Search for $0\nu2\beta$ of ^{100}Mo by NEMO-3 and Status of SuperNEMO

NEUTRINO 2014
Boston, USA

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On behalf of the NEMO Collaboration

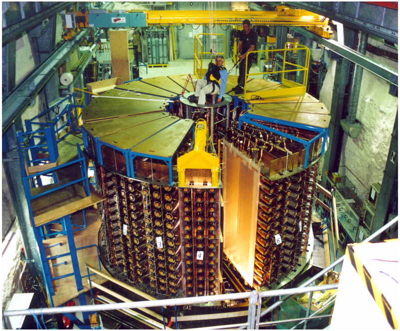
CNRS/IN2P3 - Université Paris-Sud 11 - LAL Orsay

June 6, 2014

supernemo
collaboration

NEMO-3: The Neutrino Ettore Majorana Observatory

- Located in the *Laboratoire Souterrain de Modane* (LSM) in the French Alps under 4800 m.w.e.
- Shielded by 30 cm of borated water or wood, 19 cm of steel and radon-free air tent (2004)

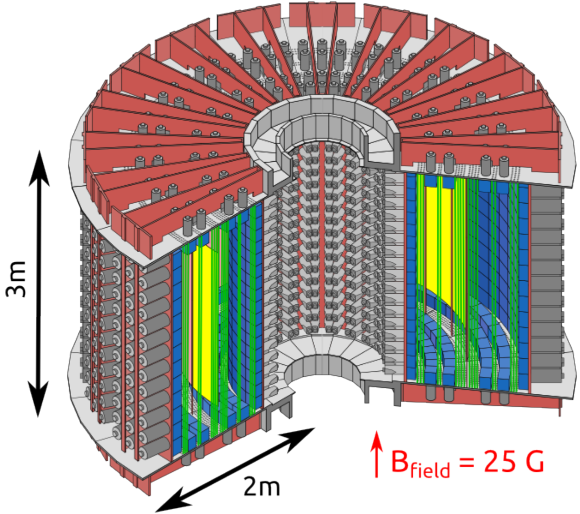


Phase 1
Feb. 2003 - Oct. 2004
$\mathcal{A}_{\text{int}}(^{222}\text{Rn}) \sim 30\ \text{mBq/m}^3$

Phase 2
Dec. 2004 - Jan. 2011
$\mathcal{A}_{\text{int}}(^{222}\text{Rn}) \sim 5\ \text{mBq/m}^3$

NEMO-3 Detector

- NEMO-3 unique tracking and calorimetric double beta decay experiment with 10 kg of sources



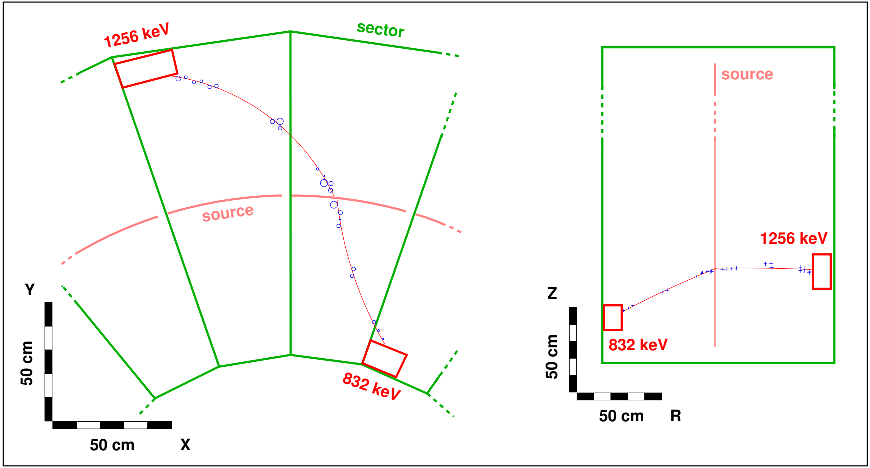
sources
60 mg/cm² foils
10 kg of ββ isotopes

tracker
6180 Geiger cells
vertex resolution :
$\sigma_{xy} \sim 3$ mm $\sigma_z \sim 10$ mm

calorimeter
1940 optical modules :
polystyren scintillators
+ 3" and 5" PMTs
$FWHM_E \sim 15\% / \sqrt{E_{MeV}}$
$\sigma_t \sim 250$ ps

