Searching for $0\nu\beta\beta$ decay with the SuperNEMO demonstrator
A sensitivity study

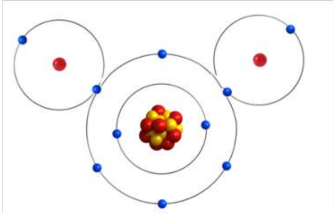
Cloé Girard-Carillo

Laboratoire de l'Accélérateur Linéaire, Orsay

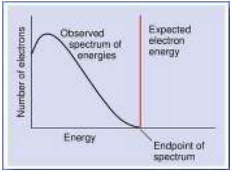
Rencontres des Jeunes Physicie^{n}n^{e}s - 23/11/2018

Neutrons and protons constituants

Daily matter



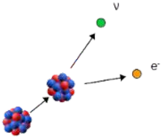
A bit of history



H.Becquerel 1896: Discovery of radioactivity
Only electron observed
→ non conservation of total energy

W.Pauli 1930: Solution to conserve total energy
→ ''Neutrino''

- Neutral
- Spin 1/2
- Small or null mass
- Small interaction probability

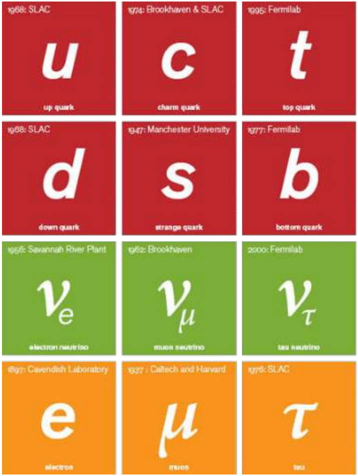


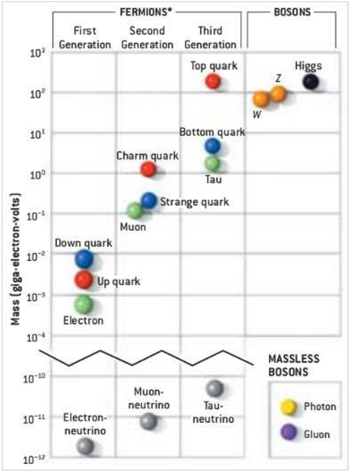
E.Fermi 1934: Effective theory
→ Foundation stone of weak interaction

C.Cowan & F.Reines 1956: Neutrino discovery

The Standard Model of particle physics

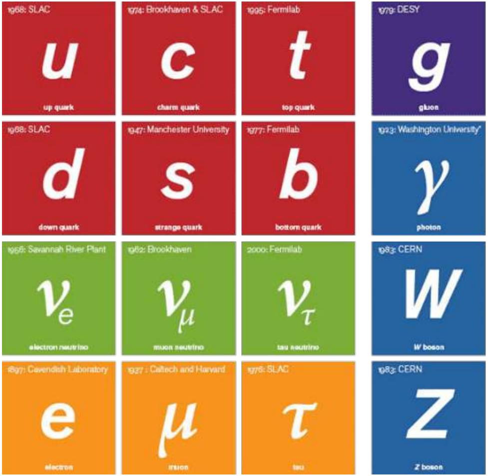
Such different particle masses !



