Search for neutrinoless double beta decay: from NEMO3 to SuperNEMO

Arnaud Chapon
on behalf of the NEMO/SuperNEMO collaboration

LPC Caen, ENSICAEN, Université de Caen, CNRS/IN2P3, Caen, France

11 october 2010

Contents

Double beta decay

The two decay processes

The allowed 2ν process ($2\nu 2\beta$)

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

- $\Delta L = 0$
- $\nu \neq \bar{\nu}$
- $(T^{2\nu}_{1/2})^{-1} = G_{2\nu}|M_{2\nu}|^2$
- $T^{2\nu}_{1/2} \approx 10^{19} - 10^{21} years$

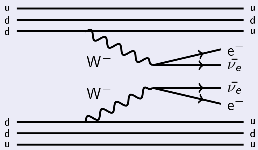


Fig.: $2\nu 2\beta$ mechanism

The 0ν process beyond the SM ($0\nu 2\beta$)

$$(\mathrm{A,Z}) \rightarrow (\mathrm{A,Z{+}2}) + 2\mathrm{e}^-$$

- $\Delta L = 2$
- $\nu \equiv \bar{\nu}$
- $(T^{0\nu}_{1/2})^{-1} = G_{0\nu}|M_{0\nu}|^2|m_{\beta\beta}|^2$
- $T^{0\nu}_{1/2} \geq 10^{24} years$

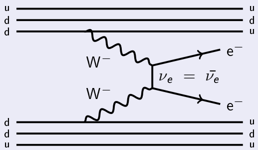


Fig.: $0\nu 2\beta$ mechanism

Double beta decay

Experimental principle

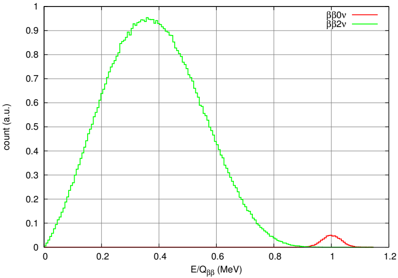


Fig.: 2β decay spectrum

The tracko-calo technique enables to :

- measure the energy of the 2 electrons with a good energy resolution (fwhm $\approx$ 10% @ 1 MeV)
- identify individually the 2 emitted electrons (E$_{e_1}$, E$_{e_2}$, Δt, cosθ)
- measure background components
- have an efficiency $\approx$ 30%

Double beta decay

Choice of 2β isotopes

Experimentally :

$$T^{0\nu}_{1/2} \geq k.\frac{\epsilon}{A}\sqrt{\frac{M.t}{N_{bgr}.r}}$$

with $k = \dfrac{ln2.N_A}{1.64}$: constant, ϵ : efficiency, A : molecular weight, M : source mass, t : time of measurement, N_{bgr} : background events and r : energy resolution

Choice of 2β isotopes

- high $Q_{\beta\beta}$
  - $E_\gamma(^{208}Tl) = 2.6$ MeV
  - $Q_\beta(^{214}Bi) = 3.3$ MeV
- high $G_{0\nu}$ (low $T^{0\nu}_{1/2}$)
- high $T^{2\nu}_{1/2}$ (low $2\nu2\beta$)
- high mass :
  - natural abundance
  - low atomic mass A
  - enrichment

2β isotope	$Q_{\beta\beta}$ (keV)	nat. ab. (%)	$T^{2\nu}_{1/2}$ (years)	$G_{0\nu}$ ($10^{-25}yr^{-1}$)
^{48}Ca	4272	0,187	4.2×10^{19}	2,44
^{82}Se	2995	8,73	9.2×10^{19}	1,08
^{96}Zr	3350	2,8	20.0×10^{18}	2,24
^{100}Mo	3034	9,63	7.1×10^{18}	1,75
^{116}Cd	2805	7,49	3.0×10^{19}	1,89
^{130}Te	2528,9	33,8	9.0×10^{20}	1,70
^{136}Xe	2479	8,9	8.5×10^{21}	1,81
^{150}Nd	3368,1	5,6	7.0×10^{18}	8,00