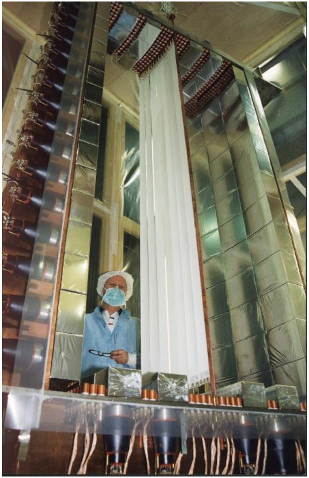
NEMO-3 Unique Features

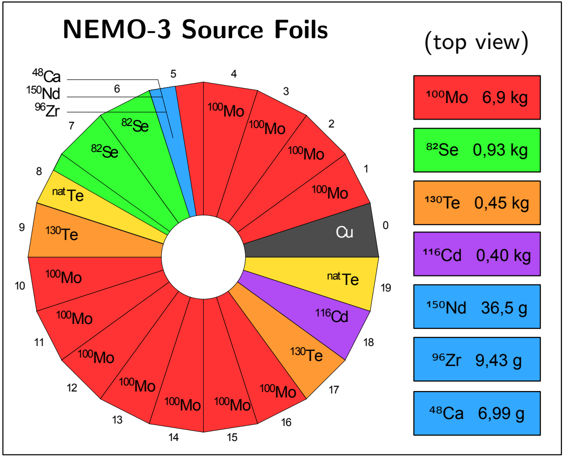
- Individual electron energies (E_1, E_2), time of arrival (t_1, t_2), curvature in magnetic field $(\pm)$, emission vertex and angle $(\cos\theta)$
- Unique DBD experiment with the direct reconstruction of the $2e^-$
  $\rightarrow$ full signature of $0\nu2\beta$ events and powerful background rejection



NEMO-3 Source Foils

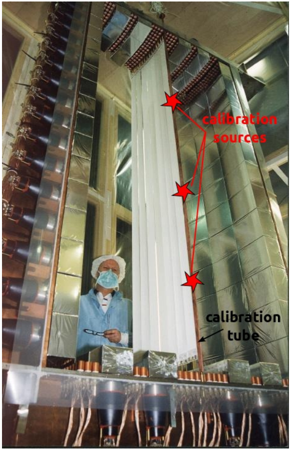
- NEMO-3 is able to study most of the double beta decay isotopes
- Metallic or composite (glue + isotope powder on mylar) source foils
- Blank sources to check the backgrounds (Cu & ^{nat}Te)

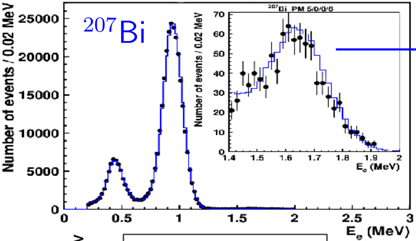




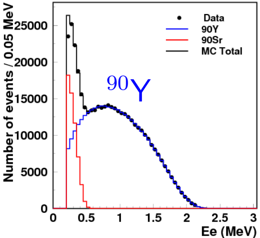
NEMO-3 Energy Calibrations

- 20 calibration tubes close to foils for sources at 3 vertical positions:
  - reconstruction of the $1e^-$ events from the source to the calorimeter
  - ^{207}Bi: 482 and 976 keV conversion electrons every 2-3 weeks
  - ^{90}Sr-^{90}Y: β-decay end-point $Q_\beta = 2280$ MeV
  - ^{207}Bi: 1682 keV conversion electrons $\rightarrow$ test the energy scale





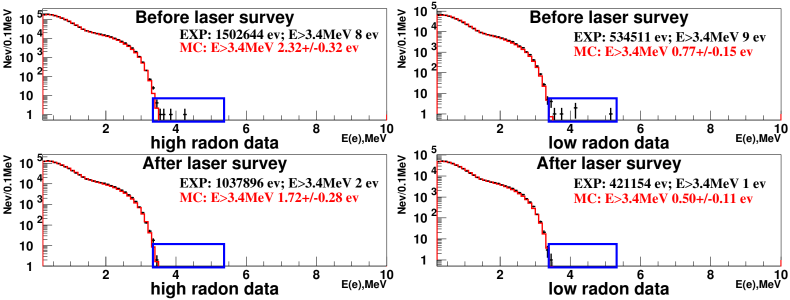
99 % PMTs
Data/MC < 0.2 %



NEMO-3 Energy Survey

- Light injection into each calorimeter block through optical fibers:
  - linearity better than 1 % between 0 and 4 MeV
  - PMT gain and timing survey twice a day (82 % PMTs < 5 %)
- ^{214}Bi β-decay end-point ($\mathcal{Q}_\beta = 3.27$ MeV) to validate PMT stability:
  - reconstruction of the BiPo $e^- \alpha_{\text{delayed}}$ events from radon (background-free channel)

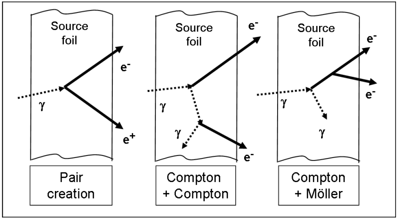
Phase 1: high radon data | Phase 2: low radon data



NEMO-3 Backgrounds

- Natural radioactivity (γ, n) from the detector components or its surroundings and cosmic rays