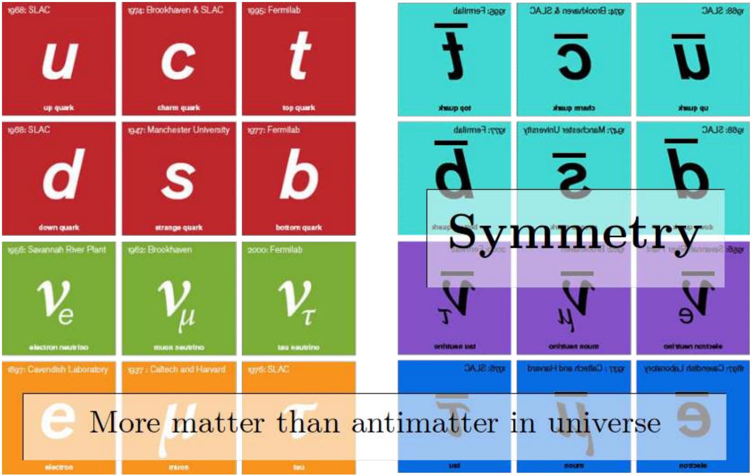


The Standard Model of particle physics

Matter-antimatter asymmetry in the universe



Bosons carry interactions



1968: SLAC
u
up quark
1974: Brookhaven & SLAC
c
charm quark
1995: Fermilab
t
top quark
1968: SLAC
d
down quark
1947: Manchester University
s
strange quark
1977: Fermilab
b
bottom quark
1956: Savannah River Plant
ν_e
electron neutrino
1962: Brookhaven
ν_μ
muon neutrino
2000: Fermilab
ν_τ
tau neutrino
1897: Cavendish Laboratory
e
electron
1937 : Caltech and Harvard
μ
muon
1976: SLAC
τ
tau
Symmetry
More matter than antimatter in universe

The Standard Model of Particle Physics

Neutrino masses are not described by the SM

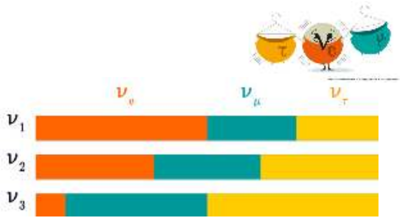
Pontecorvo, 1957 : neutrino oscillations ?

$$\nu_\alpha = U_{\text{PMNS}} \sum_{1,2,3} \nu_i$$

Oscillation probability (2 flavours) :

$$\mathcal{P}_{e\to\mu}(t) = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{2E} L$$

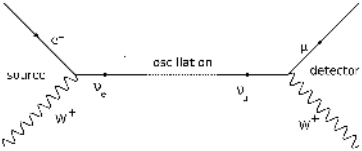
$\longrightarrow$ Possible only if neutrinos are massive particles



SuperKamiokande, 1998

Observation of neutrino oscillations

$\longrightarrow$ Considering three flavours : at least 2 massive neutrinos

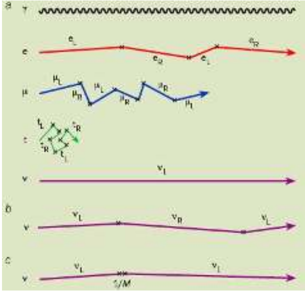


Which mechanism for the mass generation ?

$\longrightarrow$ depends on neutrino nature

Dirac particles : neutrino & antineutrino are distinct particles

$\Rightarrow$ Same mass mechanism as other fermions :
Higgs field coupling with neutrino field
$\mathcal{L}_{\nu}^{\text{Dirac}} = -\frac{v}{\sqrt{2}} \overline{\nu}_L Y^{\nu} \nu_R + \text{h.c.}$



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Beyond the Standard Model

Proof of massive neutrinos lead to extentions of SM

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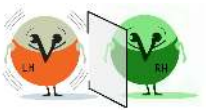
BUT

Weak interaction only talk to LH particles and RH antiparticles **AND** neutrino only interact through weak interaction

$\Rightarrow$ No LH neutrino described by the SM

$\Rightarrow$ Need to extend the SM



Sterile neutrino

Which mechanism for the mass generation ?

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$m_\nu \ll m_l \Rightarrow$ origin of neutrino masses different from those of charged fermions ?

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Majorana particles : The neutrino is its own antiparticle

Majorana mass term in the Lagrangian with no extra particle

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- leads to Lepton Number Violation (LNV) with $\Delta L = 2$ (forbidden in the SM)
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  $\longrightarrow$ could explain smallness of neurino masses

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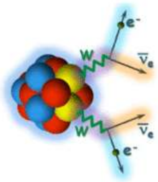
Probe : Neutrinoless double beta decay

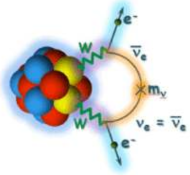
Double beta decay = 2 simultaneous neutron decays inside the nucleus

