Results of BiPo-1 and development of BiPo-3 prototypes for radiopurity measurements of the SuperNEMO source foils

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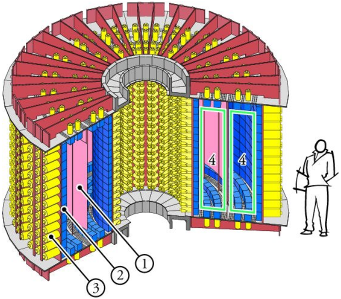
NEMO3 experiment

NEMO3 is a tracko-calo experiment in operation in the Laboratoire Souterrain de Modane since 2003.



- 10kg of 2β isotopes **(1)**
  - 6.9 kg of ^{100}Mo
  - 932 g of ^{82}Se
  - ^{130}Te, ^{116}Cd, ^{150}Nd, ^{96}Zr, ^{48}Ca
- 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)**
- Magnetic field
  - 25 Gauss

From NEMO3 to SuperNEMO

NEMO3 results - event reconstruction

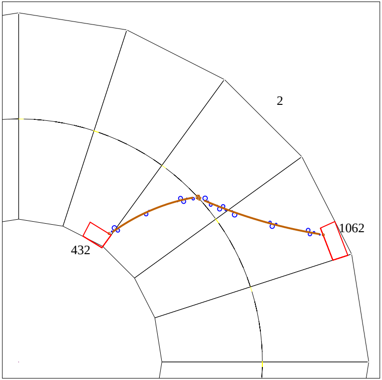


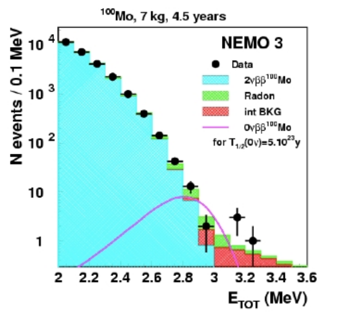
Fig.: reconstruction of a simulated $2\nu2\beta$ decay from ^{100}Mo

- Measurement of all kinematical 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^- ...

From NEMO3 to SuperNEMO

NEMO3 results - $0\nu2\beta$ from ^{100}Mo (7kg) and ^{82}Se (1kg)

^{100}Mo - 6914g

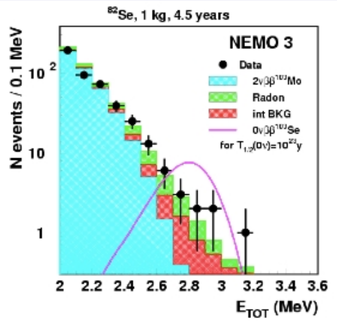


[2.8-3.2] MeV : DATA = 18 ; MC = 16.4±1.4

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

$\langle m_\nu \rangle <$ **(0.47 - 0.96) eV** [1]

^{82}Se - 932g



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

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

$\langle m_\nu \rangle <$ **(0.94 - 2.5) eV** [1]

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[1] Using NME from : - E. Caurier et al., PRL 100 (2008) 052503 - Simkovic et al., PRC 77 (2008) 045503 - Suhonnen et al., J. Mod. Phys E 17 (2008) 1

From NEMO3 to SuperNEMO

SuperNEMO design

20 modules surrounded by passive shielding

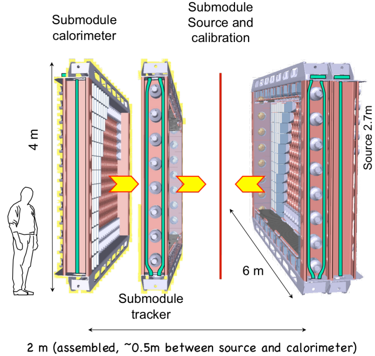


Fig.: SuperNEMO module

20 modules

- Source
  - 5kg per module ($40\ mg/cm^2$, $4 \times 2.7\ m^2$)
  - ^{82}Se first (High $Q_{\beta\beta}$, long $T_{1/2}^{0\nu}$, 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

