Results of the NEMO-3 experiment
and
the SuperNEMO proposal

Lepton number violation and neutrinoless double beta decay

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Overview

- Highlights on $\beta\beta0\nu$ physics
- The NEMO-3 experiment (2003-2011)
- The SuperNEMO proposal

Double beta decay (DBD)

A second order weak interaction nuclear transition

- $\beta\beta 2\nu$ (M. Goeppert-Mayer, 1935) :

$$(Z, A) \rightarrow (Z+2, A)^{[*]} + 2e^- + 2\bar{\nu}_e \quad (\Delta L = 0)$$

- $\beta\beta 0\nu$ (W. Furry, 1939) [or $\beta\beta 0\nu\chi$] :

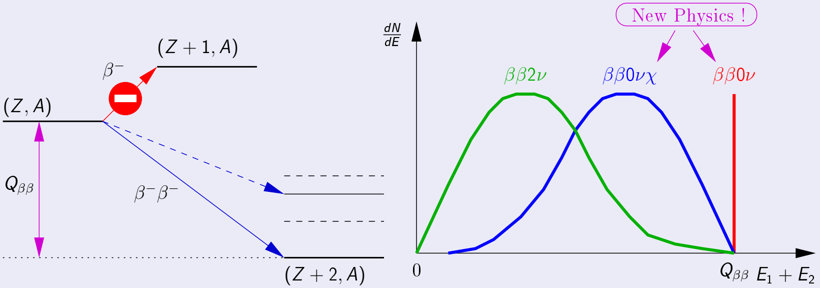
$$(Z, A) \rightarrow (Z+2, A)^{[*]} + 2e^- [+\chi] \quad (\Delta L = 2)$$

  - Lepton number violation
  - Majorana (massive) neutrino
  - Majoron
  - $\rightsquigarrow$ New Physics !

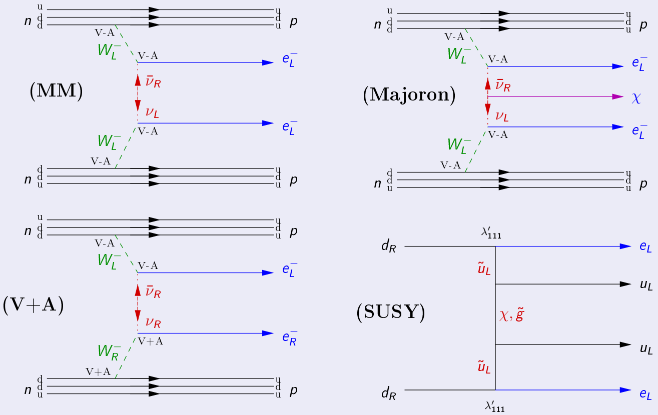
Experimental considerations (part 1)

$$(Z, A) \rightarrow (Z+2, A)^{[*]} + 2e^{-}\ [+\chi]$$

Principle : measure the energy sum of the electrons in the final state to discriminate several $\beta\beta$ processes.

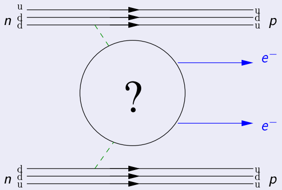


Underlying mechanisms. . .



The $\beta\beta0\nu[\chi]$ process

Whatever underlying physics mechanism...



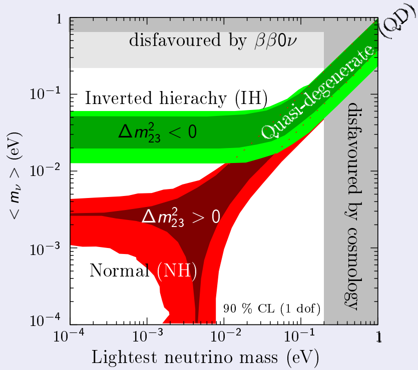
- Transition rate :

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \mid M^{0\nu} \mid^2 \epsilon^2$$

$G^{0\nu}$: phase space (y^{-1})
$M^{0\nu}$: nuclear matrix element
ϵ ($\neq 0$?) : lepton-number violating factor

- (MM) : $\epsilon \equiv < m_\nu >$
- (Majoron) : $\epsilon \equiv g_{ee}$
- (V+A) : $\epsilon \equiv \lambda, \eta$
- (SUSY) : $\epsilon \equiv \lambda'_{111}$ (R-parity violation, exchange of a virtual gluino)

Combining experimental approaches



$\beta\beta0\nu$ experiments are a probe for the ν absolute mass scale and hierarchy, complementary to:

- ν oscillation experiments
- Direct mass measurements
- Cosmology

Experimental considerations (part 2)

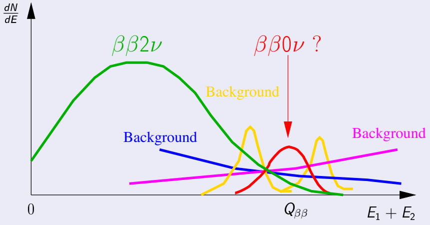
Experimental facts

- $\beta\beta0\nu$ is expected to be very rare :
  best world limit is $T_{1/2}^{0\nu}$>1.9 10^{25} y for ^{76}Ge (HM, 1990-2003)
- Long exposure: typically 5-10 years of data taking using $1 - 10$ kg of $\beta\beta$ isotopes
- DBD physics lies within the 100 keV – 10 MeV energy range

Background, background, background !

There are several processes which can mimic the $\beta\beta0\nu$ signal :

- (natural) radioactivity (^{238}U, ^{232}Th chains)
- Secondary processes induced by cosmic rays (cosmogenics)
- "allowed" $\beta\beta2\nu$ decays in the end-point region



The NEMO 3 experiment

Neutrino Ettore Majorana Observatory

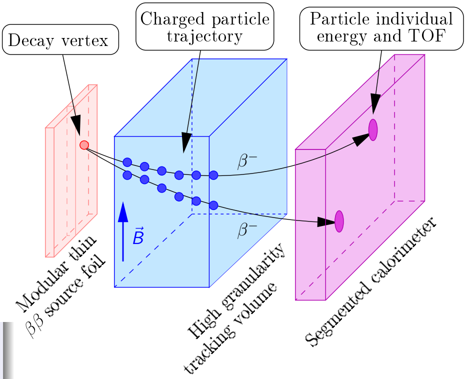
- Successor of NEMO 2 (1992-1998)
- "Tracko-calo" technique
- proposed in 1994
- R&D 1995-1999
- Commissioning (2000-2003)
- Data taking from 2003/02/14 to 2011/01/11
- 50 collaborators (France, Russia, Cz. Rep., Japan, USA, UK)
- IN2P3: CENBG, IPHC, LAL, LPC Caen
- Hosted at LSM (4800 m.w.e.)

