Searching for the neutrinoless double beta decay with the SuperNEMO experiment : Developments of reconstruction algorithms and analysis tools

Steven Calvez JRJC 15, 11/16/15

2nd year PhD in LAL (Orsay) - Supervisor Xavier GARRIDO ✎ calvez@lal.in2p3.fr

Outline

- Neutrinoless double beta decay
- The SuperNEMO experiment
- Sensitivity studies
- γ reconstruction algorithms
- Future work

Brief reminder

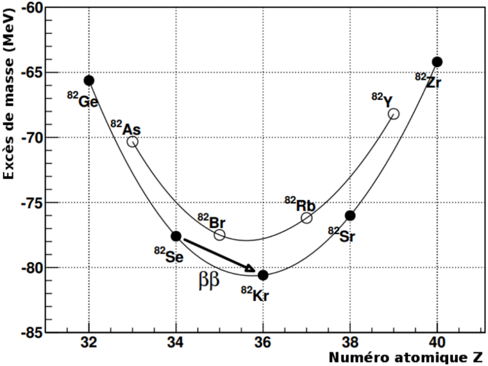
- The neutrino is the only neutral fundamental fermion
- Mass and nature unknown :

$$\textbf{Dirac particle} \Leftrightarrow \nu \neq \overline{\nu}$$
$$\textbf{Majorana particle} \Leftrightarrow \nu \equiv \overline{\nu}$$

- If neutrinos are Majorana particles :
  - Lepton number violation
  - See-Saw mechanism (small neutrino masses)
  - Leptogenesis (matter/antimatter asymmetry)
- Best known experimental way :
  search for the neutrinoless double beta decay

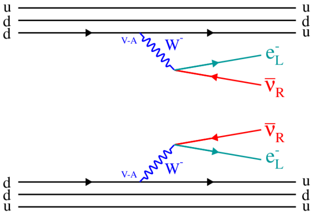
Double beta decay

- Radioactive decay naturally occuring in a few even-even nuclei where the single beta decay is energetically impossible (^{48}Ca,^{76}Ge,^{82}Se,^{96}Zr,^{100}Mo,^{116}Cd,^{130}Te,^{136}Xe,^{150}Nd, ...)



Double beta decay

$2\nu2\beta$



- Allowed in the Standard Model and already observed
- Second order process :

$$T_{1/2}^{2\nu2\beta} \sim 10^{18} - 10^{21} \text{ years}$$

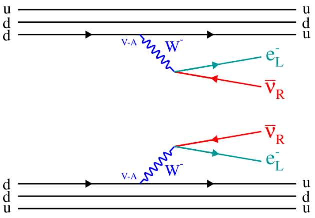
$0\nu2\beta$

- Forbidden by the Standard Model
- Only if Majorana neutrinos

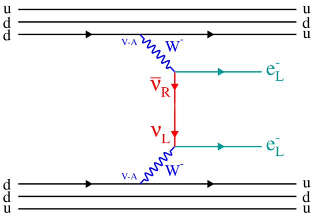
$$T_{1/2}^{0\nu2\beta} > 10^{24} - 10^{25} \text{ years}$$

Double beta decay

$2\nu 2\beta$



$0\nu 2\beta$



- Allowed in the Standard Model and already observed
- Second order process :

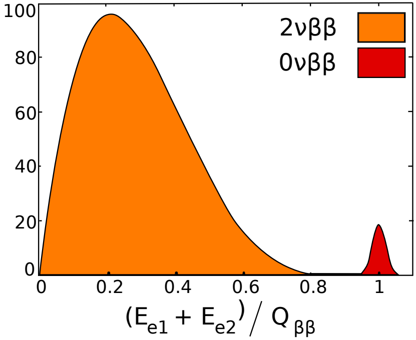
$$T_{1/2}^{2\nu 2\beta} \sim 10^{18} \text{ - } 10^{21} \text{ years}$$

- Forbidden by the Standard Model
- Only if Majorana neutrinos

$$T_{1/2}^{0\nu 2\beta} > 10^{24} \text{ - } 10^{25} \text{ years}$$

Double beta decay : Experimental signature

- Two different energy spectra

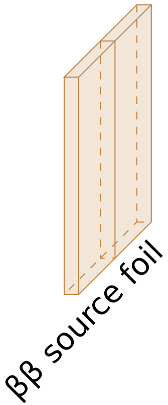


- $2\nu2\beta$: continuous β-like spectrum, the neutrinos escape the detection
- $0\nu2\beta$: peak at the transition energy $Q_{\beta\beta}$, all the energy is carried by the two electrons