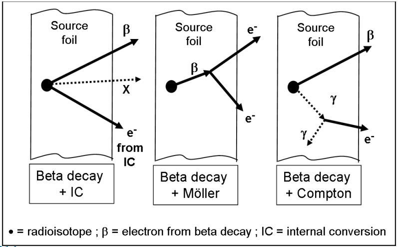
External background



$0\nu2\beta$:
^{208}Tl γ 2.6 MeV
(n, γ) up to $\sim$10 MeV

- Radioactive contaminations inside the source foils (^{238}U, ^{232}Th, ^{40}K) or radon daughters deposition on the foils or on the tracking wires

Internal background

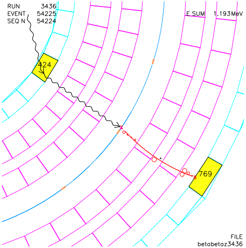


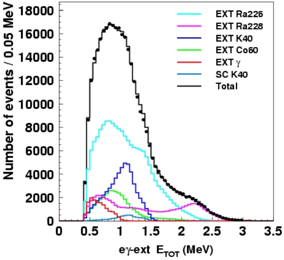
$0\nu2\beta$:
^{208}Tl $Q_\beta = 5.0$ MeV
^{214}Bi $Q_\beta = 3.27$ MeV

NEMO-3 External Background Measurements

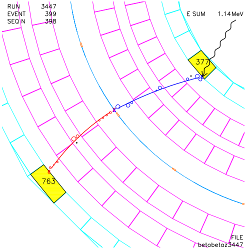
- Particle identification: e^-, e^+, γ and $external\ TOF$
- Measurement of all contributions through 2 analysis channels:

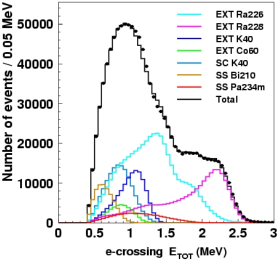
$(\gamma e^-)_{\text{ext}}$





e^-_{crossing}

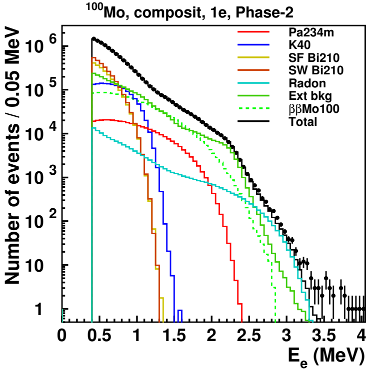


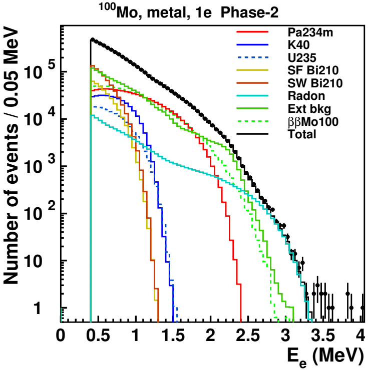


[NIM A 606 (2009) 449–465]

NEMO-3 Internal Background Measurements

- Particle identification: e^-, e^+, γ, α and $internal\ TOF$
- Direct measurements through e^-, $e^- N\gamma$ or $e^-\alpha$ analysis channels
- Example of fit in the e^- channel:



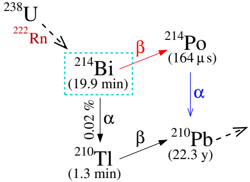


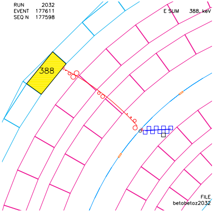
Neutron background not included in these fits (high energy tail)

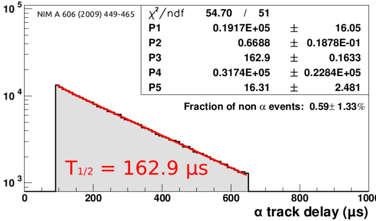
[NIM A 606 (2009) 449–465]

NEMO-3 Radon and Internal ^{214}Bi Measurements

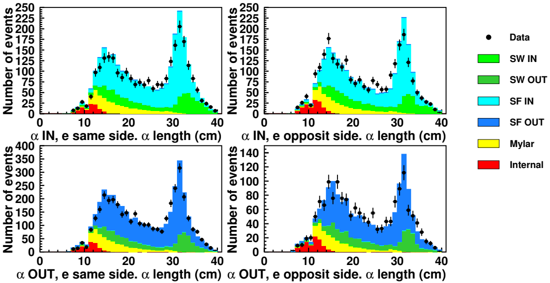
- Reconstruction of the BiPo $e^{-}\alpha_{\text{delayed}}$ events
- α track length and event topology allow to distinguish the origin