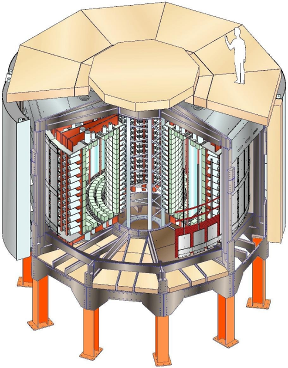
Physics goals

- Search for $\beta\beta0\nu$ decay for ^{100}Mo and ^{82}Se :
  Target sensitivity : $T^{0\nu}_{1/2} \simeq 10^{24}$ y (^{100}Mo)
  MM : $< m_\nu > \lesssim 0.5 - 1$ eV
- Search for $\beta\beta0\nu\chi$ (Majoron) :
  sensitivity $T^{0\nu\chi}_{1/2} \simeq 10^{22}$ y
- Investigate $\beta\beta2\nu$ decay :
  - Sensitivity : $T^{2\nu}_{1/2} \simeq 10^{21}$ y
  - $\neq$ nuclei,
  - $\beta\beta$ decays to excited states,
  - SSD vs. HSD mechanisms,
  - Experimental measurement of n.m.e. ($M^{2\nu}$)

The NEMO-3 technique : Calorimetry + Tracking

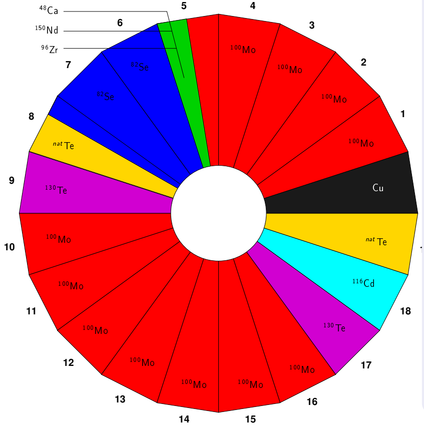
- Reconstruction of final state topology:
  - $e^{\pm}$ individual energy
  - charged particle trajectory
  - time of flight
  - magnetic field curvature
  - angular distribution
  - vertex
- Background rejection through particle identification: e^-, e^+, γ, α
- Source is separated from the detector: can measure several $\beta\beta$ isotopes
- "tracko-calo" $\neq$ "pure calorimeter" technique (HM, IGEX, Cuoricino. . .).





- Rn trapping facility + tent
- Low radioactivity materials
- Fréjus Underground Lab. (4800 m.w.e.)

- Source: 10 kg of $\beta\beta$ isotopes, S=20 m^2, $e \simeq$60 mg/cm^2
- Tracking detector: 30 m^3 drift wire chamber operating in Geiger mode (6180 cells)
  gas: He+4% ethyl alcohol...
- Calorimeter: 1940 plastic scintillators coupled to low radioactivity PMTs
- Magnetic field: 25 gauss (e^+e^- discrimination)
- Gamma/neutron shield: pure Iron (18 cm), borated water (30 cm, ext. wall), wood (40 cm, top+bottom)



Isotope	Mass (g)	$Q_{\beta\beta}$ (keV)
$\beta\beta0\nu$ search + $\beta\beta2\nu$ meas.		
^{100}Mo	6914	3034
^{82}Se	932	2995
$\beta\beta2\nu$ measurement		
^{116}Cd	405	2805
^{96}Zr	9.4	3350
^{150}Nd	37.0	3367
^{48}Ca	7.0	4272
^{130}Te	454	2529
External background measurement		
^{nat}Te	491	see ^{130}Te
Cu	621	-

Enriched isotopes produced by centrifugation in Russia

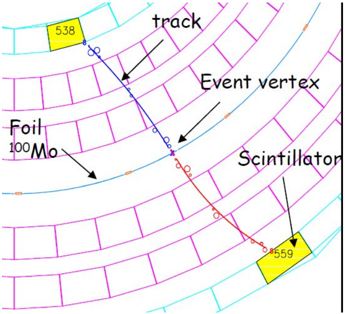
$(2e)_{internal}$ selection

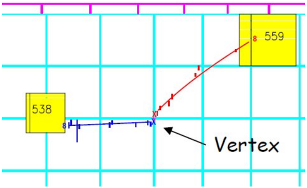
- 2 tracks with $Q < 0$
- 2 PMTs associated with tracks
- common vertex
- internal event from the foil (TOF cut)
- No unassociated PMT (γ rejection)
- No delayed short tracks (α rejection from ^{214}Bi-^{214}Po cascade)
- $\beta\beta$ rate: 1 event / 2.5 minutes

Other channels

- Able to measure its own backgrounds
- Using independant channels : $(e\gamma)$, $(e\gamma\gamma)$, $(e\gamma\alpha)$...
- Elaboration of background models

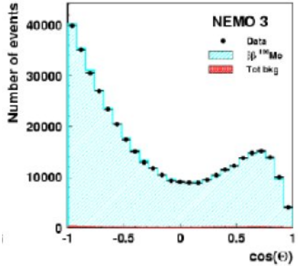
Typical $\beta\beta2\nu$ candidate event @ $\simeq$1 MeV

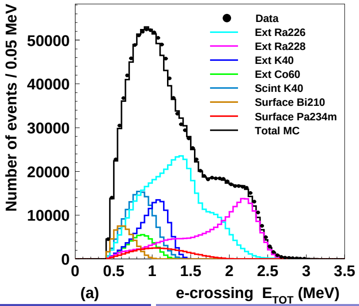


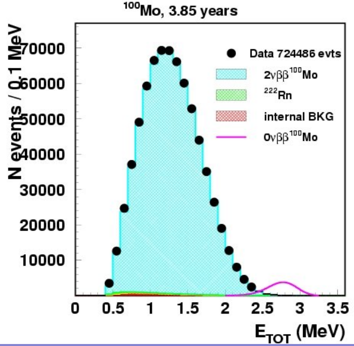


$\beta\beta2\nu$ results

Isotope	S/B	$T_{1/2}^{2\nu}$ (y)
^{100}Mo	40	$(7.17 \pm 0.01 \pm 0.54) \times 10^{18}$
exc. states	4	$(5.7^{+1.3}_{-0.9} \pm 0.8) \times 10^{20}$
^{82}Se	4	$(9.6 \pm 0.1 \pm 1.0) \times 10^{19}$
^{116}Cd	7.5	$(2.88 \pm 0.04 \pm 0.16) \times 10^{19}$
^{96}Zr	1	$(2.35 \pm 0.14 \pm 0.16) \times 10^{19}$
^{150}Nd	2.8	$(9.11^{+0.25}_{-0.22} \pm 0.63) \times 10^{18}$
^{48}Ca	6.8	$(4.4^{+0.5}_{-0.4} \pm 0.4) \times 10^{19}$
^{130}Te	0.35	$(7.0 \pm 0.9 \pm 1.0) \times 10^{20}$







$\beta\beta0\nu$ and $\beta\beta0\nu\chi$ results

No evidence for new physics.

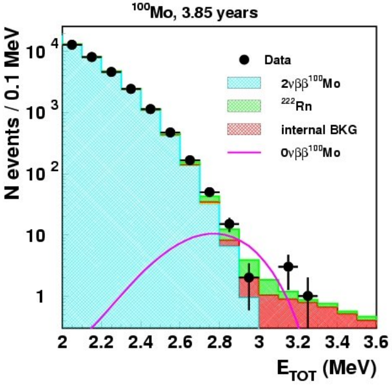
$\beta\beta0\nu$

Isotope	$T_{1/2}^{0\nu}$ (y) (90 %CL)	$< m_\nu >$ upper limit
^{100}Mo	$> 1.0 \cdot 10^{24}$ y *	0.47-0.96 eV
^{82}Se	$> 3.2 \cdot 10^{23}$ y *	0.94-2.5 eV
^{130}Te	$> 1 \cdot 10^{23}$ y	
^{150}Nd	$> 1.8 \cdot 10^{22}$ y	
^{116}Cd	$> 1.6 \cdot 10^{22}$ y	
^{48}Ca	$> 1.3 \cdot 10^{22}$ y	
^{96}Zr	$> 9.2 \cdot 10^{21}$ y	