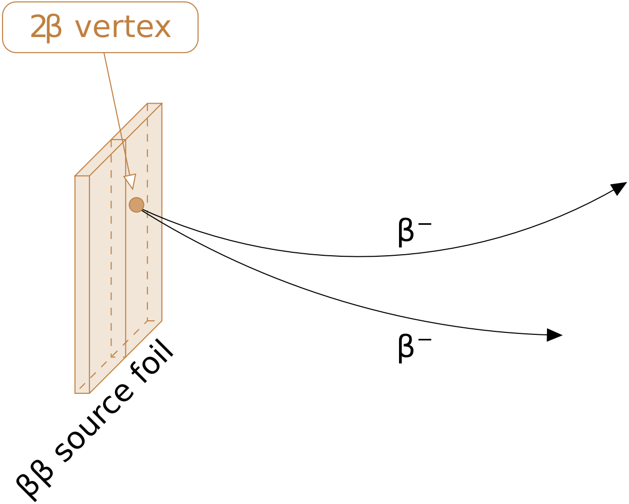
The SuperNEMO experiment

- Neutrinoless double beta decay
- The SuperNEMO experiment
- Sensitivity studies
- γ reconstruction algorithms
- Future

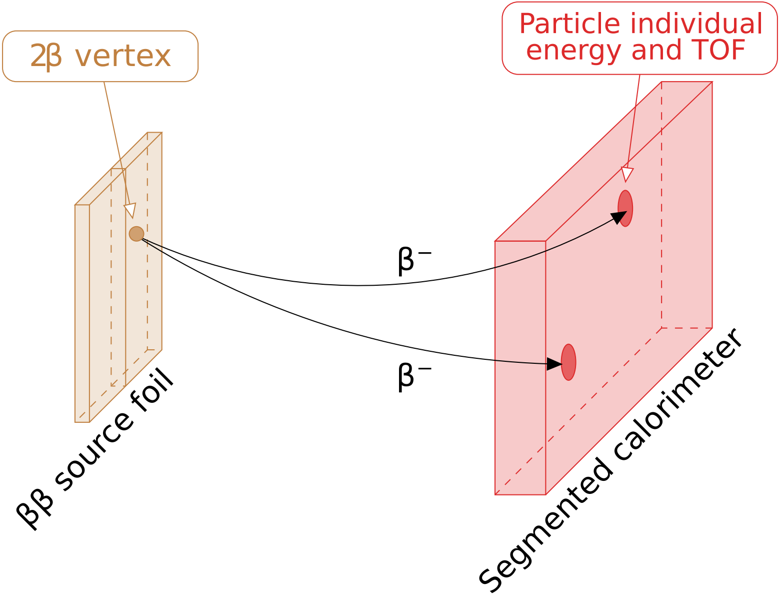
NEMO experimental principle



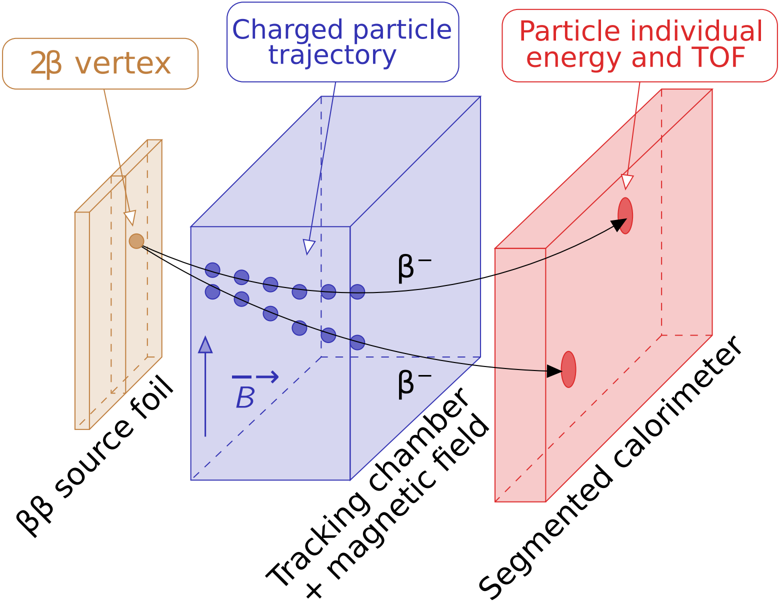
NEMO experimental principle



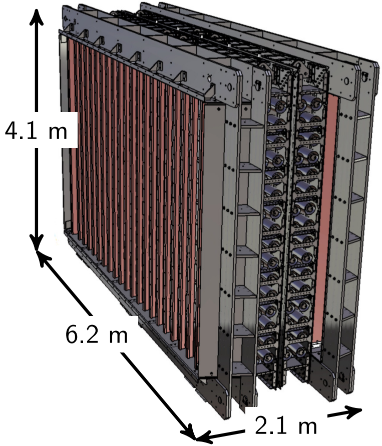
NEMO experimental principle



NEMO experimental principle



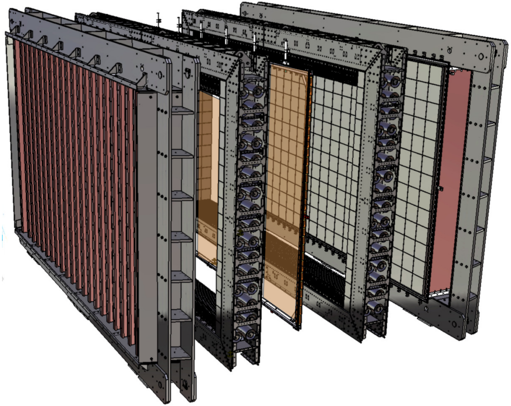
The SuperNEMO experiment



x 20 = SuperNEMO

Located in Modane (LSM)
under 4200 m.w.e.

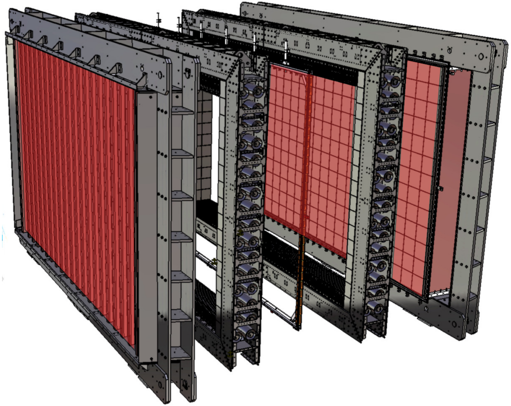
SuperNEMO demonstrator



$\beta\beta$ source foil :

7 kg of ^{82}Se (d = 53 mg/cm^2)

SuperNEMO demonstrator



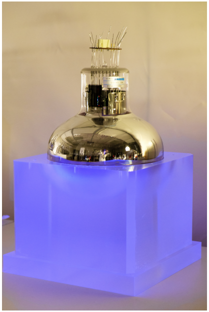
ββ source foil :

7 kg of ^{82}Se (d = 53 mg/cm^2)

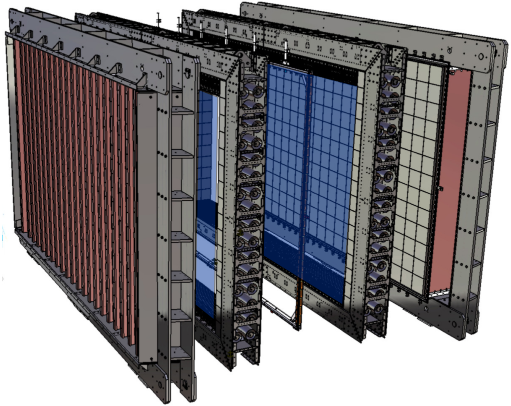
Calorimeter :

520 x 8" PM + 192 x 5" PM

coupled to polystyrene scintillators



SuperNEMO demonstrator



$\beta\beta$ source foil :

