

Latest $0\nu 2\beta$ results on ^{100}Mo with NEMO-3

GDR neutrino in Orsay

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for the NEMO Collaboration

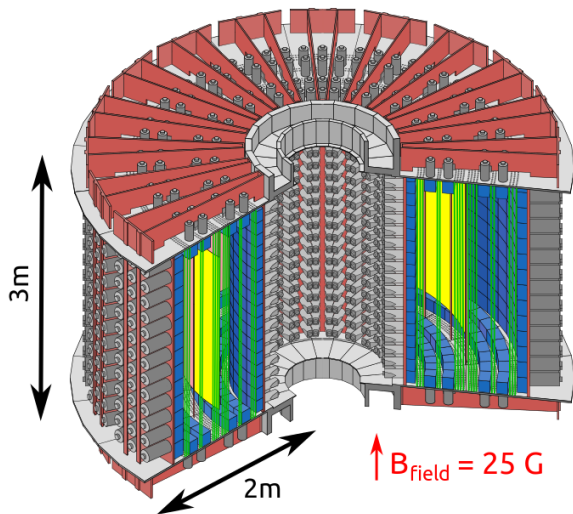
LAL Orsay, UCL London

2014/06/17



UCL

NEMO-3 : The Neutrino Ettore Majorana Observatory



sources

60 mg/cm² foils
10 kg of $\beta\beta$ isotopes

tracker

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

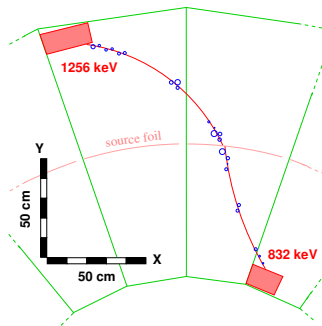
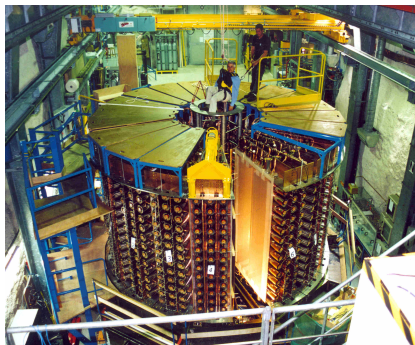
calorimeter

1940 optical modules :
polystyren scintillators
+ 3" and 5" PMTs
 $\sigma_E \sim 6.4\% / \sqrt{E_{\text{MeV}}}$
 $\sigma_t \sim 250 \text{ ps}$

NEMO-3 : the Neutrino Ettore Majorana Observatory

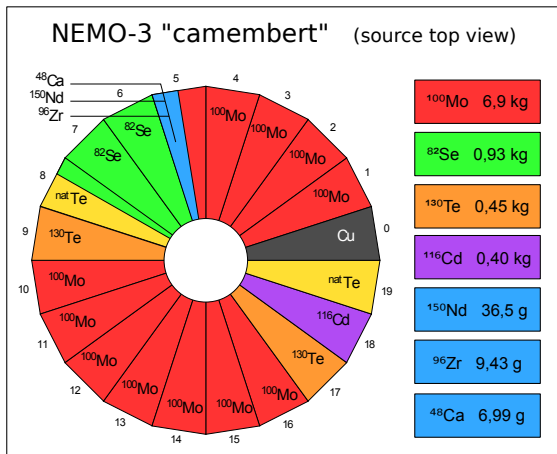


- ▶ Ran from 2003 to 2011 at the LSM
- ▶ Unique 2β experiment with the $2e^-$ direct reconstruction
⇒ high background rejection
- ▶ Direct measurement of the various backgrounds ($1e^-$, $1e^-n\gamma$...)