$\beta\beta0\nu\chi$

	$T_{1/2}^{0\nu\chi}$ (y) (90 %CL)	$< g_{ee} >$ upper limit
^{100}Mo	$> 2.7 \cdot 10^{22}$ y *	(0.4-1.8) 10^{-4}
^{82}Se	$> 1.5 \cdot 10^{22}$ y *	(0.66-1.9) 10^{-4}
^{150}Nd	$> 1.52 \cdot 10^{21}$ y	(1.7-3.0) 10^{-4}

* Best world limits



NEMO 3 summary

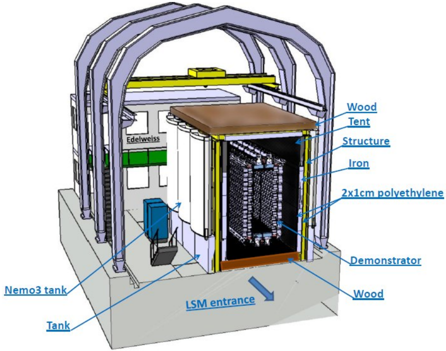
- Exposure $\simeq$ 4.9 y with $\lesssim$ 7 kg ^{100}Mo, $\lesssim$ 1kg ^{82}Se
- $\beta\beta2\nu$ measurements for :
  - ^{100}Mo, ^{82}Se (large statistics)
  - Other studies : ^{116}Cd, ^{150}Nd, ^{48}Ca, ^{130}Te, ^{96}Zr, $\beta\beta2\nu$ to excited states (^{100}Mo$\rightarrow$^{100}Ru*), disentangling SSD/HSD mechanism (^{100}Mo), input for n.m.e. calculation
- $\beta\beta0\nu$: no evidence for lepton number violation up to $T^{0\nu}_{1/2} \simeq 10^{24}$ y (^{100}Mo)
- Background is well understood (internal, external, radon)
- First "tracko-calo" experiment @ 10^{24} y
- Two more years of data analysis before final results.
- Now dismantling the detector at LSM

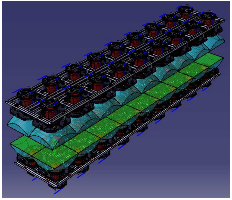
Future of DBD

- 1990-2010 : two experimental approaches
  - Calorimeter :
    HM, IGEX (^{76}Ge) : $T^{0\nu}_{1/2} > 1.5$–$1.9\ 10^{25}$ y ($< m_\nu > <$ 200–600 meV)
    Cuoricino (^{130}Te) : $T^{0\nu}_{1/2} > 3\ 10^{24}$ y ($< m_\nu > <$ 190–680 meV)
  - Tracko-calo :
    NEMO3 (^{100}Mo) : $T^{0\nu}_{1/2} > 1\ 10^{24}$ y ($< m_\nu > <$ 470–960 meV)
- 2010-2020 : investigating the $< m_\nu > =$ 50–200 meV region
  - $T^{0\nu}_{1/2} \gtrsim 10^{24-25}$ y $\rightarrow 10^{26-27}$ y
  - Exposure ($M \times t$) : $\lesssim$ 50 kg.y $\rightarrow \gtrsim$ 500 kg.y
  - Background :
    $b_{ROI} \simeq 10^{-1} \rightarrow 10^{-2}$-$10^{-3}$ count/y/keV/kg (calorimeter)
    $b_{ROI} \simeq 10^{-3} \rightarrow 10^{-4}$ count/y/keV/kg (tracko-calo)
- Main issue : background reduction by $\simeq$ 2 orders of magnitude
- Most new projects have a step approach to reach their target sensitivity
- The scale of future $\beta\beta$ experiments increases significantly (100 kg): $\rightarrow$ 20–40 M€

New projects

Experiment	Isotope	Mass (kg)	Sensitivity $T^{0\nu}_{1/2}$ (y)	Sensitivity $\langle m_\nu \rangle$ (meV)	Status	Start of data taking
Pure calorimeter						
CUORE	^{130}Te	200	$2.1 \cdot 10^{26}$	40-90	in prog.	$\sim$ 2013
GERDA-I	^{76}Ge	17.9	$3 \cdot 10^{25}$	180-440	comm.	$\sim$ 2012
GERDA-II	^{76}Ge	40	$2 \cdot 10^{26}$	70-170		$\sim$ 2012
MAJORANA	^{76}Ge	30-60	$(1-2) \cdot 10^{26}$	70-200	in prog.	$\sim$ 2013
EXO-200	^{136}Xe	200	$6.4 \cdot 10^{25}$	100-200	comm.	$\sim$ 2011
KamLAND-ZEN	^{136}Xe	400	$4 \cdot 10^{26}$	40-80	in prog.	$\sim$ 2011
SNO+	^{150}Nd	150	$4.5 \cdot 10^{24}$	160-218	in prog.	$\sim$ 2014
Tracko-calorimeter						
SuperNEMO-I	^{82}Se	7	$6.6 \cdot 10^{24}$	160-390	R&D	2014
SuperNEMO	^{82}Se	100	$1 \cdot 10^{26}$	40-100		$>$ 2015
	^{150}Nd	100	$4 \cdot 10^{25}$	54-73		
	^{48}Ca	50	$1.9 \cdot 10^{26}$	30		



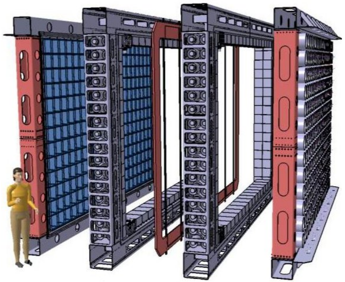


supernemo collaboration

The SuperNEMO project

- Initiated by the NEMO Collaboration in 2003
- R&D started in 2005→2010 :
  - A shared R&D program : Cz. Rep., France, Japan, S. Korea, Russia, Spain, UK, USA. . . (100 people)
  - Improve energy resolution of the calorimeter from 15% to 8% (FWHM @ 1 MeV)
  - Master source contamination (^{214}Bi, ^{208}Tl)
  - Solve radon issues
  - Optimize the geometry (efficiency, tracker, # channels, scalability, costs. . .)
  - Strong support from IN2P3 : CENBG, CPPM, IPHC, LAL, LPC, LSM
    1 M€+ manpower ($\simeq$ 1 M€/y) (+ ANR)
- Two steps:
  - Phase 1 (2011-2013, 4.1 M€) : demonstrator module (17 kg.y, this proposal)
  - Phase 2 (2015+, 34.5 M€) : full size experiment (500 kg.y)

- Re-use NEMO 3 technique and know-how (tracko-calo)
- 20 modules with 5 kg enriched $\beta\beta$ source $\equiv$ 100 kg
- A SuperNEMO module ($\simeq$ 1/2 NEMO 3)
  - Source: 5 kg (50 mg/cm^2)
  - Tracking chamber : 2000 drift cells (Geiger regime)
  - Calorimeter : 500–700 scintillator blocks/8" PMts, 8% FWHM resolution @ 1 MeV (NEMO 3: $\simeq$15%)
  - Coil (B=25 gauss), shielding (300 t)...
  - $\simeq$ 6500 electronics channels
- Baseline: ^{82}Se
  $Q_{\beta\beta} = 2995$ keV ($> E_\gamma(^{208}\mathrm{Tl})$)
  $T^{2\nu}_{1/2} \simeq 10^{20}$ y ($> 10 \times T^{2\nu}_{1/2}(^{100}\mathrm{Mo})$)