7 kg of ^{82}Se (d = 53 mg/cm^2)

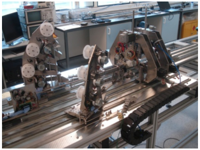
Calorimeter :

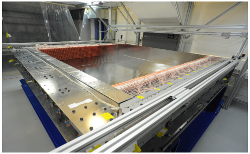
520 x 8" PM + 192 x 5" PM

coupled to polystyrene scintillators

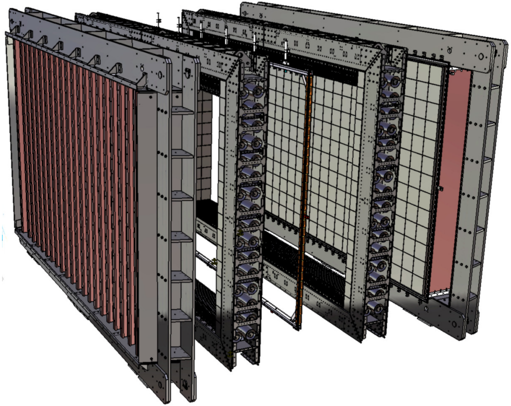
Tracking chamber :

2034 wires in Geiger regime





SuperNEMO demonstrator



$\beta\beta$ source foil :

7 kg of ^{82}Se (d = 53 mg/cm^2)

Calorimeter :

520 x 8" PM + 192 x 5" PM

coupled to polystyrene scintillators

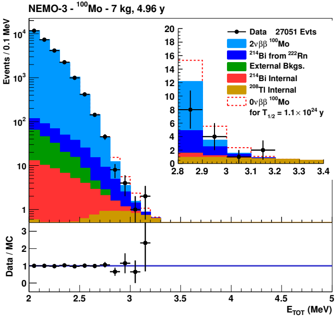
Tracking chamber :

2034 wires in Geiger regime

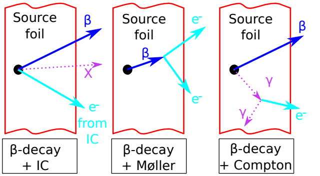
→ **Commissioning and data taking by the end of 2016**

Experimental challenges

- Find a peak at the end of the 2ν2β spectrum
- 2ν2β irreducible background → improve energy resolution
- High $Q_{\beta\beta}$ isotope to rise above natural radioactivity
- Radiopure source and materials

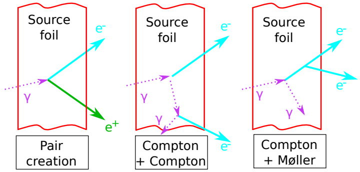


Internal (source contamination,
Radon on source surface, ...)