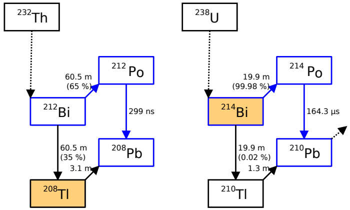
SuperNEMO design

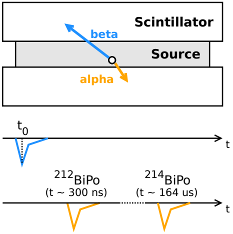
NEMO3		SuperNEMO
^{100}Mo	isotope	^{82}Se or ^{48}Ca or ^{150}Nd
7kg	isotope mass	100kg
18%	efficiency	30%
FWHM = 8% @ 3MeV	energy resolution	FWHM = 4% @ 3MeV
^{208}Tl : $\approx 100\mu$Bq/kg ^{214}Bi : $< 300\mu$Bq/kg Rn : 5 mBq/m^3	internal contaminations in the $\beta\beta$ foils Rn in the tracker[2]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

[2] NIM A606 (2009) 449-465

The BiPo detector

Principle





SuperNEMO source foils

Source production

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

Radiopurity measurement

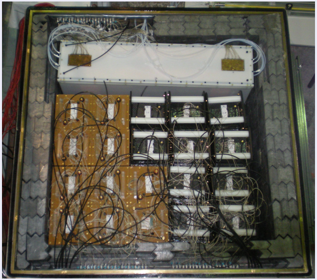
- ^{214}Bi and ^{208}Tl contaminations measured by BiPo processes from natural radioactivity chains
- β and α particles detected by thin radiopure plastic scintillators coupled to light-guides and low radioactivity PMTs

The BiPo detector

BiPo-1 prototype

BiPo-1 prototype

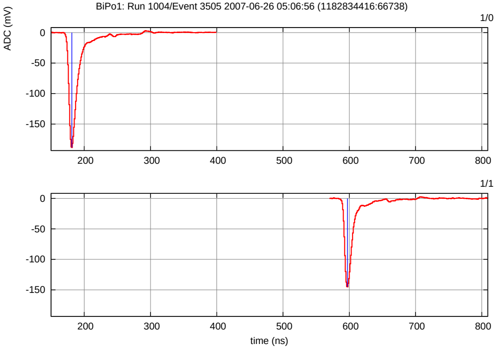
- 0.8 m^2 - Feb 2008 to now in LSM
- 20 similar high radiopurity modules
  - $200 \times 200 \times 3$ mm^3 Polystyrene scintillators [POPOP + pTp]
  - entrance face aluminized with 200 nm of ultra pure aluminum
  - PMMA light guides
  - side reflector in Teflon (0.2 mm)
  - 5" Hamamatsu R6594-MOD low background PMTs



- lead and pure iron shielding, radon free air flushing
- matacq VME digitizer boards : 2.5 μs @ 1 GHz, 1 V & 12 bit
- trigger boards for longer delays (^{214}Bi)

The BiPo detector

BiPo-1 prototype - signal digitalization



- amplitude, total charge
  $\Rightarrow$ deposited energy
- time difference
- pedestal
- charge ratio
  $\Rightarrow$ e^-/α discrimination

The BiPo detector

BiPo-1 prototype - validation of the technique[3]

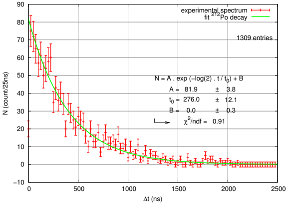
Validation of the technique

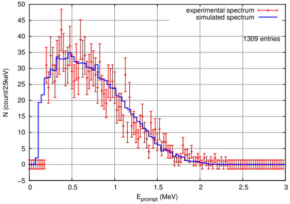
- calibrated 150 μm aluminium foil (40 mg/cm^2) in one module with

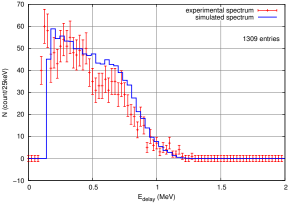
$$\mathbf{A(^{212}Bi \rightarrow {}^{212}Po) = 0.19 \pm 0.04\ Bq/kg}$$

- 160 days of data and 1309 BiPo events detected
  - $T_{1/2} = 276 \pm 12_{stat}$ ns ($T_{1/2}$ (^{212}Po) = 299 ns)
  - β and α spectra on the basis of simulations

$$\mathbf{A(^{212}Bi \rightarrow {}^{212}Po) = 0.16 \pm 0.01_{stat} \pm 0.03_{syst}\ Bq/kg}$$