NEMO-3 : the Neutrino Ettore Majorana Observatory

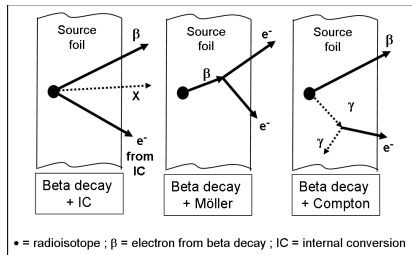
- ▶ Several double- β isotopes studied ($\sim 9\text{kg}$)
- ▶ Background checked on copper and natural tellurium sources



Backgrounds in NEMO-3

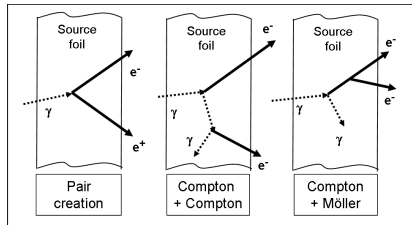
- ▶ Internal (source) and Radon on foil/tracker wires surface :

- ▶ $Q_{\beta}(^{208}\text{Tl}) = 5.0 \text{ MeV}$
- ▶ $Q_{\beta}(^{214}\text{Bi}) = 3.27 \text{ MeV}$



- ▶ Other contaminations :

- ▶ neutrons :
(n, γ) up to $\sim 10 \text{ MeV}$
- ▶ ^{208}Tl γ with
 $E_{\gamma} = 2.6 \text{ MeV}$



NEMO-3 : the Neutrino Ettore Majorana Observatory

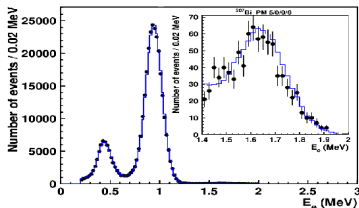
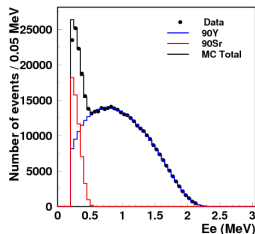
- ▶ NEMO-3 results for the $2\nu 2\beta$ process half-life
- ▶ Each of them are the current world's best

isotope	mass [g]	$Q_{\beta\beta}$ [keV]	$T_{1/2}^{2\nu}$ [10^{19} y]
^{48}Ca	6.99	4272	4.4 ± 0.6
^{82}Se	932	2996	9.6 ± 1.0
^{96}Zr	9.43	3350	2.35 ± 0.21
^{100}Mo	6914	3034	0.71 ± 0.05
^{116}Cd	405	2814	2.8 ± 0.3
^{130}Te	454	2528	70 ± 14
^{150}Nd	37	3371	0.9 ± 0.07

- ▶ Analyses still in progress on most of the isotopes (^{82}Se , ^{48}Ca , ^{96}Zr , ...)

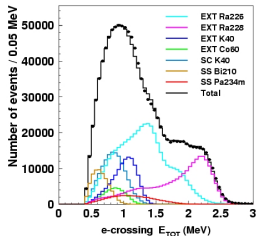
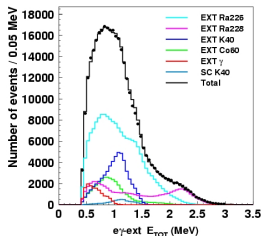
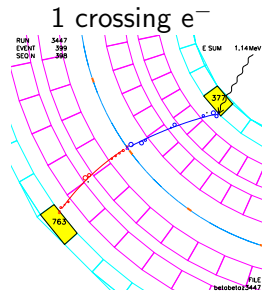
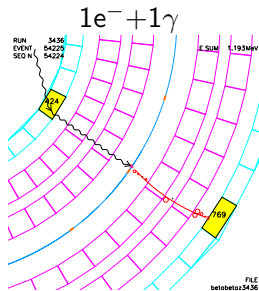
NEMO-3 Energy Calibrations

- ▶ 1 calibration tube per sector
 - ^{207}Bi : 482 and 976 keV conversion electrons every 2-3 weeks
 - ^{90}Sr sources - ^{90}Y : β -decay end-point $Q_\beta = 2280$ keV
 - ^{207}Bi : 1682 keV conversion electrons \rightarrow tests energy scale



NEMO-3 Analysis : External Backgrounds (PMT glass, ...)