NEMO3 experiment

Experimental setup

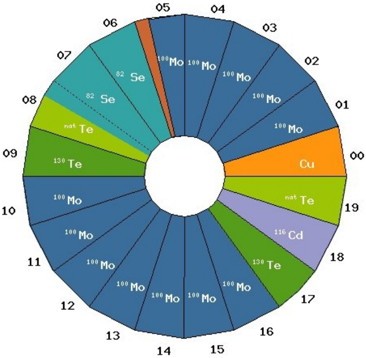


Fig.: NEMO3 sources

- Source
  - 10kg of 2β isotopes

2β isotope	$Q_{\beta\beta}$ (keV)	enrichment (%)	mass (g)
^{100}Mo	3034	96.8	6914
^{82}Se	2995	96.9	932
^{130}Te	2529	89.4	454
^{116}Cd	2802	93.2	405
^{150}Nd	3367	91.0	37
^{96}Zr	3350	57.3	9.4
^{48}Ca	4271	73.1	6.99
$^{nat}TeO_2$			0.9
Cu			0.7

NEMO3 experiment

Experimental setup

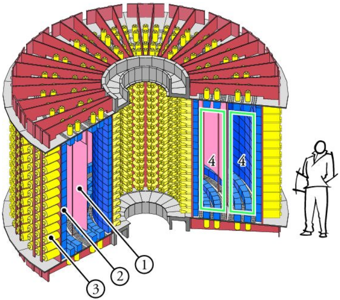


Fig.: NEMO3 setup

- Source **(1)**
    - 10kg of 2β isotopes
- Tracking detector **(4)**
    - Drift wire chamber in Geiger mode (6180 cells)
    - Gas : He + 4% ethyl alcohol + 1% Ar+ 0.1% H_2O
- Calorimeter
    - 1940 plastic scintillators **(2)** coupled to low radioactivity PMTs **(3)**

NEMO3 experiment

Experimental setup

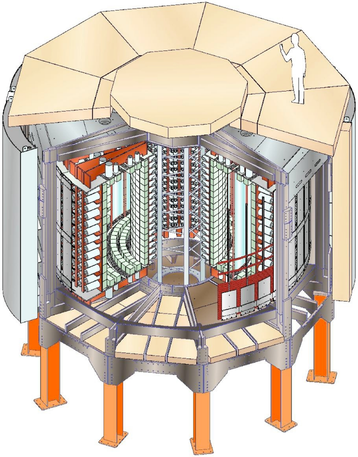


Fig.: NEMO3 setup

- Magnetic field
  - 25 Gauss
- Shielding
  - LSM (4800 m.w.e.)
  - Gamma shield : Pure Iron (18 cm)
  - Neutron shield : borated water (30 cm, wall) + Wood (40 cm, top and bottom)
- Radon free air around the detector
  - Phase I (Feb 2003 - Oct 2004) : High Radon
  - Phase II (Dec 2004 - Now) : Low Radon (reduced by factor 6)

NEMO3 experiment

Background rejection

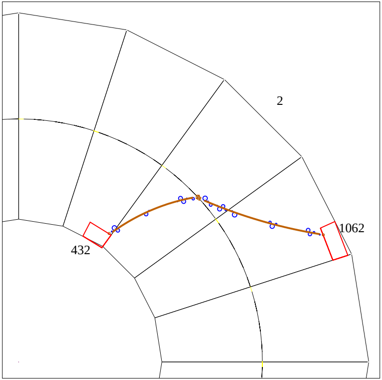


Fig.: reconstruction of a simulated $2\nu2\beta$ decay from ^{100}Mo

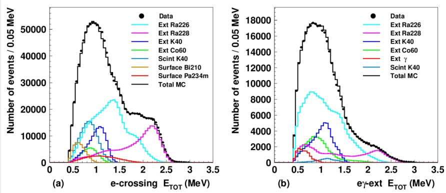
- Measurement of all kinematics parameters
  - E_{e_1}, E_{e_2}, Δt, $\cos\theta$
- Particles identification
  - e^-, e^+, γ, α
- Direct background measurements
  - e^-, $e^-\gamma$, $e^-\gamma\gamma$, $e^-\gamma\gamma\gamma$, $e^-\alpha$, crossing e^-...

