ 90% CL)

$^{100}\text{Mo}$ (6.914 kg)
$T_{1/2}(\beta\beta0\nu) > 4.6 \times 10^{23}$ y
$\langle m_\nu \rangle < 0.66 - 2.81$ eV

$^{82}\text{Se}$ (0.932 kg)
$T_{1/2}(\beta\beta0\nu) > 1.0 \times 10^{23}$ y
$\langle m_\nu \rangle < 1.75 - 4.86$ eV

Cu$^{nat}$Te$^{130}$Te
In agreement with only Radon bkg expected

Previous limits: $T_{1/2}(\beta\beta0\nu) > 5.5 \times 10^{22}$ y
Ejiri et al. (2001)

Previous limits: $T_{1/2}(\beta\beta0\nu) > 9.5 \times 10^{21}$ y
Arnold et al. (1992)

**ββ0ν Analysis: Background Measurement**

NEMO-3 can measure each component of its background!

- **External Background** \(^{208}\text{Tl}\) (PMTs)
  - Measured with \((e^-,\gamma)\) external events
    - \(\sim 10^{-3} \beta\beta0\nu\)-like events year\(^{-1}\) kg\(^{-1}\) with \(2.8<E_1+E_2<3.2\) MeV

- **External Neutrons and High Energy gamma**
  - Measured with \((e^-,e^-)_{\text{int}}\) events with \(E_1+E_2>4\) MeV
  - \(<0.02 \beta\beta0\nu\)-like events year\(^{-1}\) kg\(^{-1}\) with \(2.8<E_1+E_2<3.2\) MeV

- **\(^{208}\text{Tl}\) impurities inside the foils**
  - Measured with \((e^-,2\gamma), (e^-,3\gamma)\) events coming from the foil
    - \(\sim 0.1 \beta\beta0\nu\)-like events year\(^{-1}\) kg\(^{-1}\) with \(2.8<E_1+E_2<3.2\) MeV

- **\(^{100}\text{Mo} \beta\beta2\nu\) decay**
  - \(T_{1/2} = 7.7\ 10^{18}\) y (SSD)
  - \(\sim 0.3 \beta\beta0\nu\)-like events year\(^{-1}\) kg\(^{-1}\) with \(2.8<E_1+E_2<3.2\) MeV

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<table>
<thead>
<tr>
<th>Sources</th>
<th>A (μBq/k) from ((e^-,N\gamma))</th>
<th>A (μBq/k) HPGe meas.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{100}\text{Mo}) metal.</td>
<td>92 ± 18</td>
<td>&lt; 110</td>
</tr>
<tr>
<td>(^{100}\text{Mo}) comp.</td>
<td>115 ± 13</td>
<td>&lt; 100</td>
</tr>
<tr>
<td>(^{82}\text{Se})</td>
<td>316 ± 46</td>
<td>400 ± 100</td>
</tr>
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</table>

Only 2 \((e^-,e^-)_{\text{int}}\) events with \(E_1+E_2>4\) MeV observed after 260 days of data (without boron)

\(4253\) keV (26 Mar. 2003)
\(6361\) keV (8 Nov. 2003)

In agreement with expected background

In agreement with HPGe measurements
Limit on Majoron and V+A
Phase 1 (Feb. 2003 – Sept. 2004: 1.08 y of data) with radon bkg
(limits @ 90% CL)

Limit on Majoron

\[ ^{100}\text{Mo}: \quad T_{1/2} (\beta\beta0\nu\text{M}) > 1.8 \times 10^{22} \text{ y} \]
\[ ^{82}\text{Se}: \quad T_{1/2} (\beta\beta0\nu\text{M}) > 1.5 \times 10^{22} \text{ y} \]
\[ g_\text{M} < (5.3 – 8.5) \times 10^{-5} \quad \text{(best limit)} \]

Simkovic (1999), Stoica (1999)


Limit on V+A

\[ ^{100}\text{Mo}: \quad T_{1/2} (\beta\beta0\nu \text{ V+A}) > 2.3 \times 10^{23} \text{ y} \]
\[ ^{82}\text{Se}: \quad T_{1/2} (\beta\beta0\nu \text{ V+A}) > 1.0 \times 10^{23} \text{ y} \]
\[ \lambda < (1.5 – 2.0) \times 10^{-6} \]

Tomoda (1991), Suhonen (1994)

\[ \lambda < 3.2 \times 10^{-6} \]

Tomoda (1991)
Radon effect and fight against radon
E1+E2= 2880 keV

Run 2220, event 136.604, May 11th 2003

$^{214}$Po → $^{210}$Pb

$^{214}$Bi → $^{214}$Po

α track
(delay = 70 µs)

β decay
IN THE GAS

a $\beta\beta 0\nu$-like event due to Radon from the gas
ββ0ν Analysis: Background Measurement

Radon in the NEMO-3 gas of the wire chamber

Due to a tiny diffusion of the radon of the laboratory inside the detector

\[ A(\text{Radon}) \text{ in the lab} \sim 15 \text{ Bq/m}^3 \]