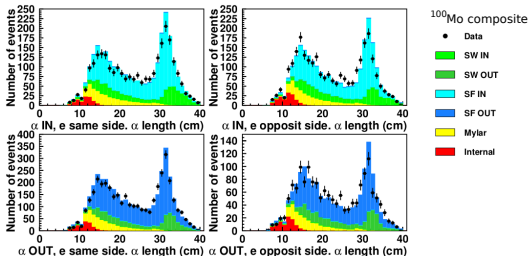
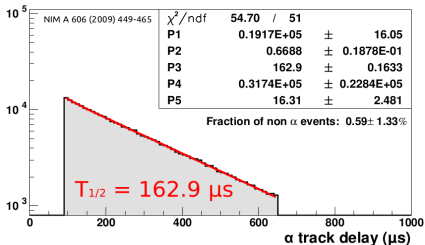
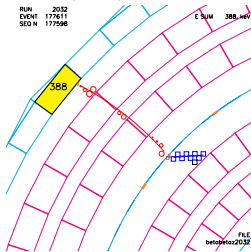
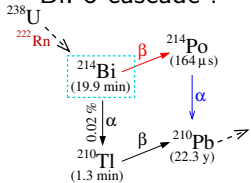
- ▶ Two channels available : $1e^-+1\gamma$ and 1 crossing e^-
- ▶ External time of flight condition



NEMO-3 Analysis : ^{214}Bi Backgrounds : Internal - Radon

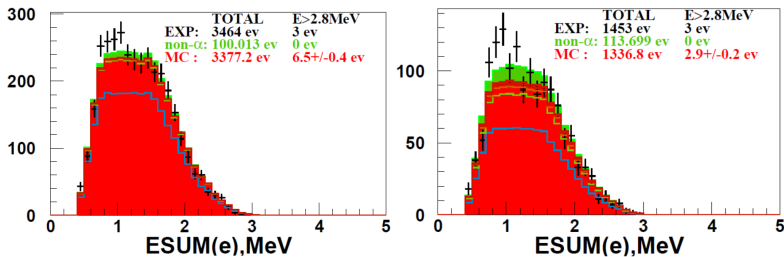
- ▶ $1e^{-}1\alpha$ channel studying BiPo events ($e^{-} + \text{delayed } \alpha$)
- ▶ Length of the α track as discriminating parameter
- ▶ Delay time to sign the BiPo events

BiPo cascade :



NEMO-3 Analysis : Internal Background - ^{214}Bi

- ▶ Comparison $1e^-1\alpha$ and $1e^-N\gamma$ channels
⇒ 10 % systematics
- ▶ Background checked in $2e^-1\alpha$ channel



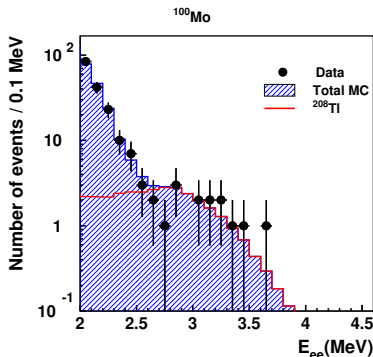
Radon on wires in blue, radon on the foils surfaces in light green
Internal contamination of mylar film in brown, internal source foils in red

non- α : $2e^-$ events with random coincidence

- ▶ in [2.8 – 3.2] MeV
Phase 1 (~ 1 y) : 3 events obs., 6.5 ± 0.4 expect.
Phase 2 (~ 4 y) : 3 events obs., 2.9 ± 0.2 expect.

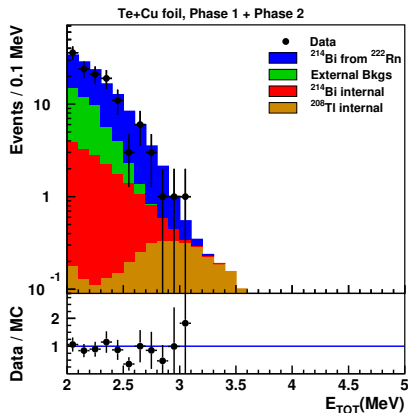
NEMO-3 Analysis : Internal Background - ^{208}Tl