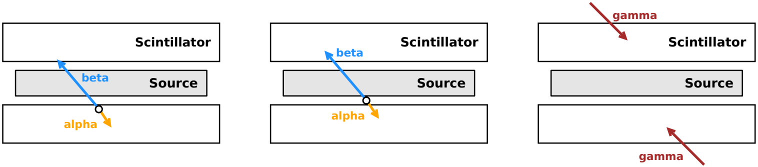
[3] NIM A 622 (2010) 120–128

The BiPo detector

BiPo-1 prototype - backgrounds measurements

3 sources of backgrounds should be considered :

- ^{238}U (^{214}Bi) and ^{232}Th (^{208}Tl) contaminations on the surface of the scintillators (include volume contaminations within ~100 μm thickness)
- ^{222}Rn and ^{220}Rn migration between the source and the scintillators
- random coincidences (external γ)



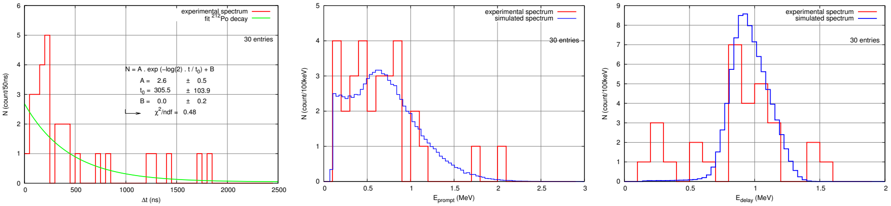
The BiPo detector

BiPo-1 prototype - backgrounds measurements[3]

Backgrounds measurements

- random coincidences
  - $\tau_{(BiPo-1)} \sim$ 20 mHz @ 150 keV
  - negligible for coincidences within 2μs
- bulk : A(^{208}Tl) $<$ 0.3 μBq/kg (90 % C.L.)
- surface : 258 days.m^2 of data and 30 BiPo events detected

$$\mathbf{A(^{208}Tl) = 1.5 \pm 0.3_{stat} \pm 0.3_{syst}\ \mu Bq/m^2}$$



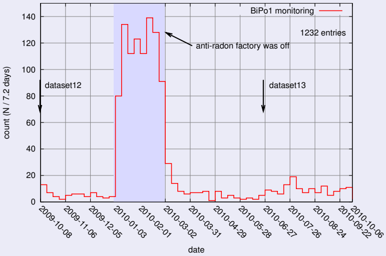
[3] NIM A 622 (2010) 120–128

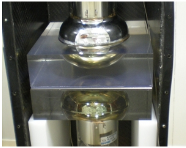
The BiPo detector

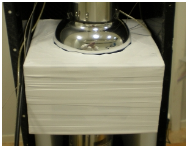
BiPo-1 prototype - backgrounds measurements

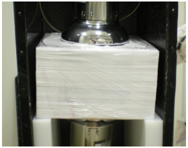
Backgrounds measurements

- ^{214}Bi scintillators background
  - dominated by radon background
  - solutions under test : radon protection film (EVOH), improvement of radon free air flushing system...









The BiPo detector

BiPo-1 prototype - first samples measurements

First samples measurements

- 5 samples of 120 μm thick Stycast samples have been measured using 5 carbon modules (102 days.m^2) :

$$\mathbf{A}_{Stycast}(^{208}\mathbf{Tl}) < \mathbf{132}\ \mu\mathbf{Bq/kg\ @\ 90\%\ CL}$$

- 3 samples of 100 μm thick Mylar samples have been measured using 3 PMMA modules (53 days.m^2) :

$$\mathbf{A}_{Mylar}(^{208}\mathbf{Tl}) < \mathbf{109}\ \mu\mathbf{Bq/kg\ @\ 90\%\ CL}$$

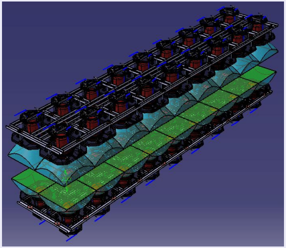
- no available measurement of ^{214}Bi contamination
- need a larger detector for more sensitive measurements