- Target sensitivity with 500 kg.y (^{82}Se): $T^{0\nu}_{1/2} \gtrsim 10^{26}$ y $\rightarrow < m_\nu >< 40 - 100$ meV
- Alternatives: ^{150}Nd, ^{48}Ca
  $Q_{\beta\beta} = 3367, 4271$ keV
  ($> E_\gamma(^{208}\mathrm{Tl})$, $Q_\beta(^{214}\mathrm{Bi}$, radon)

French tasks for the construction of a SuperNEMO demonstrator module

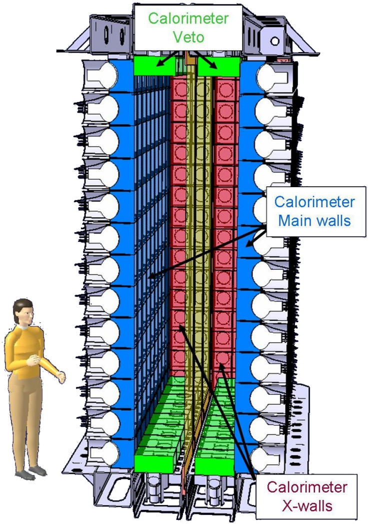
Workpackage organization

- WP1: calorimeter (CENBG, LAL, CPPM, LPC)
- WP2: electronics (LAL, LPC)
- WP3: BiPo detectors (CENBG, LAL, LPC)
- WP4: radiopurity measurements (CENBG, CPPM, LAL)
- WP5: software (LAL, LPC)
- WP6: sources (CENBG, LSM)
- WP7: surroundings (LAL, CPPM)
- WP8: integration (LAL, CPPM, CENBG, LPC. . .)
- WP9: technical coordination (LAL, CPPM)

WP1: the calorimeter (1)

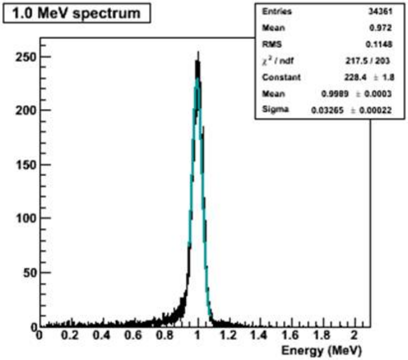
A crucial part of the project

- A fruitfull collaboration between IN2P3 labs (CENBG, LAL) and private companies to reach the objectives
- a lot of R&D for testing many different materials and geometries
- development of specific test benches and systematic experimental protocols

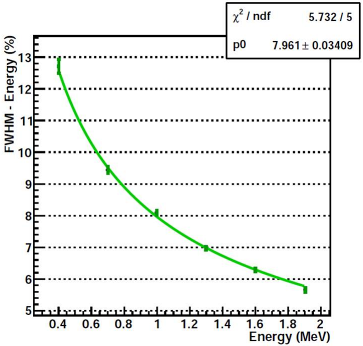


WP1: main achievements (1)

Parameter	Requirement	Results
Optical Modules		
Granularity	30×30 cm^2	256.8^2 mm^2 308^2 mm^2
Energy resolution	$\leq 8\%$	7.3 %
Energy homogeneity	$\delta E/E_{central} < 2$ %	$\delta E/E_{central} < 2$ %
Time Resolution	250 ps (sigma)	in prog.



Single electron resolution @ 1 MeV

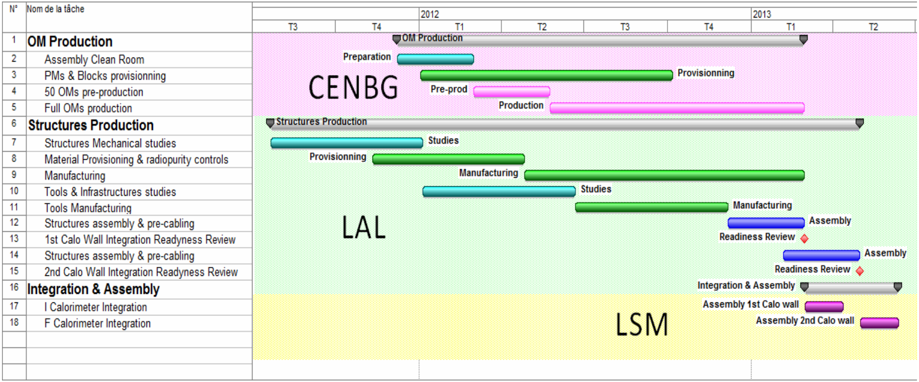


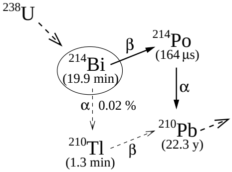
$FWHM/E \propto 1/\sqrt{E}$

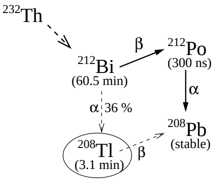
WP1: main achievements (2)

PMts		
Photocathode size QE Linearity Cathode homogeneity Radiopurity ^{226}Ra ^{228}Th	$\geq$ 8 inches $\geq$ 25% @ 420 nm Deviation <1% up to 3 MeV Deviation < 20% 40 mBq/kg 10 mBq/kg	8" 35% <1% <10% 100 mBq/kg 56 mBq/kg
Scintillators		
Thickness Electron Backscattering Light Yield Decay Time Radiopurity ^{226}Ra ^{228}Th	$\geq$ 10 cm $\leq$ 5% @ 1 MeV > 6000 photons / MeV < 5 ns < 2.5 mBq/kg < 0.6 mBq/kg	19 cm (mean value) 5% @ 1 MeV 10400 ph./MeV 1.8 ns < 0.1 mBq/kg < 0.1 mBq/kg
Calibration		
Light injection system Alpha sources	Accuracy of 1% on the gain Accuracy of 1% on the gain	< 1% < 1%

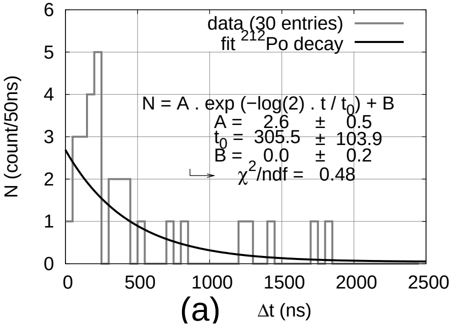
WP1: schedule





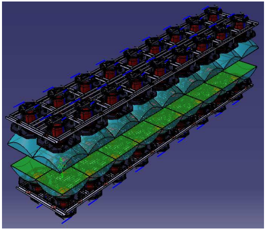


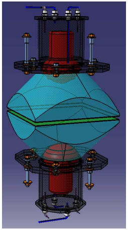
- Required radiopurities of the SuperNEMO double beta decay foils are $\mathcal{A}(^{208}\text{Tl}) < 2\ \mu\text{Bq/kg}$ and $\mathcal{A}(^{214}\text{Bi}) < 10\ \mu\text{Bq/kg}$.
- The best detection limit with HPGe (High Purity Germanium) for ^{208}Tl is around 50 μBq/kg,
- Development of a dedicated BiPo planar detector,
- Proof of validity and first prototype (BiPo-1) installed in LSM,
- SuperNEMO source foils measurement in Canfranc.



(a)

- 27% efficiency to detect the BiPo cascade from a ^{212}Bi pollution on the surface of the scintillators
- Corresponds to a surface background of the BiPo-1 prototype of $\mathcal{A}(^{208}\mathrm{Tl}) = 1.5 \pm 0.3(stat) \pm 0.3(syst)$ μBq/m^2 in ^{208}Tl.
- Level of background low enough to reach the required sensitivity of 2 μBq/kg in ^{208}Tl with a larger detector.