- ▶ ^{208}Tl measurement capabilities with known ^{232}U sources
⇒ 10 % systematics with HPGe
- ▶ Measurement in $1e^-N\gamma$ channel
- ▶ Backgrounds checked in $2e^-N\gamma$ channel



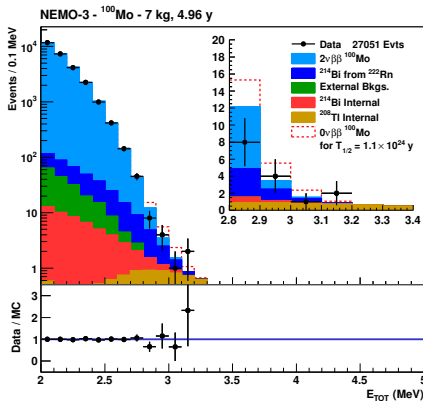
- ▶ in [2.8, 3.2] MeV
7 events obs., 8.8 expect.

NEMO-3 Validation of the background model



- ▶ Background model validated in copper and natural tellurium
- ▶ No events above 3.1 MeV in copper and natural tellurium samples with an exposure of 13.5 kg·y

NEMO-3 $0\nu 2\beta$ Results



[To appear in Phys. Rev. D - [arXiv :1311.5695](https://arxiv.org/abs/1311.5695)]

- ▶ in [2.8 – 3.2] MeV : 15 events obs., 18.0 ± 0.6 expect.
No event excess

$$\mathcal{T}_{1/2}^{0\nu}(^{100}\text{Mo}) > 1.1 \times 10^{24} \text{ yr (90 \% C.L.)}$$

$$\langle m_{\beta\beta} \rangle < 0.33 - 0.87 \text{ eV}$$

$0\nu 2\beta$ Limits

- ▶ NEMO-3 results compared to current best measurements
- ▶ Statistical and systematical errors included

Isotope	Half-life (10^{25} y) published	$\langle m_\nu \rangle$ (eV) published	$\langle m_\nu \rangle$ (eV) recalculated
^{100}Mo (this work)	0.11	0.33 - 0.87	0.33 - 0.87
^{130}Te (CUORICINO)	0.28	0.31 - 0.71	0.31 - 0.75
^{136}Xe (KamLAND-Zen)	1.9	0.14 - 0.34	0.14 - 0.34
^{76}Ge (GERDA)	2.1	0.2 - 0.4	0.26 - 0.62
^{76}Ge (HdM)	1.9	0.35	0.27 - 0.65

Using Nuclear Matrix Elements 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

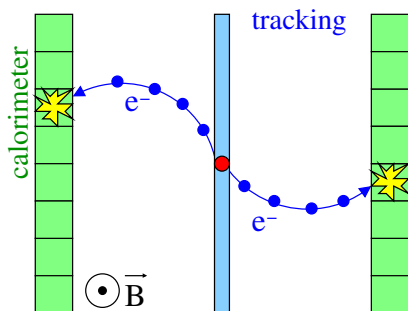
J. Menendez et al, Nucl. Phys. A 818 (2009) 139

Conclusions

- ▶ NEMO-3 : Unique experiment with full kinematics of the 2β events
- ▶ Results in ^{100}Mo with an exposure of 34.3 kg·y :
 $\mathcal{T}_{1/2}^{0\nu}(^{100}\text{Mo}) > 1.1 \times 10^{24}$ yr (90 % C.L.)
 $\langle m_{\beta\beta} \rangle < 0.33 - 0.87$ eV
- ▶ No event with an exposure of 47 kg·y exposure above 3.2 MeV
- ▶ Background-free technique for high energy $Q_{\beta\beta}$ isotopes :
 ^{48}Ca : 4.272 MeV, ^{150}Nd : 3.368 MeV or ^{96}Zr : 3.350 MeV

NEMO Experimental Techniques

- ▶ Low-background detectors in deep underground laboratories
- ▶ Passive $\beta\beta$ enriched source foil in the center
- ▶ Magnetised tracking device to identify the two electrons
- ▶ Segmented calorimeter to measure the (individual and total) energies and the time of flight of the two e^- (with the tracker)
- ▶ Shielded against neutrons and γ from the laboratory