NEMO3 experiment

Background rejection[1]

channel	background category	radio-contaminants
$e^-\gamma_{ext}$, crossing e^-	external background	^{40}K, ^{60}Co, ^{226}Ra...
$e^-\gamma$, $e^-\gamma\gamma$, $e^-\gamma\gamma\gamma$	internal background from γ-emitters	^{208}Tl, ^{207}Bi...
$1e^-$	internal background from pure β-emitters	^{234m}Pa, ^{40}K, ^{90}Y...
$e^-\alpha(N\gamma)$	radon daughters deposited on wires and source foils	^{214}Bi, ^{214}Po...

elaborate a full background model in the 500keV-3MeV region



Can measure :

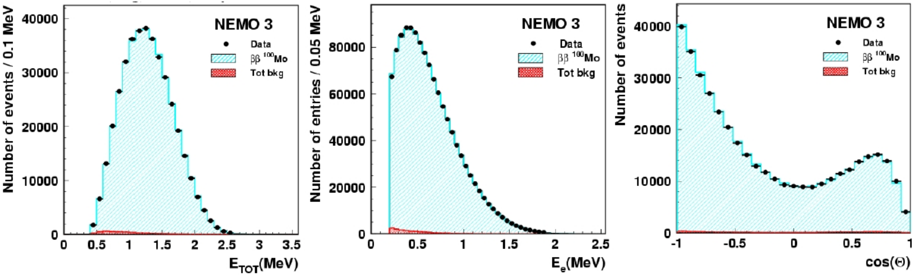
- internal backgrounds in foils
- external backgrounds from detector components
- radon in gas
- cross check with Cu foils.

---

[1] NIM A606 (2009) 449-465

NEMO3 experiment

NEMO3 results - $2\nu2\beta$ from ^{100}Mo (7kg)[2]



$$\text{Phase II } (\approx 3.5 \text{ yr}, \frac{S}{B} = 76) :$$

$$T^{2\nu}_{1/2} = (7.17 \pm 0.01_{(stat)} \pm 0.54_{(sys)}) \times 10^{18} years$$

$$\text{Phase I } (\approx 1 \text{ yr}, \frac{S}{B} = 40) : T^{2\nu}_{1/2} = (7.11 \pm 0.02_{(stat)} \pm 0.54_{(sys)}) \times 10^{18} years$$

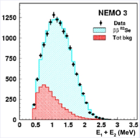
---

[2] PRL 95 (182302) 2005

NEMO3 experiment

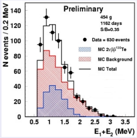
NEMO3 results - $2\nu2\beta$ from other isotopes

^{82}Se - 932g



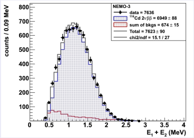
$$T^{2\nu}_{1/2}(10^{19}\,years) = 9.6 \pm 0.1_{(stat)} \pm 1.0_{(sys)}$$

^{130}Te - 454g



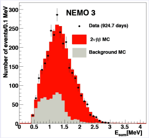
$$T^{2\nu}_{1/2}(10^{20}\,years) = 7.0 \pm 1.0_{(stat)} \pm 1.0_{(sys)}$$

^{116}Cd - 405g



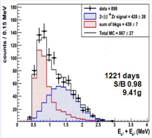
$$T^{2\nu}_{1/2}(10^{19}\,years) = 2.88 \pm 0.04_{(stat)} \pm 0.16_{(sys)}$$

^{150}Nd - 37g



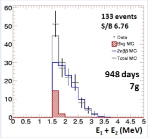
$$T^{2\nu}_{1/2}(10^{18}\,years) = 9.11 \pm 0.25_{(stat)} \pm 0.63_{(sys)}$$

^{96}Zr - 9.4g



$$T^{2\nu}_{1/2}(10^{19}\,years) = 2.35 \pm 0.14_{(stat)} \pm 0.16_{(sys)}$$

^{48}Ca - 6.99g

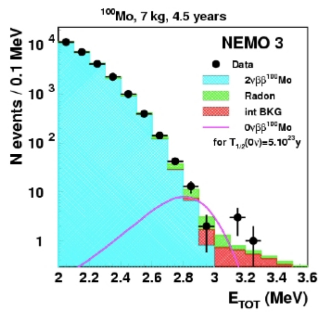


$$T^{2\nu}_{1/2}(10^{19}\,years) = 4.4 \pm 0.5_{(stat)} \pm 0.4_{(sys)}$$

NEMO3 experiment

NEMO3 results - $0\nu 2\beta$ from ^{100}Mo (7kg) and ^{82}Se (1kg)