^{100}Mo composite

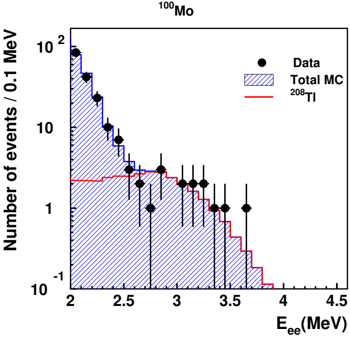


[NIM A 606 (2009) 449–465]

NEMO-3 Checking Internal ^{208}Tl and ^{214}Bi Backgrounds

- ^{208}Tl activity measurement was checked with two ^{232}U sources
  $\rightarrow$ 10 % systematics compared to HPGe measurement
- ^{214}Bi activity measurement compared in $e^-\alpha$ and $e^-N\gamma$ channels
  $\rightarrow$ 10 % systematics
- Checking these backgrounds in $2e^-N\gamma$ and $2e^-\alpha$ channels:

^{208}Tl in the $2e^-N\gamma$ channel



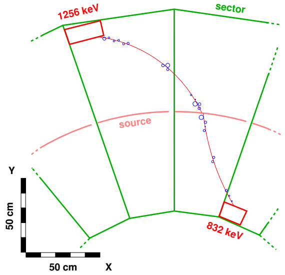
7 events in [2.8 - 3.2] MeV for 8.8 expected

^{214}Bi in the $2e^-\alpha$ channel in [2.8 - 3.2] MeV

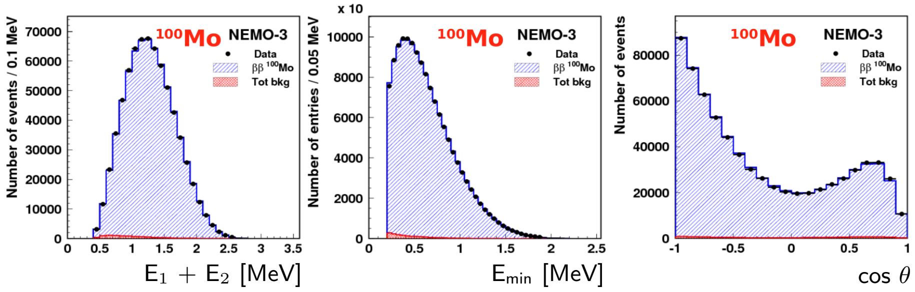
Phase 1: 3 events observed for 6.5 $\pm$ 0.4 expected

Phase 2: 3 events observed for 2.9 $\pm$ 0.2 expected

NEMO-3 $2\nu2\beta$ of ^{100}Mo Measurement



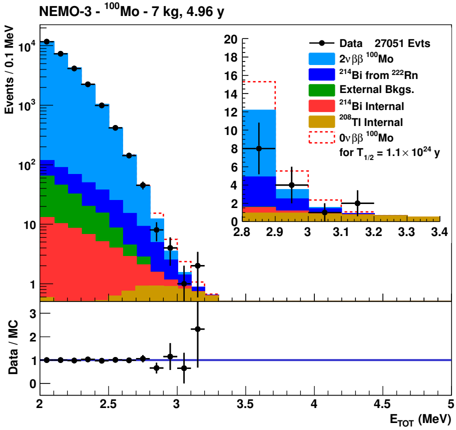
- 6.9 kg of ^{100}Mo
- ~700 000 $2\nu2\beta$ events collected
- Efficiency $\mathcal{E}_{2\nu} = 4.3$ %
- Signal to background ratio S/B = 76
- Preliminary half-life:
  $\mathcal{T}_{1/2}^{2\nu} = 7.16 \pm 0.01$ (stat) ± 0.54 (syst) 10^{18} y
  compatible with previously published [Phys. Rev. Lett. 95, 182302 (2005)]



- 0.7 % systematical uncertainty on the $2\nu2\beta$ efficiency above 2 MeV

NEMO-3 $0\nu2\beta$ Search with ^{100}Mo

- Detection efficiency $\mathcal{E}_{0\nu} = 4.7$ % in the [2.8 – 3.2] MeV region
- No event excess observed in ^{100}Mo after 34.3 kg·y exposure: $\mathcal{T}^{0\nu}_{1/2} > 1.1 \times 10^{24}$ y (90 % CL)



Expected background in [2.8 – 3.2] MeV	
$2\nu2\beta$	8.45 ± 0.05
^{214}Bi from radon	5.2 ± 0.5
External	< 0.2
^{214}Bi internal	1.0 ± 0.1
^{208}Tl internal	3.3 ± 0.3
Total	**18.0 ± 0.6**
Data	**15**

Total background
1.3×10^{-3} cts·keV^{-1}·kg^{-1}·y^{-1}

[To appear in Phys. Rev. D - arXiv:1311.5695]