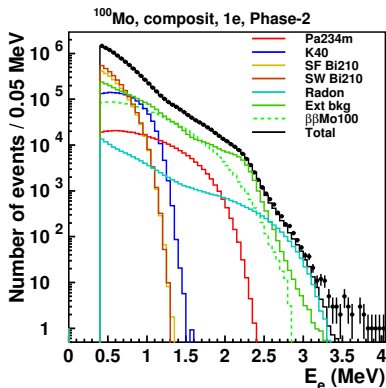
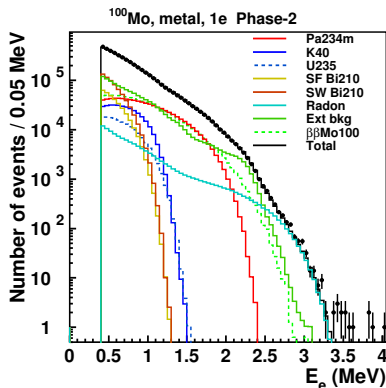
NEMO-3 : Description

- ▶ NEMO-3 ran from 2003 to 2011
- ▶ Two phases :
 - Phase 1 : high radon background phase
 - Phase 2 : low radon phase (reduction factor of 6)



NEMO-3 Analysis : Internal Backgrounds

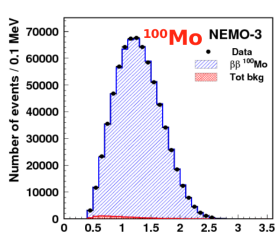
- ▶ Several channels available : $1e^-$, $1e^-1\gamma$, $1e^-N\gamma$, $1e^-1\alpha$
- ▶ Internal time of flight condition



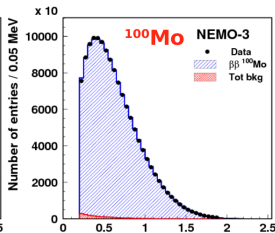
- ▶ $1e^-$ channel for metallic and composite foils
- ▶ High energetic tail due to neutron background (not included)

NEMO-3 $2\nu 2\beta$ Measurement

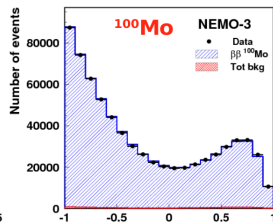
- ▶ 6.9 kg of ^{100}Mo
- ▶ $\sim 700\,000$ $2\nu 2\beta$ events collected
- ▶ Efficiency $\mathcal{E}_{2\nu} = 4.3\%$
- ▶ Signal to background ratio $S/B = 76$
- ▶ Preliminary half-life :
 $\mathcal{T}_{1/2}^{2\nu} = 7.16 \pm 0.01$ (stat) ± 0.54 (syst) 10^{18} y
compatible with previously published [Phys.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



$E_1 + E_2$ [MeV]



E_{\min} [MeV]

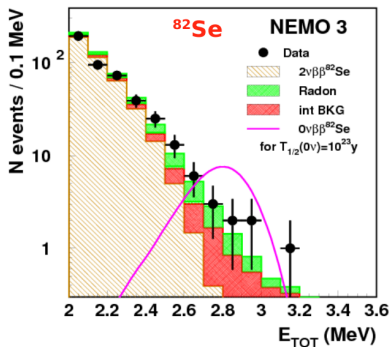


$\cos \theta$

NEMO-3 $0\nu 2\beta$ Results

- ▶ Current last results on ^{82}Se

NEMO-3 - ^{82}Se - 0.93 kg, 4.5 y



in [2.6 – 3.2] MeV :

14 events obs., 11.1 ± 1.3 expect.