● = radioisotope; β = electron from β-decay; IC = internal conversion

External (PMT glass, ...)



Comparison NEMO3 SuperNEMO

	NEMO3	SuperNEMO
Mass	7 kg	100 kg
Isotopes	^{100}Mo	^{82}Se,
	7 isotopes	^{150}Nd
Energy resolution @3MeV		
FWHM - σ	8 % - 3.4 %	4 % - 1.7 %
Source contaminations		
A(^{208}Tl)	$\sim$ 100 μBq/kg	$\leq$ 2 μBq/kg
A(^{214}Bi)	$\sim$ 300 μBq/kg	$\leq$ 10 μBq/kg
Radon in tracker		
A(^{222}Rn)	$\sim$ 5 mBq/m^3	$\leq$ 0.15 mBq/m^3
0ν efficiency	18 %	30 %
Exposure	35 kg.y	500 kg.y
Sensitivity		
$T_{1/2}^{0\nu2\beta}$ (90% C.L.)	$>$ 1.1 10 ^{24}	$>$ 1 10 ^{26}
$\langle m_{\beta\beta} \rangle$	$<$ 0.33 - 0.87 eV	$<$ 0.04 - 0.1 eV

Sensitivity : $T_{1/2}^{0\nu2\beta} \propto \begin{cases} \epsilon mt & \text{without background.} \\ \epsilon\sqrt{\frac{mt}{b\Delta E}} & \text{with background.} \end{cases}$

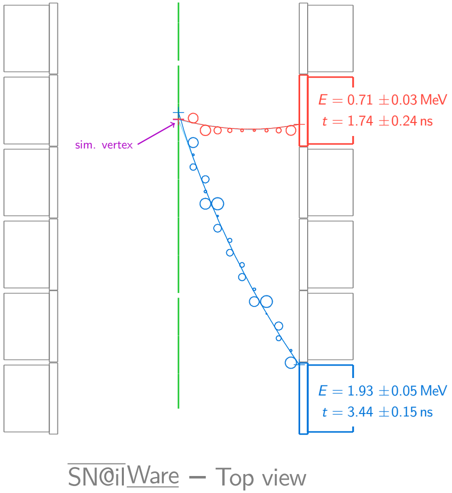
$(T_{1/2}^{0\nu2\beta})^{-1} = G^{0\nu}\ |M_{0\nu}|^2\ \langle\ m_{\beta\beta}\rangle^2$ (for Mass Mechanism)

Sensitivity studies

- Neutrinoless double beta decay
- The SuperNEMO experiment
- Sensitivity studies
- γ reconstruction algorithms
- Future

Events simulation

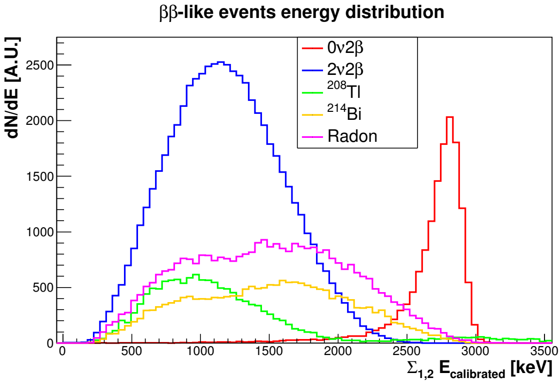
- Use SN@ilWare software developped by and for the SuperNEMO collaboration : relies on GEANT4 and Genbb (event generator).