^{100}Mo - 6914g

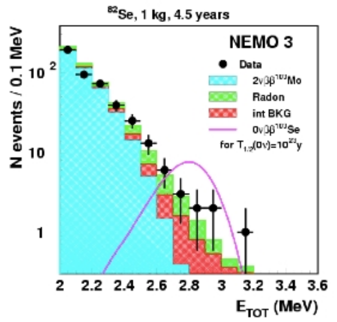


[2.8-3.2] MeV : DATA = 18 ; MC = 16.4±1.4

$$T^{0\nu}_{1/2} > 1 \times 10^{24} yr \quad @\ 90\%\ CL$$

$\langle m_\nu \rangle <$ (0.47 - 0.96) eV[3]

^{82}Se - 932g



[2.6-3.2] MeV : DATA = 14 ; MC = 10.9±1.3

$$T^{0\nu}_{1/2} > 3.2 \times 10^{23} yr \quad @\ 90\%\ CL$$

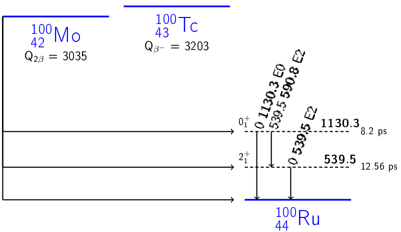
$\langle m_\nu \rangle <$ (0.94 - 2.5) eV[3]

---

[3] Using NME from : - E. Caurieret al., PRL 100 (2008) 052503 - Simkovicet al., PRC 77 (2008) 045503 - Suhonnenet al., J. Mod. Phys E 17 (2008) 1

NEMO3 experiment

NEMO3 results - other measurements



Decays to excited states[4]

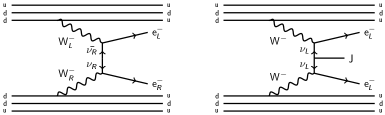
- $T^{2\nu}_{1/2}(0^+ \to 0^+_1) = (5.7^{+1.3}_{-0.9(stat)} \pm 0.8_{(sys)}) \times 10^{20} yr$
- $T^{0\nu}_{1/2}(0^+ \to 0^+_1) > 8.9 \times 10^{22} yr$ @ 90% CL
- $T^{2\nu}_{1/2}(0^+ \to 2^+_1) > 1.1 \times 10^{21} yr$ @ 90% CL
- $T^{0\nu}_{1/2}(0^+ \to 2^+_1) > 1.6 \times 10^{23} yr$ @ 90% CL

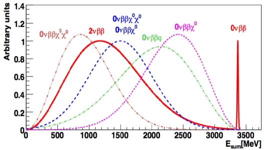
Right Handed Currents V+A

- $T^{0\nu}_{1/2} > 5.4 \times 10^{23} yr$ @ 90% CL

Majoron emission[5]

- $T^{0\nu}_{1/2} > 2.7 \times 10^{22} yr$ @ 90% CL





---

[4] Nucl. Phys. A781 (2007) 209

[5] Nucl. Phys. A765 (2006) 483

From NEMO3 to SuperNEMO

SuperNEMO design

NEMO3		**SuperNEMO**
^{100}Mo	isotope	^{82}Se or ^{48}Ca or ^{150}Nd
7kg	isotope mass	100kg
18%	efficiency	30%
^{208}Tl : $\approx 100\mu$Bq/kg ^{214}Bi : $< 300\mu$Bq/kg Rn : 5 mBq/m^3	internal contaminations in the $\beta\beta$ foils Rn in the tracker	^{208}Tl : $\leq 2\mu$Bq/kg ^{214}Bi : $\leq 10\mu$Bq/kg Rn : $\leq$ 0.15 mBq/m^3
8% @ 3MeV	energy resolution	4% @ 3MeV
$T^{0\nu}_{1/2} > 2 \times 10^{24} yr$ $\langle \mathbf{m}_\nu \rangle$ **< (0.3 - 0.9) eV**	sensitivity	$T^{0\nu}_{1/2} > 1 \times 10^{26} yr$ $\langle \mathbf{m}_\nu \rangle$ **< (0.04 - 0.11) eV**