- Construction of 40 optical sub-modules to start in April 2011 in the LAL Orsay clean room.
- Installation with the shield and clean tent in the Canfranc Underground Laboratory in November 2011.
- 6 months background measurement to start in December 2011
- 6 months measurement of the first SuperNEMO double beta source foils to start in May 2012. Validation of the radiopurity of the SuperNEMO foils available at the end of 2012.

WP4: Radiopurity measurements (goals and tools)

Radiopurity measurements is a crucial task for the study of double beta decay process:

- for the selection of all the materials entering in the construction of the SuperNEMO demonstrator by low-background gamma spectrometry measurements,
- to find a way to decrease and control the level of radon inside the tracker chamber down to 0.2 mBq/m^3

Tools at the disposal of the Collaboration for such tasks:

- at LSM, two 400 cm^3 coaxial-type HPGe detectors, a planar Broad Energy Germanium (BEGe) and a 600 cm^3 coaxial-type spectrometer with typical sensitivities of 0.13 mBq/kg for ^{214}Bi) and 0.05 mBq/kg for ^{208}Tl
- the PRISNA platform (CENBG) with two HPGe detectors with a typical sensitivity around 50 mBq/kg. This is well-adapted for cables, shielding components located outside the tracker and calorimeter part and for a pre-screening of the samples for the SuperNEMO demonstrator.

WP4: the Radon issue

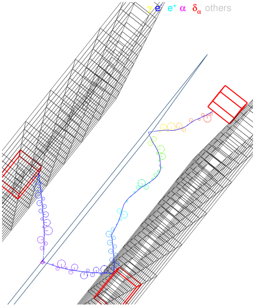
Sources of Radon by descending order of expected importance:

- Radon emanation from the materials inside the tracker (wires of the tracker, cathodic rings, support of the sources...),
- Radon emanation from the materials (PMT, shielding...) surrounding the tracker,
- Radon emanation from the laboratory and diffusion inside the tracker,
- Radon introduced in the tracker by the incoming gas

Solutions:

- tracker is isolated from the rest of the detector
- materials inside the tracker have to be very radiopure
- Radon-free air should be flushed around the PMT glass
- tracker and calorimeter are placed in an "anti-Radon tent"
- the incoming gas must be as radiopure as possible. Helium is purified by well-mastered techniques. The remaining 4% made of alcohol needs adapted charcoal or organic zeolith (CPPM).
- the Radon contamination of the gas must be measured. An electrostatic detector (such as in NEMO-3) has a sensitivity around 1 mBq/m^3.
- to reach 0.2 mBq/m^3 : coupling $\lesssim$1 mBq/m^3 sensitive detectors with a radon concentration device.

- Electronics :
  - Design and construction : calorimeter front-end, trigger, part of tracker front-end
  - Based on new generation ASICs (signal digitization, multi-channel) : LAL, LPC
  - Main responsability : LAL
- Software :
  - Online software : BiPo DAQ
  - Offline software : SuperNEMO, BiPo
  - Simulation, visualization, data analysis
  - Key contributions : LPC, LAL



WP6: sources

Choice of the isotope(s):

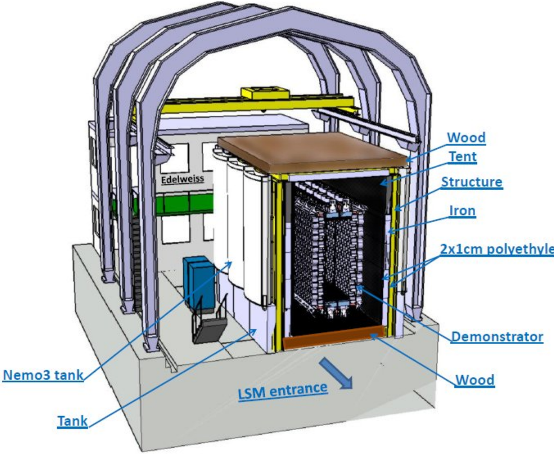
- Large phase space factor (Q_{bb}^5 dependance) and removal of some background contributions call for large Q_{bb} values
- Best compromize for SuperNEMO is ^{82}Se , transition energy is large: 2.995 MeV, $\beta\beta2\nu$ half-life is $9.6 \pm 0.3(stat) \pm 1.0(syst)10^{19}$ y (measured by NEMO-3) leading to a reduction by a factor >10 of the background from the $\beta\beta2\nu$ decay as compared to ^{100}Mo.
- ^{96}Zr, ^{150}Nd or ^{48}Ca are also very good candidates
- Possibility of enrichment by centrifugation of large amount of ^{82}Se, ^{100}Mo and ^{116}Cd and maybe ^{150}Nd
- With AVLIS (Atomic Vapor Laser Isotopic Separation), possibility for ^{150}Nd or ^{48}Ca

Source foil production:

- 5 kg ^{82}Se are already available
- ^{82}Se purification at a level of 2 and 10 μBq/kg for ^{208}Tl and ^{214}Bi is a challenge : chemical purification similar to Molybdenium purification for NEMO-3 can be used and carried out in a class 100 clean room.
- production of foils based on laser techniques is under study (CCPM).

WP7/WP8/WP9: integration, installation, coordination

- Mechanics design mainly in France (LAL, CENBG)
- Hosting site : LSM
- Key responsabilities for french labs.



The SuperNEMO demonstrator module: scientific goals

The main goals of the demonstrator module are

- demonstration of the feasibility of a full scale detector with the requested performances (e.g. calorimeter energy and time resolution, tracker efficiency and radio-purity).
- measurement of the radon background contribution especially from internal materials outgasing.
- measurement of the background contribution from the detector components.
- finalize/optimize the design of the full scale detector.
- production of a competitive measurement with ^{82}Se (2.5 years of data taking with a 7 kg source). After 17 kg.yr exposure with ^{82}Se, the sensitivity of the demonstrator will be 6.6 10^{24} y (90% CL) which is equivalent to 3 10^{25} y obtained with ^{76}Ge. This will lead to a neutrino mass sensitivity similar to GERDA Phase-I : $< m_\nu > \simeq$ 200-400 meV.
- Expected start of data taking: 2014/T2 for 3 years

Phase-I : this proposal

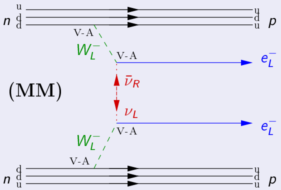
Component	Cost (k€)	Status
Calorimeter	1500	
Tracker	1500	funded (UK)
Source	500	350 k€ funded
Shielding	150	
Others	50	
BiPo	400	$\simeq$350 k€ funded
^{150}Nd	150	
Total	**4250**	2200 k€ funded 52 %
France ^{150}Nd	1400 +150	33% 3%

Summary

- SuperNEMO : "tracko-calo" DBD experiment
- SuperNEMO – Phase 1 (demonstrator) : 7 kg ^{82}Se $\times$ 2.5 y (2014-2017)
  - $T^{0\nu}_{1/2} = 6.6\ 10^{24}$ y $\rightsquigarrow < N^{0\nu}_{obs} > = 3.5$
  - Background : < 1
    - $< N^{2\nu}_{obs} > \lesssim 0.5$
    - $b_{ROI} = 1.10^{-4}$ /kev/y/kg $\rightsquigarrow < N^{bkgd}_{obs} \lesssim 0.5$
  - $< m_\nu > < 200$–400 meV
- Only experiment to investigate:
  - $\beta\beta0\nu\chi$ for $g_{ee} < 10^{-4}$
  - $\beta\beta0\nu$ to excited states
- 20-years know-how (NEMO 2, NEMO3)
- Funding: $\simeq$ 1.5 M€/ 4.3 (NEMO 3 : $\simeq$2.5 M€)
- Timescale for physics : 2014-2017
- Step to 500 kg.y DBD experiment (baseline : ^{82}Se) : 2016+

Back slides

The *mass mechanism* (MM)



$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \mid M^{0\nu} \mid^2 < m_\nu >^2$$

where $< m_\nu >$ is the effective Majorana neutrino mass:

$$< m_\nu > \equiv \mid \cos^2\theta_{13} \left(\mid m_1 \mid \cos^2\theta_{12} + \mid m_2 \mid e^{2i\phi_1} \sin^2\theta_{12} \right) + \mid m_3 \mid e^{2i(\phi_2 - \delta)} \sin^2\theta_{13} \mid$$

θ_{ij} : mixing angles (ν oscillation exp.)