- Visualization of a $0\nu2\beta$ event from the source foil

Example of $0\nu 2\beta$ event

- Simulate and select $\beta\beta$-like events :
  - 0ν : signal
  - 2ν : irreducible background
  - ^{208}Tl and ^{214}Bi : source contamination
  - Radon : gas in tracker



- $Q_{\beta\beta}(^{82}Se) = 2.996$ Mev
- $Q_{\beta}(^{214}Bi) = 3.272$ Mev
- $Q_{\beta}(^{208}Tl) = 5.001$ Mev

$\beta\beta$-event selection

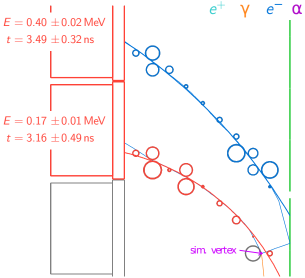
- Applying the right cuts to keep only 2 electrons events (and no γ's or α's)

	$0\nu2\beta$	$2\nu2\beta$	^{208}Tl	^{214}Bi	Radon (wire)
2 electrons	29 %	11.6 %	0.14 %	0.18 %	0.033 %
$E \geq 2$ MeV	27 %	0.3 %	$1.26\ 10^{-2}$ %	$4.07\ 10^{-2}$ %	$7.45\ 10^{-3}$ %

$\rightarrow$ Topological informations allow the identification of some background events mimicking a $\beta\beta$ decay and provide a powerful background rejection

Vertices distance cuts

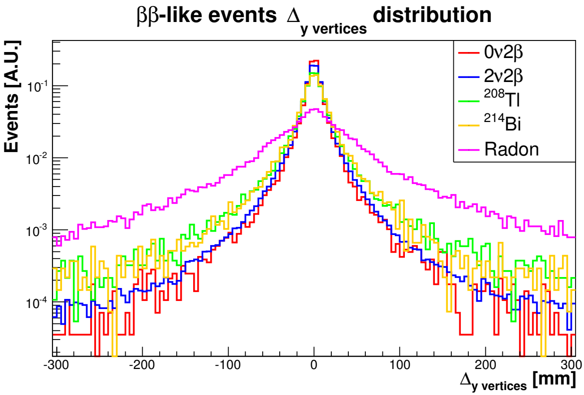
- The Radon deposits on the wires and decays to a ^{214}Bi nucleus which then emits 2 electrons according to one of the previous process :



SN@ilWare – Top view

→ Can be removed by requiring the two electrons tracks to originate from the same vertex

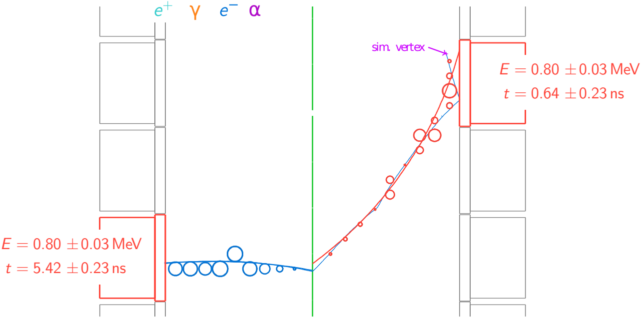
Vertices distance cuts



→ Remove ∼ 50 % of the radon while keeping 95 % of the signal.

Time-of-Flight cut

- One electron scatters inside the detector



SN@ilWare – Top view

→ Can be removed by requiring the two electrons tracks to have a good internal probability *i.e.* to be compatible in time

Time-of-Flight cut

TOF and internal probability

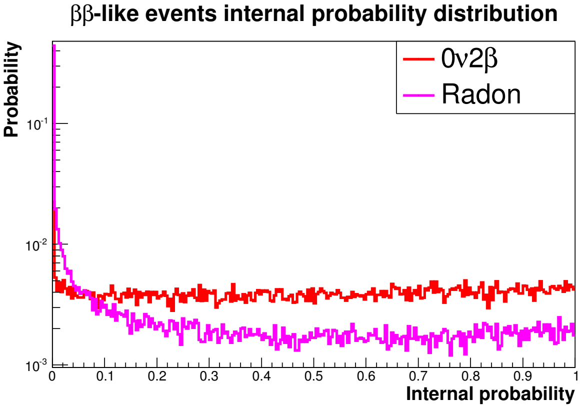
$$\chi^2_{int} = \frac{\left((t_2^{exp} - t_1^{exp}) - (\frac{l_2}{\beta_2 c} - \frac{l_1}{\beta_1 c})\right)^2}{\sigma^2_{t_1} + \sigma^2_{t_2}}$$

$$\sigma^2_{t_i} = (\frac{\partial t_{int}}{\partial t_i^{meas}})^2 \sigma^2_{t_i^{meas}} + (\frac{\partial t_{int}}{\partial E_i})^2 \sigma^2_{E_i}$$

with $\sigma_{t_i^{meas}} = 400$ ps and energy FWHM = 8 % (at 1 MeV). For two electrons, the track length uncertainty is negligeable.
Then,

$$P(\chi^2_{int}) = 1 - \frac{1}{\sqrt{2\pi}} \int_0^{\chi^2_{int}} x^{-\frac{1}{2}} e^{-\frac{x}{2}} dx$$

Time-of-Flight cut



→ Requiring the internal probability to be > 1 % removes ~ 50 % of the Radon events.