From NEMO3 to SuperNEMO

SuperNEMO design

20 modules surrounded by passive shielding

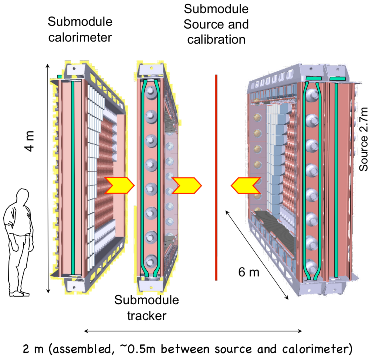


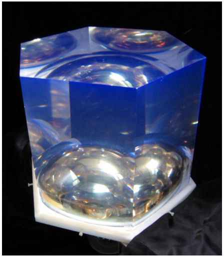
Fig.: SuperNEMO module

20 modules

- Source
  - 5kg per module (40 mg/cm^2, 4 × 2.7 m^2)
  - ^{82}Se first (High $Q_{\beta\beta}$, long $T^{0\nu}_{1/2}$, proven enrichment technology)
  - ^{48}Ca and ^{150}Nd under consideration
- Tracking detector
  - Drift wire chamber in Geiger mode (2000 cells)
- Calorimeter
  - 600 plastic scintillators coupled to low radioactivity PMTs

From NEMO3 to SuperNEMO

R&D developments



Calorimeter

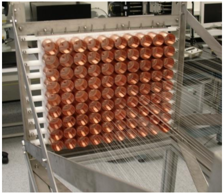
Scintillator and PMT R&D :
requires resolution demonstrated with 28cm hexagonal blocks (≥10cm thick) directly coupled to 8" PMT.

FWHM = 4% @ 3MeV

Tracker

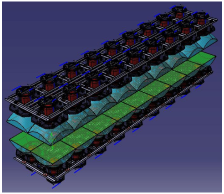
Basic cell design developed and verified.
Required performances demonstrated using cosmic muon data.

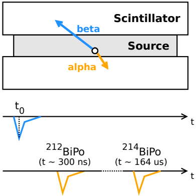
$$\epsilon_{Geiger} > \mathbf{98\%}$$



From NEMO3 to SuperNEMO

R&D developments





BiPo[6] : $\beta\beta$ source foils measurement

Enrichment

- 100kg by centrifugation is feasible

Radio-purity

- Chemical and physical purification
- requirements :
  - ^{208}Tl : $< 2\ \mu$Bq/kg
  - ^{214}Bi : $< 10\ \mu$Bq/kg

Foil production

- $\approx$ 40 mg/cm ^{2} “composite” foil

^{208}Tl : Required sensitivity demonstrated after 3 months

^{214}Bi : investigating ^{214}Bi/radon sensitivity

---

[6] NIM A 622 (2010) 120–128

Conclusion

Summary

- Nemo experiments use "tracking + calorimetry" technique
  - Full event reconstruction
  - Clear $\beta\beta$ event signature
  - Excellent background rejection
  - New physics studies using event topology

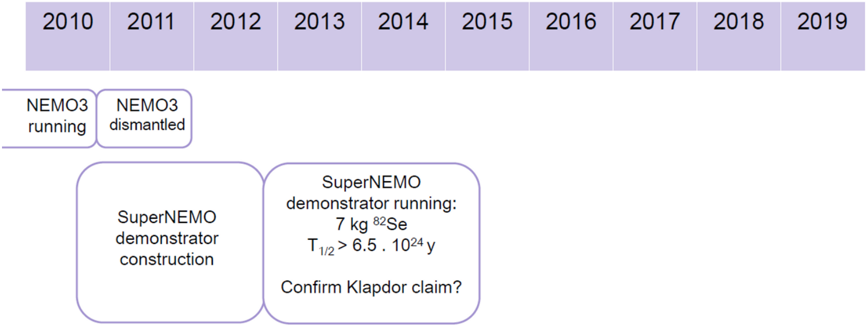
- NEMO3 is a running $2\nu2\beta$ factory
  - $T^{2\nu}_{1/2} = (7.17 \pm 0.01_{(stat)} \pm 0.54_{(sys)}) \times 10^{18}$ *years* in ^{100}Mo
  - 7 isotopes studied (^{100}Mo, ^{82}Se, ^{130}Te, ^{116}Cd, ^{150}Nd, ^{96}Zr, ^{48}Ca)