Two independent measurements of radon in NEMO-3 gas

- Radon detector at the input/output of the NEMO-3 gas
  - ~ 20 counts/day for 20 mBq/m³
- \((1e^- + 1 \alpha)\) channel in the NEMO-3 data:
  - Delayed tracks (<700 µs) to tag delayed α from \( ^{214}\text{Po} \)
  - \( ^{214}\text{Bi} \rightarrow ^{214}\text{Po} (164 \mu s) \rightarrow ^{210}\text{Pb} \)
  - ~ 200 counts/hour for 20 mBq/m³

Good agreement between the two measurements

\[ A(\text{Radon}) \text{ in NEMO-3} \approx 20-30 \text{ mBq/m}^3 \]

~ 1 ββ0ν-like events/year/kg with \( 2.8 < E_1 + E_2 < 3.2 \) MeV

Radon is the dominant background today for ββ0ν search in NEMO-3 !!!
NEMO Tent for Free-Radon air Installation

May 2004: Tent surrounding the detector
Free-Radon Air factory


1 ton charcoal @ -50°C, 7 bars

Activity: $A^{222}\text{Rn} < 15 \text{ mBq/m}^3$ !!!

Flux: 125 m$^3$/h a factor 1000
(Without Radon)
NEMO-3 Expected sensitivity

Background

External Background: negligible

Internal Background: $^{208}\text{Tl}$: 60 µBq/kg for $^{100}\text{Mo}$
$^{214}\text{Bi}$: $< 300$ µBq/kg
$^{82}\text{Se}$: 300 µBq/kg

$\sim 0.1$ count kg$^{-1}$ y$^{-1}$ with $2.8 < E_1 + E_2 < 3.2$ MeV

$\beta\beta_{2\nu}^{100}\text{Mo}$: $T_{1/2} = 7.14 \times 10^{18}$ y
$\sim 0.3$ count kg$^{-1}$ y$^{-1}$ with $2.8 < E_1 + E_2 < 3.2$ MeV

in 2009 after 5 years of data

6914 g of $^{100}\text{Mo}$
$T_{1/2}(\beta\beta0\nu) > 4 \times 10^{24}$ y (90% C.L.)
$<m_\nu> < 0.2 - 1.3$ eV

932 g of $^{82}\text{Se}$
$T_{1/2}(\beta\beta0\nu) > 8 \times 10^{23}$ y (90% C.L.)
$<m_\nu> < 0.6 - 1.7$ eV

From NEMO 3 to SuperNEMO
Expected values of $<m_\nu>$ from neutrinos oscillations parameters

From NEMO 3 to Super-NEMO

Pascoli and Petcov, hep-ph/0310003
(best fit $\nu_{\text{atm}} + \nu_{\text{sol}}$)

Quasi-Degenerate (QD):

$<m_\nu> > 50$ meV

Inverted Hierarchy (IH):

$15$ meV $< <m_\nu> < 50$ meV

Normal Hierarchy (NH):

$<m_\nu> < 5$ meV

$2\beta$ could give the absolute neutrino mass

(hep-ph/0503246 A.Strumia and F.Vissani)
From NEMO to SuperNEMO

Factor 100 on the $\beta\beta(0\nu)$ period $T_{1/2}$, reach few $10^{26}$ years

Light Majorana neutrino exchange: $\langle m_\nu \rangle \sim 50$ meV

Detection efficiency $\times$ Mass of isotope $\beta\beta$ (g)

$T_{1/2}^{0\nu} (y) > \frac{\ln 2 \cdot N_{\text{F}}} {k_{\text{C.L.}}} \cdot \frac{E}{A} \cdot \sqrt{\frac{m \cdot t}{N_{\text{BDF}} \cdot R}}$

$N$: Avogadro Number
$k_{\text{C.L.}} = 1.6 \pm 90\%$ C.L.
$A$: Mass number
$t$: measurement time (y)

Detection efficiency improvement by a factor 2

Background (y$^{-1}$ . g$^{-1}$ . keV$^{-1}$)
FWHM (keV)

Mass
~100 kg

Resolution
(FWHM): ~ 7% at 3 MeV (will be dominated by source foil)
instead of ~ 11% at 3 MeV for NEMO 3 (dominated by calorimeter)

Efficiency improvement by a factor 2

Background
internal contaminations in $^{208}$Tl and $^{214}$Bi to be improved by a factor of 10
SuperNEMO preliminary design

Plane geometry

Source (40 mg/cm²) 12m², tracking volume (~3000 channels) and calorimeter (~1000 PMT)

Modular (~ 5 kg of enriched isotope/module)

100 kg: 20 modules
  ~ 60 000 channels for drift chamber
  ~ 20 000 PMT
Water shield

Need of cavity of ~ 60m x 15m x 15m
Possible in Gran Sasso or in Modane if a new cavity
Concluding Remarks

- NEMO3 is running for ≈ 5 years
- What we learnt with NEMO
  - to identify and measure all the sources of background
  - to build a very low-background detector
  - to prove the reliability of the chosen techniques
  - to purify $\beta\beta$ isotopes by removing parents of $^{214}$Bi, $^{208}$Tl
  - to remove background due to Radon (recently)

technique can be extrapolated

R&D program for Super NEMO

Thank you