Cuts combined

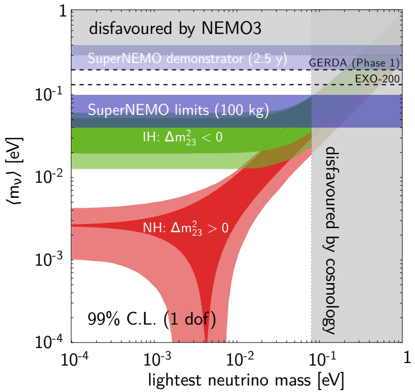
- These topological cuts combined provide a rejection of almost 80% of the radon events while keeping more than 93 % of the signal.

$(E \geq 2$ MeV$)$	$0\nu2\beta$	$2\nu2\beta$	^{208}Tl	^{214}Bi	Radon
2β selection	27 %	0.3 %	1.26 10^{-2} %	4.07 10^{-2} %	7.45 10^{-3} %
TOF & Δ_y & Δ_z	25.2 %	0.28 %	0.93 10^{-2} %	3.60 10^{-2} %	1.53 10^{-3} %

- Topological cuts are less efficient on the source contamination : ultra-radiopure foil ($A(^{208}$Tl$) \leq$ 2 μBq/kg, $A(^{214}$Bi$) \leq$ 10 μBq/kg).

Demonstrator performance

- Should reach the NEMO3 sensitivity in less than a year.
- Less than one background count in total in the energy region of interest in the demonstrator.
- Demonstrator with 17.5 kg.y should reach $\langle m_{\beta\beta} \rangle < 0.2$ - 0.4 eV

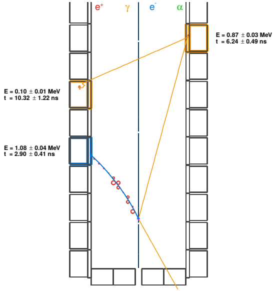


γ reconstruction algorithms

- Neutrinoless double beta decay
- The SuperNEMO experiment
- Sensitivity studies
- γ reconstruction algorithms
- Future

SuperNEMO events topology

- The NEMO experiments are able to look for $0\nu2\beta$ and to measure the backgrounds thanks to a variety of event topology : $1e^-$, $2e^-$, $1e^-1e^+$, $1e^-1\alpha$, $1eN\gamma$, $2eN\gamma$...

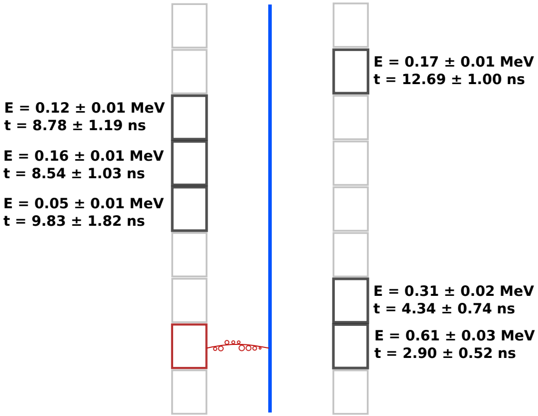


→ Look for ^{208}Tl and ^{214}Bi events in the $1eN\gamma$ channels

- The γ reconstruction is important for :
  - background identification
  - study of double beta decay towards the excited states of the daughter nucleus.