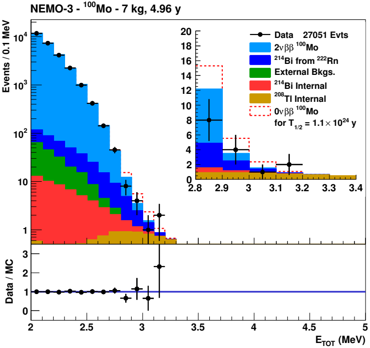
NEMO-3 $0\nu 2\beta$ Limits with ^{100}Mo

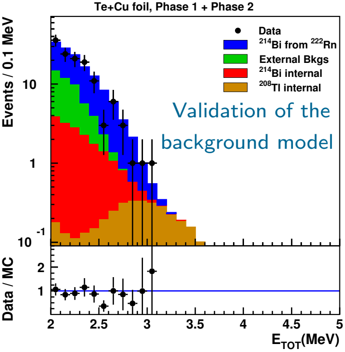
- Detection efficiency $\mathcal{E}_{0\nu} = 11.3$ % in the [2.0 – 3.2] MeV region
- Modified frequentist analysis [T. Junk, Nucl. Inst. Meth. A 434 (1999) 435]
- Include statistical and systematic uncertainties and their correlations (background systematics presented above
  $+$ 7 % on the reconstruction efficiency from ^{207}Bi calibration)

Isotope	Half-life (10^{25} y) published	$\langle m_\nu \rangle$ (eV) published	$\langle m_\nu \rangle$ (eV) recalculated	$\langle \lambda \rangle$ (10^{-6}) published	$\langle \eta \rangle$ (10^{-8}) published	λ'_{111}/f (10^{-2}) published	$\langle g_{ee} \rangle$ (10^{-5}) published
^{100}Mo (this work)	0.11	0.33 - 0.87	0.33 - 0.87	0.9 - 1.3	0.5 - 0.8	4.4 - 6.0	1.6 - 4.1
^{130}Te (CUORICINO)	0.28	0.31 - 0.71	0.31 - 0.75	1.6 - 2.4	0.9 - 5.3		17 - 33
^{136}Xe (KamLAND-Zen)	1.9	0.14 - 0.34	0.14 - 0.34				0.8 - 1.6
^{76}Ge (GERDA)	2.1	0.2 - 0.4	0.26 - 0.62				
^{76}Ge (HdM)	1.9	0.35	0.27 - 0.65	1.1	0.64		8.1

Using NME from:
J. Suhonen and O. Civitarese, J. Phys. G 39 (2012) 124005
F. Šimkovic et al, Phys. Rev. C 87 (2013) 045501
J. Barea et al., Phys. Rev. C 79 (2009) 044301
P. K. Rath et al., Phys. Rev. C 82 (2010) 064310
T.R. Rodriguez and G. Martinez-Pinedo, Phys. Rev. Lett. 105 (2010) 252503
J. Menendez et al, Nucl. Phys. A 818 (2009) 139

NEMO-3 High Energy Background





[To appear in Phys. Rev. D - arXiv:1311.5695]

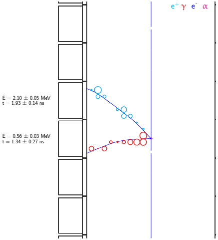
- No events in ^{100}Mo after 34.3 kg·y exposure above 3.2 MeV
- No events in copper and natural tellurium samples after 13.5 kg·y exposure above 3.1 MeV
- Background-free technique for high energy $\mathcal{Q}_{\beta\beta}$ isotopes: ^{48}Ca: 4.272 MeV, ^{150}Nd: 3.368 MeV or ^{96}Zr: 3.350 MeV

From NEMO-3 to SuperNEMO

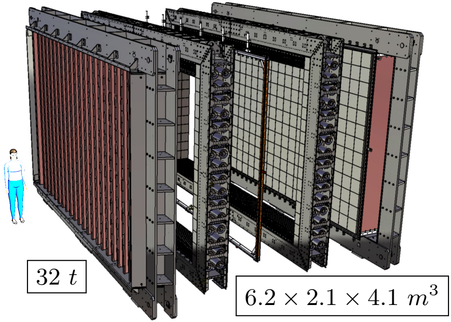
	NEMO-3	SuperNEMO
Mass	6.9 kg	100 kg
Isotopes	^{100}Mo	^{82}Se
	7 isotopes	^{150}Nd, ^{48}Ca
Energy resolution (σ | FWHM)		
@ 3 MeV	3.4 | 8 %	1.7 | 4 %
Radon in tracker		
$\mathcal{A}(^{222}\text{Rn})$	5.0 mBq/m^3	0.15 mBq/m^3
Sources contaminations		
$\mathcal{A}(^{208}\text{Tl})$	$\sim$ 100 μBq/kg	$<$ 2 μBq/kg
$\mathcal{A}(^{214}\text{Bi})$	60 - 300 μBq/kg	$<$ 10 μBq/kg
Total background		
cts·keV^{-1}·kg^{-1}·y^{-1}	1.3×10^{-3}	5×10^{-5}
Sensitivity (90 % CL)		
$\mathcal{T}^{0\nu}_{1/2}$	$> 1.1 \times 10^{24}$ y	$> 1 \times 10^{26}$ y
$\langle m_\nu \rangle$	$<$ 0.33 - 0.87 eV	$<$ 0.04 - 0.10 eV