The BiPo detector

BiPo-3 prototype

BiPo-3 prototype

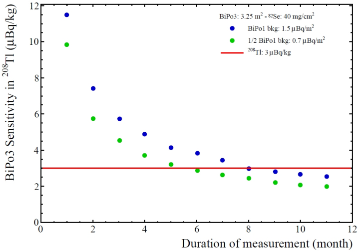
- The BiPo-3 detector (3.24 m^2) can measure 1.3 kg of SuperNEMO ^{82}Se foil (40 mg/cm^2) with 6.5% efficiency
- 2 identical modules of 2.7×0.6 m^2
- each high radiopurity module consists of 18×2 light lines (total 72)
  - $300 \times 300 \times 2$ mm^3 Polystyrene scintillators [POPOP + pTp]
  - entrance face aluminized with 200 nm of ultra pure aluminum
  - PMMA light guides
  - side reflector in Tyvek (0.2 mm)
  - 5" Hamamatsu R6594-MOD low background PMTs



- lead and pure iron shielding, radon free air flushing
- electronics similar to BiPo-1

BiPo-3 sensitivity

- assuming BiPo-1 background from the scintillator surface
  - A(^{208}Tl) $\sim$1.5 μBq/m^2 (^{214}Bi is still unknown in BiPo-1)
- Surface background reduced by factor 3 with the source
- BiPo-3 sensitivity for SuperNEMO ^{82}Se sources is :
  - A(^{208}Tl) $<$ 10-12 μBq/kg in 1 month
  - A(^{208}Tl) $<$ 3-4 μBq/kg in 6 months



Summary

- NEMO3 data and HPGe measurements of $\beta\beta$ sources show a small tension in ^{208}Tl $\Rightarrow$ the BiPo detector should remeasure these sources
- BiPo-1 prototype has validated the technique and gave very good results
- BiPo-1 first measurements
  - $A_{Mylar}(^{208}Tl) < 109\ \mu Bq/kg$ @ 90% CL
  - $A_{Stycast}(^{208}Tl) < 132\ \mu Bq/kg$ @ 90% CL
- a BiPo-3 prototype (2 light-lines) helps us to finalize BiPo-3 design
- BiPo-3 detector should be running before summer 2011 (LSC) with sensitivity for SuperNEMO ^{82}Se sources
  - $A(^{208}Tl) <$ 10-12 $\mu Bq/kg$ in 1 month
  - $A(^{208}Tl) <$ 3-4 $\mu Bq/kg$ in 6 months
- investigations for ^{214}Bi background reduction are in progress $\Rightarrow$ no measurement available until now

BiPo-1 e^-/α discrimination

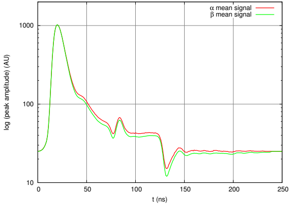
Backup slide

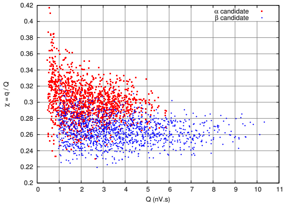
BiPo-1 e^-/α discrimination

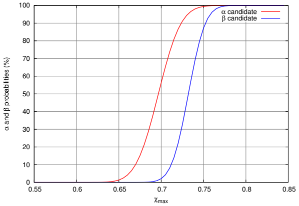
- longer half-life scintillation states excited by α particles but not by e^- because of much larger energy loss
- signal tail is higher for α particles than e^-

discrimination parameters : $\chi = q_{tail}/Q_{total}$

Cut $\chi < 0.7$: 56% α saved and 98% e^- rejected







Phoswich prototype

Backup slide

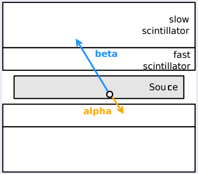
Phoswich prototype

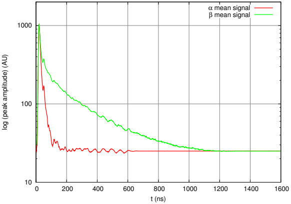
- 2 scintillators with different scintillation times
- no better electron rejection

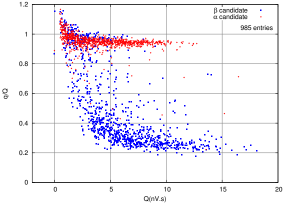
discrimination parameters : $\chi = q_{tail}/Q_{total}$