ϕ_k : Majorana phase; δ : CP-violating phase

Isotopes of experimental interest

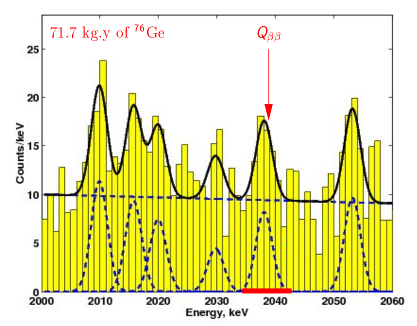
Isotope	%	$Q_{\beta\beta}$ (keV)	$G^{0\nu}$ (y^{-1})	$G^{2\nu}$ (y^{-1})
^{48}Ca*	0.187	4271	$2.439\ 10^{-25}$	$3.968\ 10^{-17}$
^{76}Ge	7.4	2039	$2.445\ 10^{-26}$	$1.305\ 10^{-19}$
^{82}Se*	8.73	2995	$1.079\ 10^{-25}$	$4.348\ 10^{-18}$
^{96}Zr*	2.8	3350	$2.242\ 10^{-25}$	$1.927\ 10^{-17}$
^{100}Mo*	9.6	3034	$1.754\ 10^{-25}$	$9.434\ 10^{-18}$
^{116}Cd*	7.49	2802	$1.894\ 10^{-25}$	$8.000\ 10^{-18}$
^{130}Te*	33.8	2533	$1.698\ 10^{-25}$	$4.808\ 10^{-18}$
^{136}Xe	8.9	2480	$1.812\ 10^{-25}$	$4.831\ 10^{-18}$
^{150}Nd*	5.6	3367	$8.000\ 10^{-25}$	$1.189\ 10^{-16}$

$$\beta\beta 2\nu : (T^{2\nu}_{1/2})^{-1} = G^{2\nu} \mid M^{2\nu} \mid^2$$

The Heidelberg-Moscow experiment (1990-2003)

- 5 ultrapure HPGe detectors (11 kg ^{76}Ge)
- Exposure :
  $\simeq$ 72 kg.y of ^{76}Ge
- Background (ROI) :
  $\simeq$ 80 counts
- Limit : $T^{0\nu}_{1/2} \gtrsim 2\ 10^{25}$ y

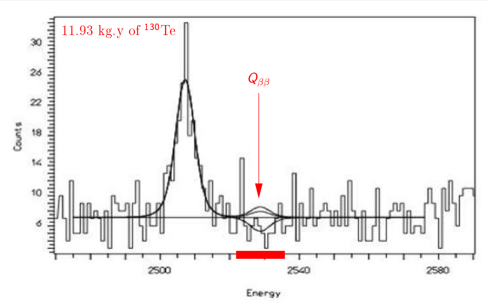
$< m_\nu > < 0.2 - 0.6$ eV



The Cuoricino experiment (2003-2006)

- 62 TeO_2 bolometers (11 kg ^{130}Te)
- Exposure : $\simeq 12$ kg.y of ^{130}Te
- Background (ROI) : $\simeq 70$ counts
- Limit : $T^{0\nu}_{1/2} > 3\ 10^{24}$ y

$< m_\nu > < 0.19 - 0.68$ eV



Experimental techniques: "pure" calorimeter experiments

A very powerful approach

- Large mass of $\beta\beta$ source isotopes
- High efficiency
- Very good energy resolution
- Compacity of the experimental setup and shielding

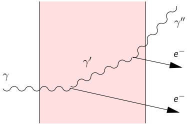
Counterpart

- Only one observable (energy sum)
- No direct identification of the final state particles
- Only one $\beta\beta$ isotope (detector≡source)

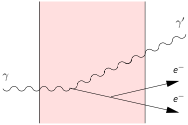
Expected backgrounds in the $(2e)$ channel

- "External" background : γ flux from PMT glass...
- "Internal" background : source foil contaminants, gas, wires...

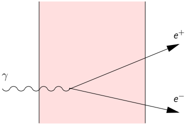
External (^{208}Tl, n capture):



double Compton

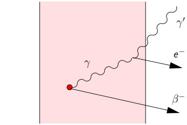


Compton+ Möller

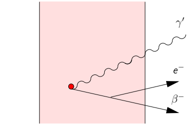


pair production

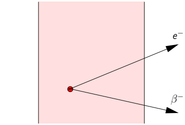
Internal (^{214}Bi , ^{208}Tl):



β^-+ Compton



β^-+ Möller



β^-+ IC

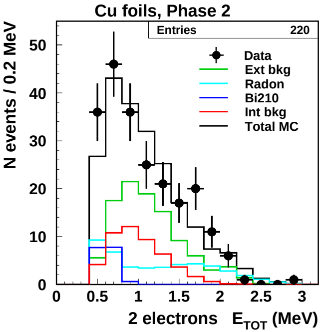
Elaborate a background model

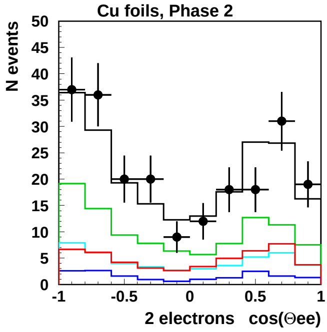
NEMO-3 is able to measure each components of its background

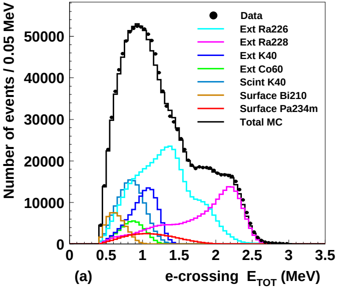
- using independant channels to identify and measure different sources of background:

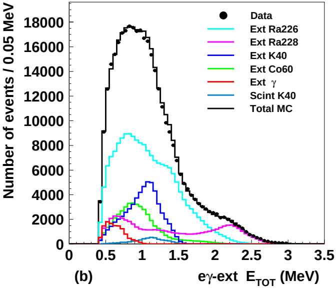
Channel(s)	Background category	Radio-contaminants
$e\gamma_{external}$, $e_{crossing}$	external background	^{40}K, ^{60}Co, ^{226}Ra...
$e\gamma$, $e\gamma\gamma$, $e\gamma\gamma\gamma$	internal background from γ-emitters	^{208}Tl, ^{207}Bi...
$1e$	internal background from pure β-emitters	^{234m}Pa, ^{40}K, ^{90}Y...
$e\alpha(\gamma)$	radon daughters deposited on wires and source foils	^{214}Bi, ^{214}Po ^{212}Bi, ^{212}Po