SuperNEMO Demonstrator Goals

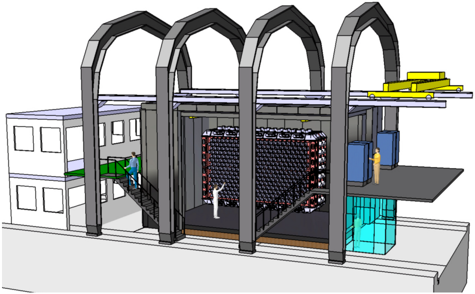
- SuperNEMO demonstrator module construction started in 2012
  - NEMO-3 sensitivity in only 5 months (90 % CL):
    $\mathcal{T}^{0\nu}_{1/2} > 1.1 \times 10^{24}$ y $\rightarrow \langle m_\nu \rangle < 0.33 - 0.87$ eV
  - No background in the $0\nu2\beta$ region in 2.5 years for 7 kg of ^{82}Se
  - Sensitivity after 17.5 kg·y exposure (90 % CL):
    $\mathcal{T}^{0\nu}_{1/2} > 6.5 \times 10^{24}$ y $\rightarrow \langle m_\nu \rangle < 0.20 - 0.40$ eV



- Commissioning and physics data taking expected in Summer 2015



Replacing NEMO-3 in the actual LSM

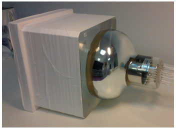


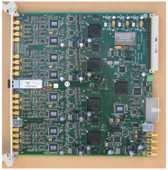
SuperNEMO Demonstrator Construction Status

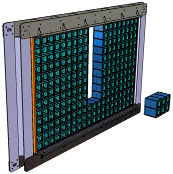
Calorimeter

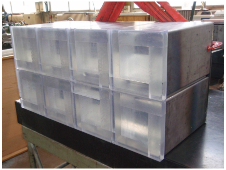
- Optical modules: 5" under assembly and 8" modules under production
- FE digitizer boards built, control and trigger boards under development
- Magnetic shields produced and mechanical structure under construction

$256 \times 256 \times 194$ mm^3



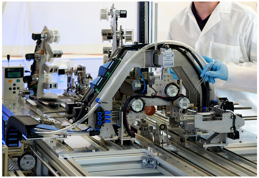


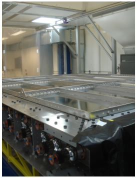


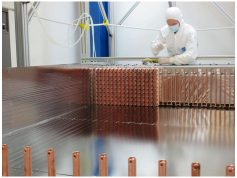


Tracker

- Automated drift cells production ongoing with the wiring robot
- First 1/4 tracker C0 has been tested for radon emanation
- Cells population of C0 has reached its nominal rate: 144 cells installed







Sources

- Already 5.56 kg of enriched ^{82}Se and 4.56 kg purified
- Foils materials (glue, films...) under HPGe and BiPo selection processes
- Calibration sources deployment system and light injection under test

Summary

NEMO-3:

- Unique DBD experiment with the direct reconstruction of the $2e^-$
  $\rightarrow$ full signature of $0\nu2\beta$ events and powerful background rejection
- Total ^{100}Mo exposure of 34.3 kg·y gave no event excess:
  $\mathcal{T}^{0\nu}_{1/2} > 1.1 \times 10^{24}$ y (90 % CL) $\rightarrow$ $\langle m_\nu \rangle < 0.33 - 0.87$ eV
- Background-free technique for high energy $\mathcal{Q}_{\beta\beta}$ isotopes

SuperNEMO demonstrator with 7 kg of ^{82}Se under construction:

- Commissioning and physics data by Summer 2015
- No background in the $0\nu2\beta$ region in 2.5 years for 7 kg of ^{82}Se:
  $\mathcal{T}^{0\nu}_{1/2} > 6.5 \times 10^{24}$ y $\rightarrow$ $\langle m_\nu \rangle < 0.20 - 0.40$ eV (90 % CL)

Full SuperNEMO with 100 kg of ^{82}Se:

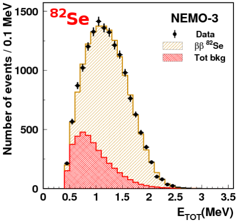
$\mathcal{T}^{0\nu}_{1/2} > 1 \times 10^{26}$ y $\rightarrow$ $\langle m_\nu \rangle < 0.04 - 0.10$ eV