- NEMO3 provides competitive $0\nu2\beta$ limits
  - $T^{0\nu}_{1/2} > 1 \times 10^{24} yr$ @ 90% *CL* ($\langle m_\nu \rangle <$ (0.47 - 0.96) eV)

- SuperNEMO is next generation experiment
  - R&D objectives reached : energy resolution, BiPo sensitivity
  - Demonstrator module sensitive to Klapdor claim by 2015
  - Full detector sensitivity by 2019 : $T^{0\nu}_{1/2} > 1 \times 10^{26} yr$ ($\langle m_\nu \rangle <$ (0.04 - 0.11) eV)
  - Possibility to probe $0\nu2\beta$ mechanism

Conclusion

Schedule



2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019

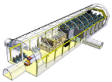
NEMO3 running

NEMO3 dismantled

SuperNEMO demonstrator construction

SuperNEMO demonstrator running:
7 kg ^{82}Se
$T_{1/2} > 6.5 . 10^{24}$ y

Confirm Klapdor claim?

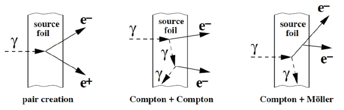


Full SuperNEMO construction:
-Likely to be located in new LSM Hall
Full Sensitivity by 2019
($m_\nu \sim 0.05$ eV)

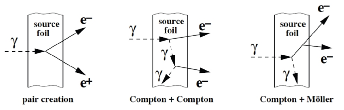
Backgrounds for $\beta\beta$ decays

Backup slide

- External γ
  - Origin : natural radioactivity of the detector or neutrons
  - Main background for $2\nu2\beta$ but negligeable for $0\nu2\beta$ (^{100}Mo and ^{82}Se : $Q_{\beta\beta} \approx 3\text{MeV} > E_\gamma(^{208}\text{Tl}) = 2.6\text{MeV}$)



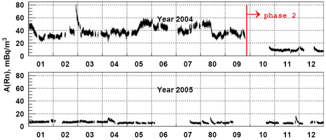
- ^{208}Tl and ^{214}Bi contamination inside the $\beta\beta$ source foils



- Radon inside the tracking detercor
  - Deposits on the wires near the $\beta\beta$ foils
  - Deposits on the surface of the $\beta\beta$ foils

Radon trapping facility

Backup slide



Radon trapping facility

- 1 ton of charcoal @ -50°C, 9 bars
- air flux = 150 m3/h

- Input : A(^{222}Rn) 15 Bq/m^3
- Output : A(^{222}Rn) < 15 mBq/m^3 ! ! !

reduction factor of 1000

- Inside the NEMO3 tent : factor of 100 - 300
- Inside NEMO3 : almost factor of 10 A(^{222}Rn) : 6 mBq/m^3

Probing new physics[7]

Backup slide

In case of observaton, measure energy difference and cosine of separating angle between electrons to identify mechanism of $0\nu2\beta$.

Fig.: pure MM

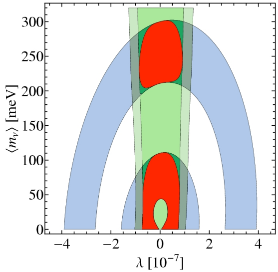


Fig.: 70% MM + 30 % RHC$_A$ admixture

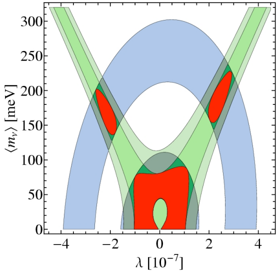
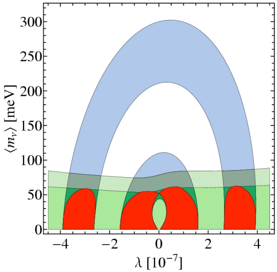


Fig.: pure RHC$_A$



Combination of half-life measurement (blue contour) and topological parameter reconstruction (green contours) leads to parameter space restriction (red contour) at 1 standard deviation.

---

[7] arXiv :1005.1241, accepted by EJP C for publication