- elaborating a background model for each $\beta\beta$ isotope
- $\rightsquigarrow$ predicting background contamination in $2e$ channel, particularly at the $Q_{\beta\beta}$ end point for $\beta\beta0\nu$ search


Cu foils, Phase 2
Entries 220
Data
Ext bkg
Radon
Bi210
Int bkg
Total MC
N events / 0.2 MeV
2 electrons E_TOT (MeV)

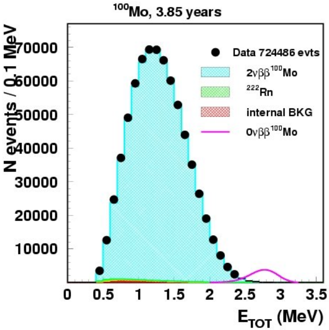

Cu foils, Phase 2
N events
2 electrons cos(Θee)


Data
Ext Ra226
Ext Ra228
Ext K40
Ext Co60
Scint K40
Surface Bi210
Surface Pa234m
Total MC
Number of events / 0.05 MeV
(a)
e-crossing E_TOT (MeV)

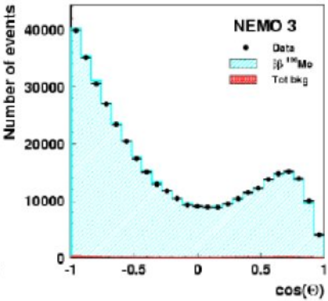

Data
Ext Ra226
Ext Ra228
Ext K40
Ext Co60
Ext γ
Scint K40
Total MC
Number of events / 0.05 MeV
(b)
eγ-ext E_TOT (MeV)

$\beta\beta2\nu$ results

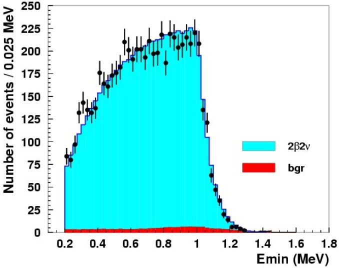
Isotope	Measurement time, days	Number of 2ν events	S/B	$T_{1/2}(2\nu)$, y
^{100}Mo	389	219000	40	$(7.17 \pm 0.01 \pm 0.54) \times 10^{18}$
^{100}Mo-^{100}Ru(0_1^+)	334.3	37.5	4	$(5.7^{+1.3}_{-0.9} \pm 0.8) \times 10^{20}$
^{82}Se	389	2750	4	$(9.6 \pm 0.1 \pm 1.0) \times 10^{19}$
^{116}Cd	168.4	1371	7.5	$(2.88 \pm 0.04 \pm 0.16) \times 10^{19}$
^{96}Zr	1221	428	1	$(2.35 \pm 0.14 \pm 0.16) \times 10^{19}$
^{150}Nd	939	2018	2.8	$(9.11^{+0.25}_{-0.22} \pm 0.63) \times 10^{18}$
^{48}Ca	943.16	116	6.8	$(4.4^{+0.5}_{-0.4} \pm 0.4) \times 10^{19}$
^{130}Te	1152	236	0.35	$(7.0^{+1.0}_{-0.8} \pm 0.9 \pm 1.0) \times 10^{20}$



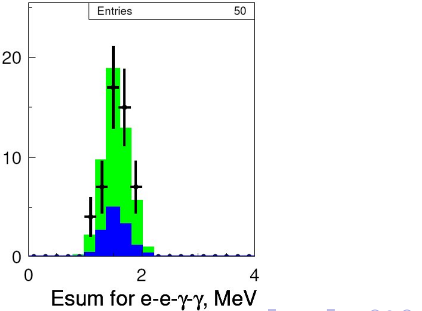
^{100}Mo, 3.85 years
N events / 0.1 MeV
Data 724486 evts
$2\nu\beta\beta\ ^{100}$Mo
^{222}Rn
internal BKG
$0\nu\beta\beta\ ^{100}$Mo
E_{TOT} (MeV)



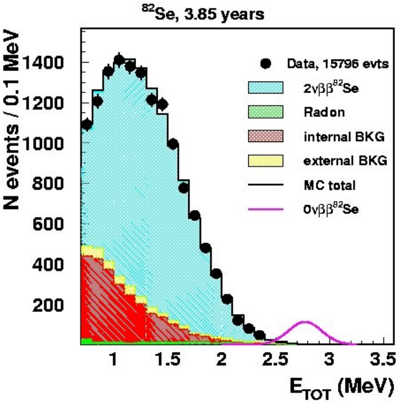
NEMO 3
Number of events
Data
Tot bkg
cos(Θ)

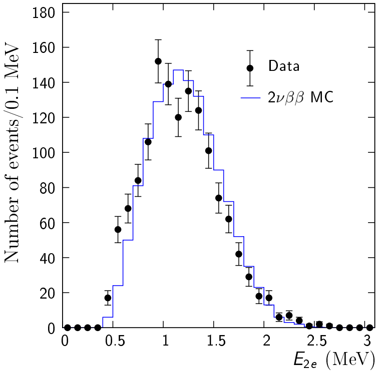


Number of events / 0.025 MeV
$2\beta2\nu$
bgr
Emin (MeV)

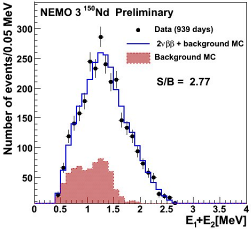


Entries 50
Esum for e-e-γ-γ, MeV

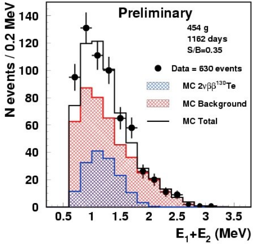

82Se, 3.85 years
N events / 0.1 MeV
1400
1200
1000
800
600
400
200
Data, 15796 evts
2νββ82Se
Radon
internal BKG
external BKG
MC total
0νββ82Se
1
1.5
2
2.5
3
3.5
ETOT (MeV)


Number of events/0.1 MeV
180
160
140
120
100
80
60
40
20
0
Data
2νββ MC
0
0.5
1
1.5
2
2.5
3
E2e (MeV)