Posters Session

106. The isotopic double beta decay source for SuperNEMO - A. Remoto
107. High resolution low background calorimeter for SuperNEMO - C. Cerna
108. The SuperNEMO tracking detector - J. Evans
109. Pattern recognition and track reconstruction in SuperNEMO - F. Nova
110. An assay of radiopurity and radon emanation of the SuperNEMO detector - X.R. Liu
111. The calibration source deployment and light injection monitoring systems for the SuperNEMO experiment - J. Cesar
112. Search for neutrinoless double beta decay of ^{100}Mo with the NEMO-3 detector - F. Piquemal

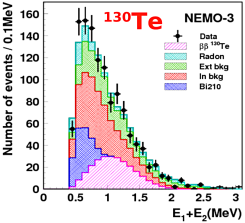
Backup

NEMO-3 $2\nu2\beta$ Measurement of Lower Mass Isotopes



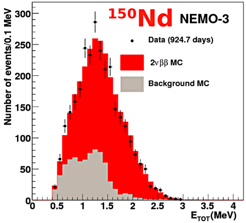
$\mathcal{T}_{1/2} = 9.6 \pm 1.0\ 10^{19}$ y

PRL 95, 182302 (2005)



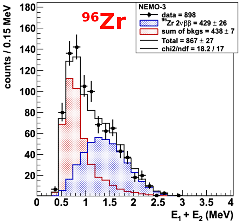
$\mathcal{T}_{1/2} = 7.0 \pm 1.4\ 10^{20}$ y

PRL 107, 062504 (2011)



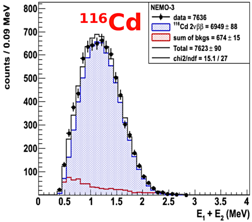
$\mathcal{T}_{1/2} = 9.1 \pm 0.7\ 10^{18}$ y

Phys. Rev. C 80, 032501 (2009)



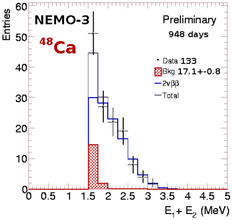
$\mathcal{T}_{1/2} = 2.35 \pm 0.21\ 10^{19}$ y

Nucl. Phys. A 847, 168 (2010)



$\mathcal{T}_{1/2} = 2.9 \pm 0.3\ 10^{19}$ y

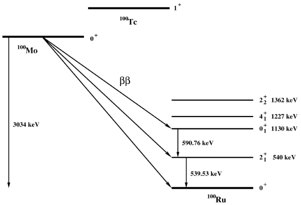
To be published



$\mathcal{T}_{1/2} = 4.4 \pm 0.6\ 10^{19}$ y

Systematics under study

NEMO-3 Double Beta Decay to Excited States



$2\nu2\beta$ to excited states of ^{100}Mo:

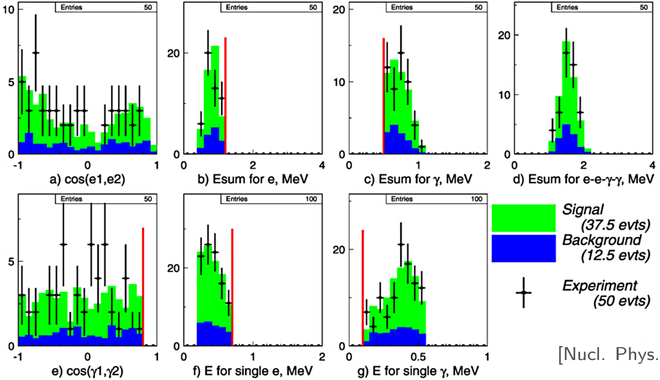
$\mathcal{T}^{2\nu}_{1/2}(0^+ \rightarrow 0^+_1) = 5.7\ ^{+1.3}_{-0.9}$ (stat) $\pm$ 0.8 (stat) 10^{20} y

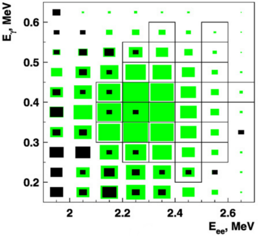
$\mathcal{T}^{2\nu}_{1/2}(0^+ \rightarrow 2^+_1) > 1.1\ 10^{21}$ y @ 90 % CL

$0\nu2\beta$ to excited states of ^{100}Mo:

$\mathcal{T}^{0\nu}_{1/2}(0^+ \rightarrow 0^+_1) > 8.9\ 10^{22}$ y @ 90 % CL

$\mathcal{T}^{0\nu}_{1/2}(0^+ \rightarrow 2^+_1) > 1.6\ 10^{23}$ y @ 90 % CL



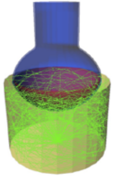


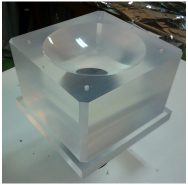
[Nucl. Phys. A 781 (2007) 209-226]