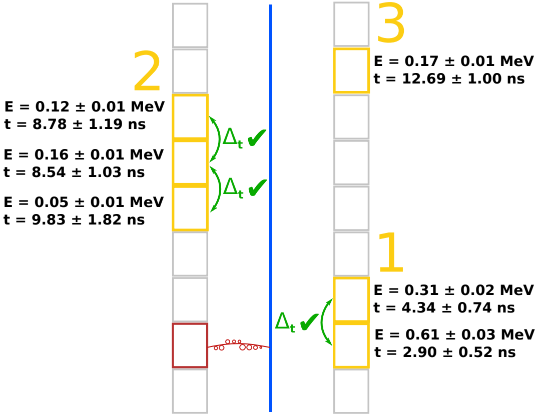
γ-tracko-clustering principle

I. Unassociated calorimeter hits



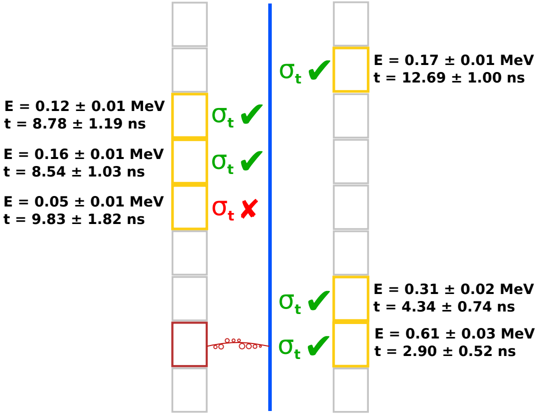
γ-tracko-clustering principle

II. Clustering :
3 clusters with Δ_t < 2.5 ns



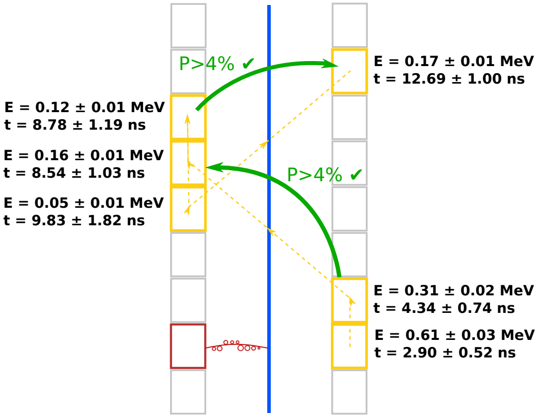
γ-tracko-clustering principle

III. Tracking :
1 hit will not be used (σ_t>1.5 ns)



γ-tracko-clustering principle

IV. Tracking :
linking clusters with P>4%



Performance results

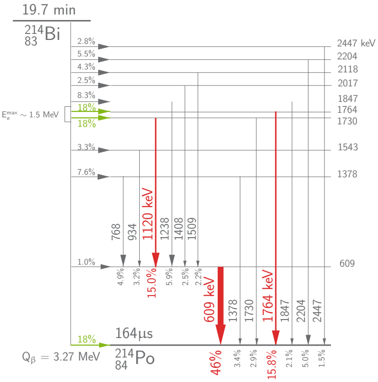
- ϵ_{rec} : the fraction of the decays (with more than one γ detected) correctly reconstructed

	ϵ_{rec}		
	γ-clustering	γ-tracking	γ-tracko-clustering
^{208}Tl	56 %	61 %	65 %
^{214}Bi	63 %	72 %	75 %

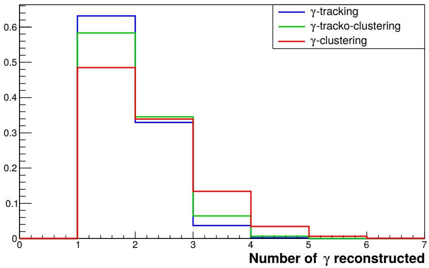
→ The γ-tracko-clustering provides a better reconstruction fidelity.

Number of γ's reconstructed in ^{214}Bi

- Between 0 and 2 γ's emitted : γ-clustering overestimates the number of γ's

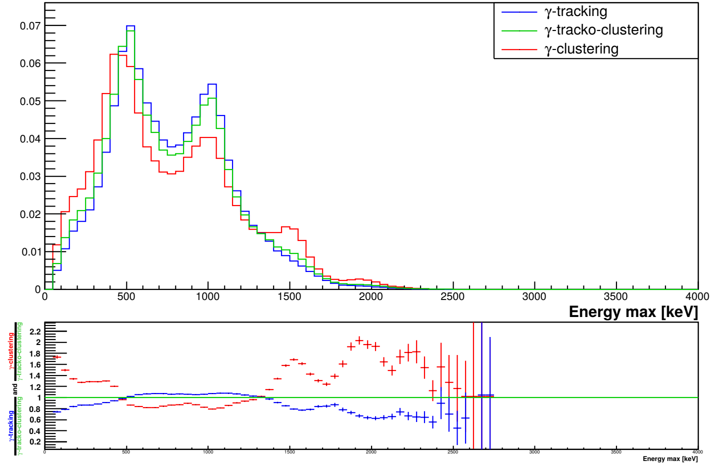


Number of γ's reconstructed



Example of ^{214}Bi : spectra comparison

- **Highest enery γ spectrum in the ^{214}Bi 1e2γ channel** :
  the γ-clustering splits γ's



Future work

- Software developments :
  - Development of the end of the reconstruction chain : topology identification and relevant topological informations measurement algorithms.
  - Analysis pipeline : channel classification based on the topological informations then automated plot generation.
  - Build the background model : generate huge Monte-Carlo sets and evaluate the sensitivity for background measurement
  - Use BDT or other machine learning to optimize analysis
- Demonstrator :
  - Carry on the demonstrator integration in Modane
  - Commissioning
  - First SuperNEMO data analysis

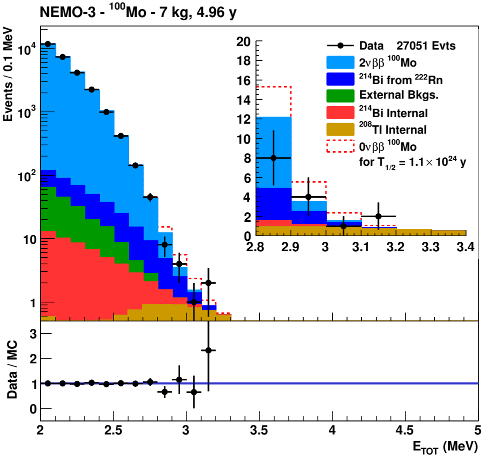
The end

Thank you for your attention !