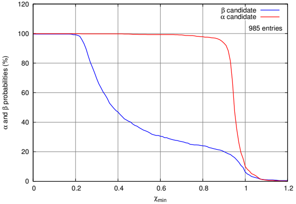
Cut $\chi > 0.9$:

93% α saved and 80% e^- rejected







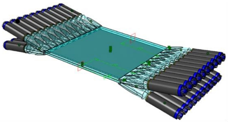


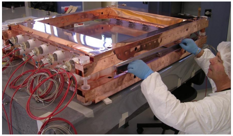
The BiPo-2 prototype

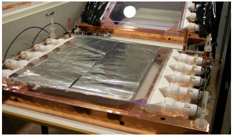
Backup slide

BiPo-2 prototype

- more compact and sophisticated technique with spatial position reconstruction (∼2 cm resolution)
- 2 polished scintillator plates 0.56 m^2 :
  - $75 \times 75 \times 1$ cm^3 Polystyrene scintillators [POPOP + pTp]
  - naked scintillators
  - PMMA light guides
  - side reflector in Teflon (0.2 mm)
  - 3" Hamamatsu R6091-MOD low background PMTs
- BiPo-2 encountered several problems (calibration, acquisition...) from the beginning and it was long to solve ⟶ results coming soon

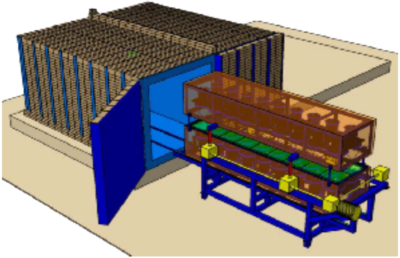






BiPo-3 shielding

Backup slide



Total size : 3.2×2.6 m^2
Load on the floor : 5.5 tons/m^2

BiPo-3 shielding

- lead and pure iron shielding
  - pure Iron tank (thickness = 20 mm) $\Rightarrow$ 5.5 tons of iron
  - lead shield (using Lead bricks 10 cm thick) $\Rightarrow$ 37 tons of lead
- radon free air flushing

Double beta decay processes

Backup slide

The allowed 2ν process ($2\nu2\beta$)

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

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

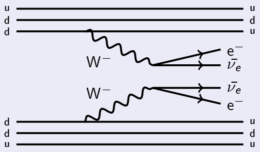


Fig.: $2\nu2\beta$ mechanism

The 0ν process beyond the SM ($0\nu2\beta$)

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

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

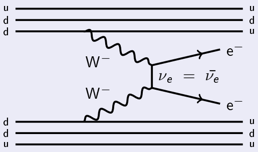
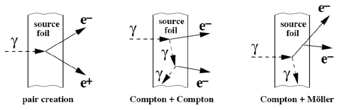


Fig.: $0\nu2\beta$ mechanism

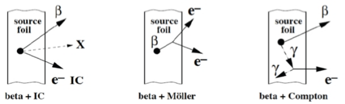
Backgrounds for $\beta\beta$ decays

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 : $Q_{\beta\beta} \approx 3$MeV $> E_\gamma(^{208}\text{Tl}) = 2.6$MeV)



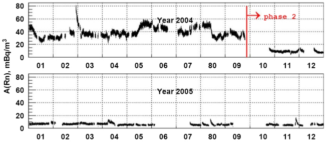
- ^{208}Tl and ^{214}Bi contamination inside the $\beta\beta$ source foils



- 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

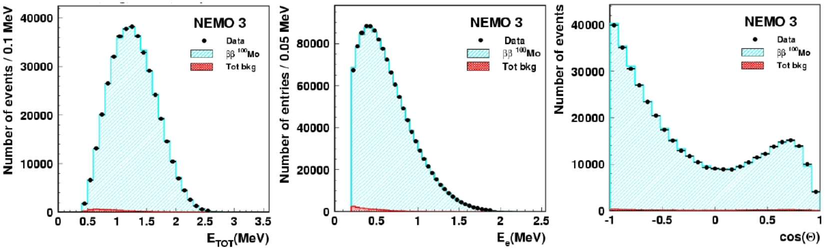
- Input : A(^{222}Rn) 15 Bq/m^3
- Output : A(^{222}Rn) < 15 mBq/m^3 ! ! !

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

NEMO3 results : $2\nu2\beta$ from ^{100}Mo (7kg)[5]

Backup slide



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

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

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

[5] PRL 95 (182302) 2005