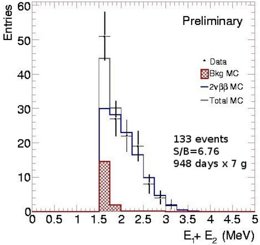
^{150}Nd



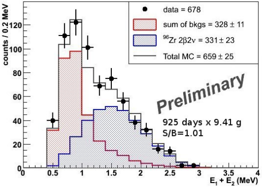
^{130}Te



^{48}Ca



^{96}Zr



$\beta\beta0\nu$ and $\beta\beta0\nu\chi$ results

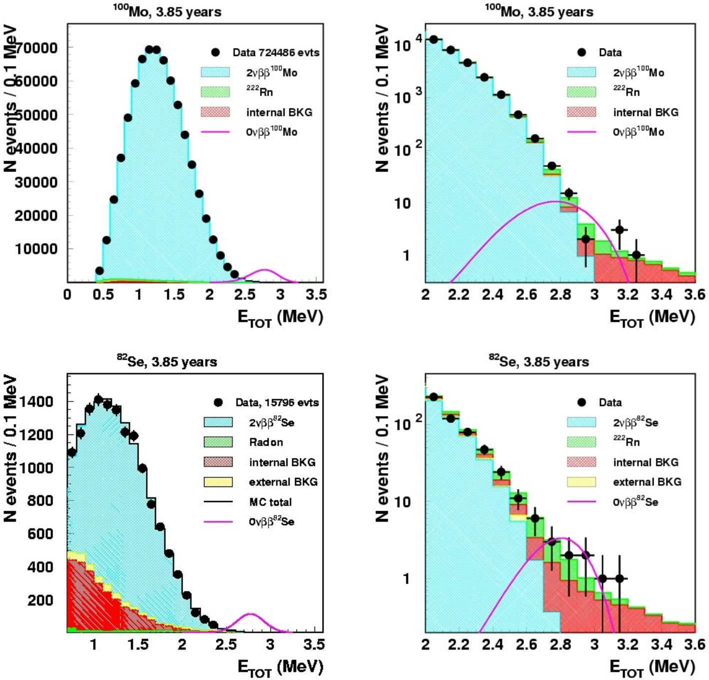
$\beta\beta0\nu$

Isotope	Measurement time, days	$T^{0\nu}_{1/2}$, y (90 %CL)	$< m_\nu >$ upper limit
^{100}Mo	1409	$> 1.0 \cdot 10^{24}$ y *	0.47-0.96 eV
^{82}Se	1409	$> 3.2 \cdot 10^{23}$ y *	0.94-2.5 eV
^{130}Te	1221	$> 1 \cdot 10^{23}$ y	
^{150}Nd	939	$> 1.8 \cdot 10^{22}$ y	
^{116}Cd	77	$> 1.6 \cdot 10^{22}$ y	
^{48}Ca	943	$> 1.3 \cdot 10^{22}$ y	
^{96}Zr	1221	$> 9.2 \cdot 10^{21}$ y	

$\beta\beta0\nu\chi$

		$T^{0\nu\chi}_{1/2}$, y (90 %CL)	$< g_e e >$ upper limit
^{100}Mo		$> 2.7 \cdot 10^{22}$ y *	(0.4-1.8) 10^{-4}
^{82}Se		$> 1.5 \cdot 10^{22}$ y *	(0.66-1.9) 10^{-4}
^{150}Nd		$> 1.52 \cdot 10^{21}$ y	(1.7-3.0) 10^{-4}

* Best world limits



100Mo, 3.85 years
N events / 0.1 MeV
Data 724486 evts
2νββ 100Mo
222Rn
internal BKG
0νββ 100Mo
E_TOT (MeV)
100Mo, 3.85 years
N events / 0.1 MeV
Data
2νββ 100Mo
222Rn
internal BKG
0νββ 100Mo
E_TOT (MeV)
82Se, 3.85 years
N events / 0.1 MeV
Data, 15796 evts
2νββ 82Se
Radon
internal BKG
external BKG
MC total
0νββ 82Se
E_TOT (MeV)
82Se, 3.85 years
N events / 0.1 MeV
Data
2νββ 82Se
222Rn
internal BKG
external BKG
0νββ 82Se
E_TOT (MeV)

Figure of merit of $\beta\beta$ isotopes

- Parameters of experimental interest :

$$N^{0\nu}_{obs} \equiv \frac{M}{m_A} N_A t \varepsilon \frac{\log(2)}{T^{0\nu}_{1/2}}$$
$$\equiv \frac{M}{m_A} N_A t \varepsilon \log(2) G^{0\nu} \mid M^{0\nu} \mid^2 < m_\nu >^2$$

- Experimental factor of merit for t=constant (5 y) and $M^{0\nu} \simeq 3$ (no background experiment):

$$FOM \equiv \left(\frac{M}{m_A} \varepsilon G^{0\nu} \right)^{1/2}$$

- Comparison with 100 kg of ^{76}Ge :

$$FOM(^{76}Ge, 100kg) \simeq 16(A.U.)$$

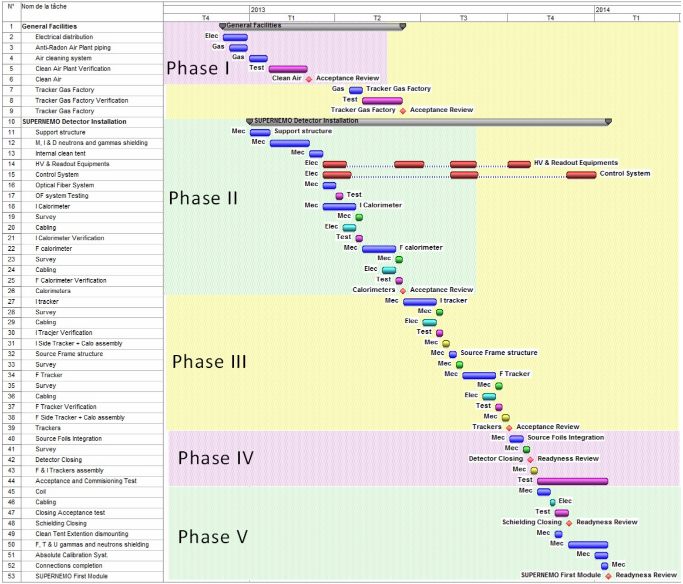
Isotope	$G^{0\nu}$ (A.U.)	ε	Mass (kg)
^{76}Ge	0.24	0.8 (calo)	100
^{130}Te	1.7	0.8 (calo)	25
^{82}Se	1.08	0.25 (tracko-calo)	75
^{150}Nd	8.0	0.25 (tracko-calo)	20

From NEMO-3 to SuperNEMO:

Parameter	NEMO-3	SuperNEMO
Isotope	^{100}Mo	^{82}Se or other
Mass (kg)	7	100
Exposure (kg.yr)	31.5	500
Efficiency $\beta\beta0\nu$ (%)	18	$\simeq 30$
Energy resolution at 1 MeV e^-	~ 15	~ 8
^{208}Tl in foil (μBq/kg)	< 20	< 2
^{214}Bi in foil (μBq/kg)	< 300	< 10 (only for ^{82}Se)
^{222}Rn in gas (mBq/m^3)	$\simeq 5$	< 0.2 (only for ^{82}Se)
^{220}Rn in gas (mBq/m^3)	$\simeq 0.15$	< 0.03 (only for ^{82}Se)
Internal background, cts/mass/year	0.5	0.5
$T_{1/2}^{0\nu\beta\beta}$ sensitivity (10^{26} years)	> 0.02	> 1
$< m_\nu >$ sensitivity (meV)	470–960	40–110

Comparison of the main NEMO-3 and SuperNEMO parameters.

The SuperNEMO demonstrator module: milestones



SuperNEMO

- 200 kg ^{150}Nd $\times$ 5 y ($Q_{\beta\beta} = 3.3$ MeV):
  - $T^{0\nu}_{1/2} = 2\ 10^{26}$ y $\rightsquigarrow < N^{0\nu}_{obs} > = 3$
  - $< N^{2\nu}_{obs} > \lesssim 1.0$
  - No E_γ=2.6 MeV (^{208}Tl), no ^{214}Bi, no radon
  - $< m_\nu > <$ 20–50 meV
  - $\simeq$ ^{76}Ge 1-ton experiment
- 50 kg ^{48}Ca $\times$ 5 y ($Q_{\beta\beta} = 4.2$ MeV):
  - $T^{0\nu}_{1/2} = 1.9\ 10^{26}$ y $\rightsquigarrow < N^{0\nu}_{obs} > \simeq 1$
  - $< N^{2\nu}_{obs} > \lesssim 1.0$
  - No ^{208}Tl, ^{214}Bi, no radon
  - $< m_\nu > <$ 30–50 meV
- R&D for enrichement...