BACKUP

NEMO-3 results

NEMO3 results for the $0\nu2\beta$ search in ^{100}Mo (*Phys. Rev. D 92, 072011*):

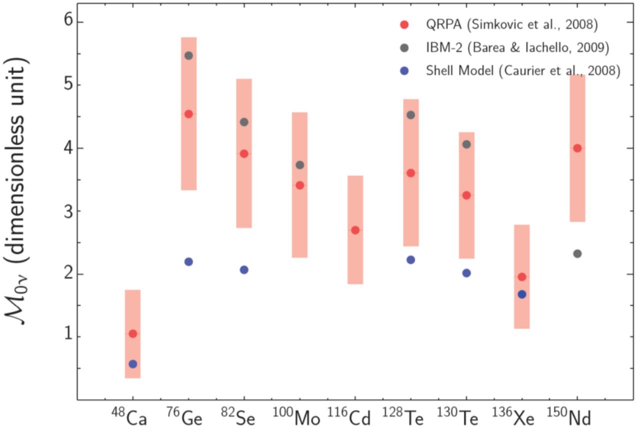


Isotope choice

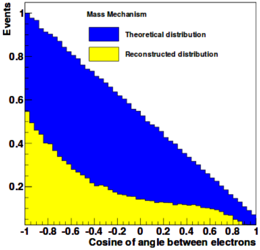
$$(T_{1/2}^{0\nu2\beta})^{-1} = G^{0\nu}\ |M_{0\nu}|^2\ \langle\ m_{\beta\beta}\rangle^2\ \text{(for Mass Mechanism)}$$

2β	$Q_{\beta\beta}$ [MeV]	$G_{0\nu}$ $[10^{-14}\ y^{-1}]$	$\mathcal{T}_{1/2}^{2\nu}$ [y]	NA [%]
^{48}Ca	**4.274**	6.35	$4.3\ 10^{19}$	**0.187**
^{76}Ge	**2.039**	**0.62**	$\mathbf{1.3\ 10^{21}}$	7.61
^{82}Se	2.996	2.70	$9.2\ 10^{19}$	8.73
^{96}Zr	**3.348**	5.63	$2.0\ 10^{19}$	2.8
^{100}Mo	3.035	4.36	$\mathbf{7.0\ 10^{18}}$	9.63
^{116}Cd	2.805	4.62	$3.0\ 10^{19}$	7.49
^{130}Te	2.530	4.09	$\mathbf{6.1\ 10^{20}}$	**34.1**
^{136}Xe	2.462	4.31	$\mathbf{2.1\ 10^{21}}$	8.9
^{150}Nd	**3.368**	**19.2**	$7.9\ 10^{18}$	5.6

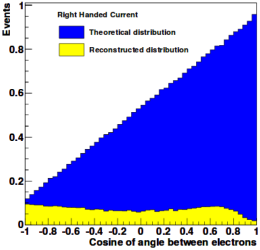
Nuclear matrix elements



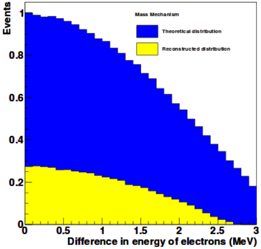
Underlying mechanisms



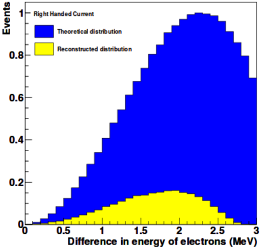
(a)



(b)



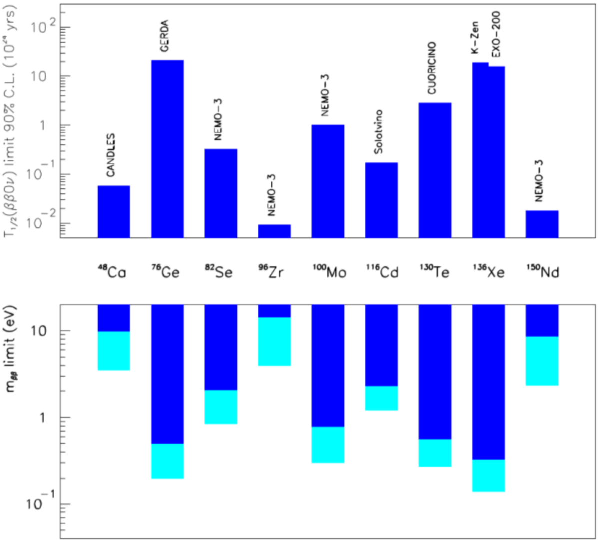
(c)



(d)

Current experiments sensitivities

ββ experiments current sensitivities



Underground laboratory