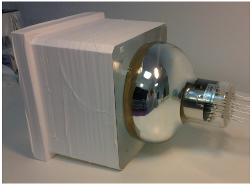
- Other results coming soon on ^{150}Nd and ^{96}Zr

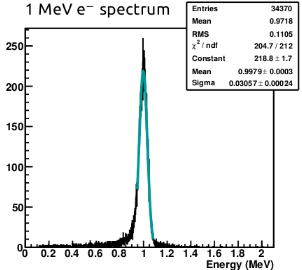
SuperNEMO Calorimeter Improvement

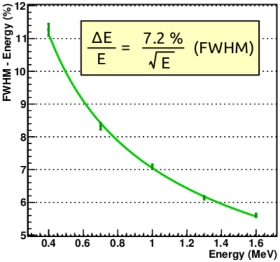
- Energy resolution of 7 % FWHM at 1 MeV achieved:
  - High QE large 8" PMTs (Hamamatsu R5912) directly coupled to the scintillator (no light guide) and improved HV divider
  - PVT plastic scintillators (also 8 % achieved for PS)
  - Optimization of the scintillator blocks geometry
  - Electronics sampling the PMT pulses $\sim$ 2 GS/s (MatAcq/SNFEB)





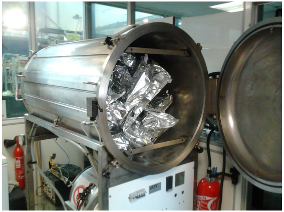




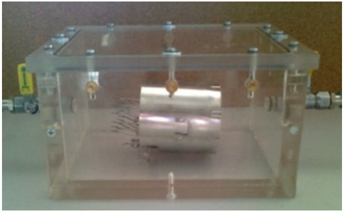


Reduce the Radon Background

- Goal: reduce the internal radon background to 0.15 mBq/m^3
- Select detector materials and protections (seals, films...)



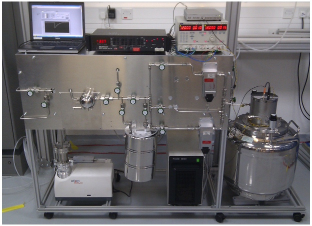
Bordeaux emanation tank



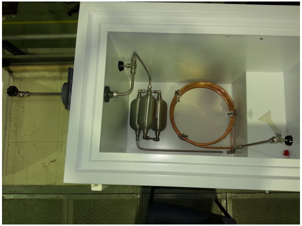
Bratislava emanation setup

Prague permeability setup

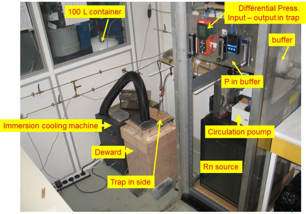
- Measure the radon in the detector or gases and radon purification



London concentration line



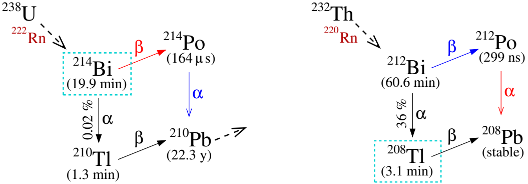
Gases purification



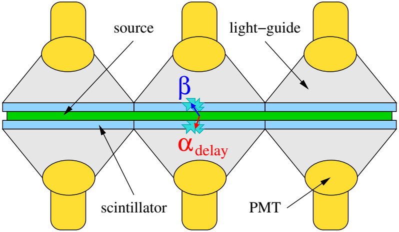
Marseille radon adsorption

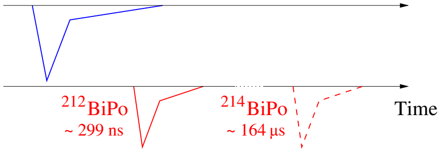
Measure the Radiopurity of the SuperNEMO Sources

- HPGe γ spectroscopy not sufficient to reach few μBq/kg today (factor 50 improvement needed for thin foils)
- Main contaminations for $0\nu2\beta$ search (^{214}Bi and ^{208}Tl) measured through BiPo processes from natural radioactivity chains:



- β and α particles detected by thin radiopure plastic scintillators coupled to light-guides and low radioactivity PMTs:





The BiPo3 Detector

- 2 modules of 3.0x0.6 m^2 can measure 1.4 kg of ^{82}Se foil (40 mg/cm^2)
- 2 mm thick aluminized polystyrene scintillators, PMMA light guides and 5" Hamamatsu low radioactivity PMTs
- PMT pulses digitized by MatAcq boards and dedicated trigger board
- Running since 2012 in Canfranc Underground Lab (LSC, Spain)
- Sensitivity: ^{208}Tl $< 2\ \mu$Bq/kg and ^{214}Bi $< 10\ \mu$Bq/kg