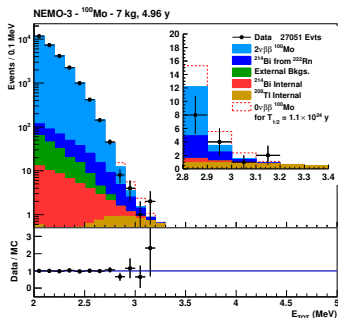
$$\mathcal{T}_{1/2}^{0\nu}(^{82}\text{Se}) > 3.2 \cdot 10^{23} \text{ yr} \ \& \ \langle m_{\beta\beta} \rangle < 0.85 - 2.08 \text{ eV}$$

Other $0\nu 2\beta$ Limits

- ▶ NEMO-3 results compared to current best measurements
- ▶ Statistical and systematical errors included

Isotope	$\langle\lambda\rangle$ (10^{-6}) published	$\langle\eta\rangle$ (10^{-8}) published	λ'_{1111}/f (10^{-2}) published	$\langle g_{ee}\rangle$ (10^{-5}) published
^{100}Mo (this work)	0.9 - 1.3	0.5 - 0.8	4.4 - 6.0	1.6 - 4.1
^{130}Te (CUORICINO)	1.6 - 2.4	0.9 - 5.3		17 - 33
^{136}Xe (KamLAND-Zen)				0.8 - 1.6
^{76}Ge (GERDA)				
^{76}Ge (HdM)	1.1	0.64		8.1

NEMO-3 $0\nu 2\beta$ Results



[To appear in Phys. Rev. D -
[arXiv :1311.5695](https://arxiv.org/abs/1311.5695)]

Expected background in [2.8 – 3.2] MeV

$2\nu 2\beta$	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**

SuperNEMO Demonstrator Goals

- ▶ SuperNEMO demonstrator module construction started in 2012

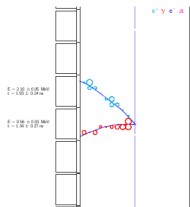
- ▶ NEMO-3 sensitivity in only 5 months (90 % CL):

$$\mathcal{T}_{1/2}^{0\nu} > 1.1 \times 10^{24} \text{ y} \rightarrow \langle m_\nu \rangle < 0.33 - 0.87 \text{ eV}$$

- ▶ No background in the $0\nu 2\beta$ region in 2.5 years for 7 kg of ^{82}Se

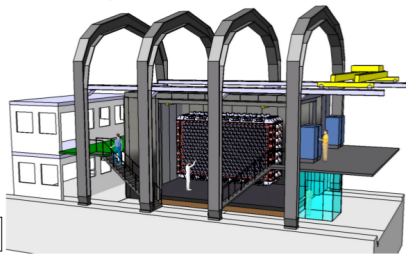
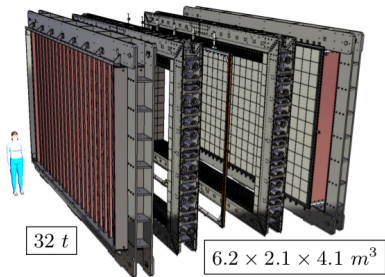
- ▶ Sensitivity after 17.5 kg·y exposure (90 % CL):

$$\mathcal{T}_{1/2}^{0\nu} > 6.5 \times 10^{24} \text{ y} \rightarrow \langle m_\nu \rangle < 0.20 - 0.40 \text{ eV}$$



- ▶ Commissioning and physics data taking expected in Summer 2015

Replacing NEMO-3 in the actual LSM

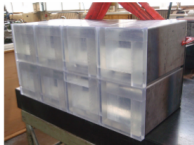
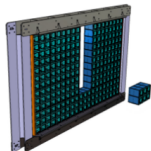
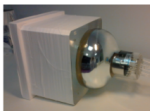


SuperNEMO Demonstrator Construction Status

Calorimeter

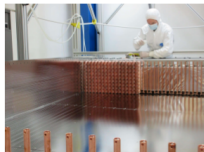
- ▶ Optical modules: 5" under assembly and 8" modules under production
- ▶ FE digitizer boards built, control and trigger boards under development
- ▶ Magnetic shields produced and mechanical structure under construction

256 × 256 × 194 mm³



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 ⁸²Se and 4.56 kg purified
- ▶ Foils materials (glue, films...) under HPGe and BiPo selection processes
- ▶ Calibration sources deployment system and light injection under test