$2\nu\beta\beta$

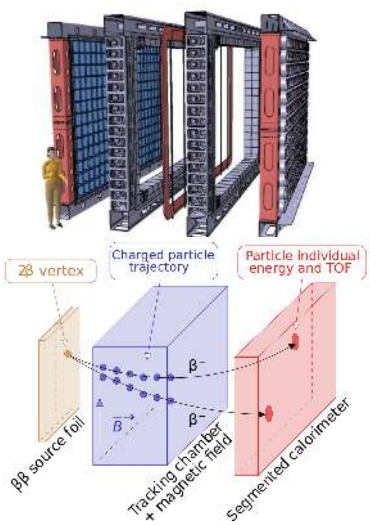


- Allowed in SM
- Has been observed in several isotopes
- $T^{2\nu\beta\beta} \sim 10^{18} - 10^{21}$ years

$0\nu\beta\beta$

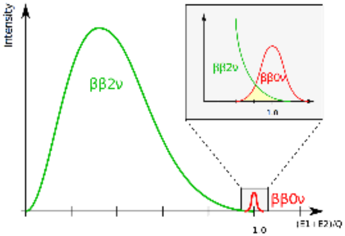


- Forbidden in SM
- Possible only if neutrinos are Majorana partciles
- $T_{1/2}^{0\nu\beta\beta} > 10^{24} - 10^{26}$ years



The SuperNEMO demonstrator :

- Searching for $0\nu\beta\beta$ decay
- Tracker + calorimeter
  $\Rightarrow$ unique experiment : reconstruction of the tracks of the particles AND measurement of the deposited energies
- Magnetic field 25 G



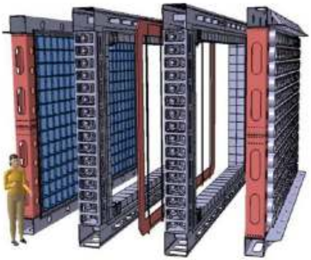
- High $Q_{\beta\beta}$ to reduce natural radioactivity background
  $Q_{\beta\beta} > 2.615$ MeV
- $(T^{0\nu}_{1/2})^{-1} = g_A^4 G^{0\nu} |M^{0\nu}|^2 \left|\frac{m_{\beta\beta}}{m_e}\right|^2$
  High phase space factor $G^{0\nu}$ and matrix elements $M^{0\nu}$ to minimise $0\nu\beta\beta$ half life
- Isotopic abundance
- Highest $T^{2\nu}_{1/2}$ to reduce the $2\nu\beta\beta$ background contribution

...

Isotope	$Q_{\beta\beta}$ (MeV)	$G_{0\nu}$ (10^{-15} y^{-1})	$T^{2\nu}_{1/2}$ (y)	η (%)
^{48}Ca	4.273	24.81	6.37×10^{19}	0.187
^{76}Ge	2.039	2.363	1.926×10^{21}	7.8
^{82}Se	2.995	10.16	9.6×10^{19}	9.2
^{96}Zr	3.350	20.58	2.35×10^{19}	2.8
^{100}Mo	3.035	15.92	6.93×10^{18}	9.6
^{116}Cd	2.809	16.70	2.8×10^{19}	7.6
^{130}Te	2.530	14.22	6.9×10^{20}	34.5
^{136}Xe	2.458	14.58	2.165×10^{21}	8.9
^{150}Nd	3.367	63.03	9.11×10^{18}	5.6

The SuperNEMO demonstrator

Source foils installed ! !



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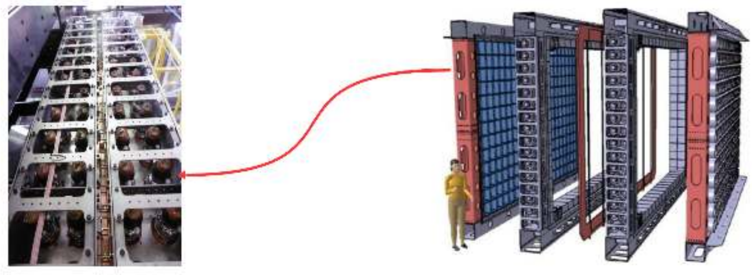

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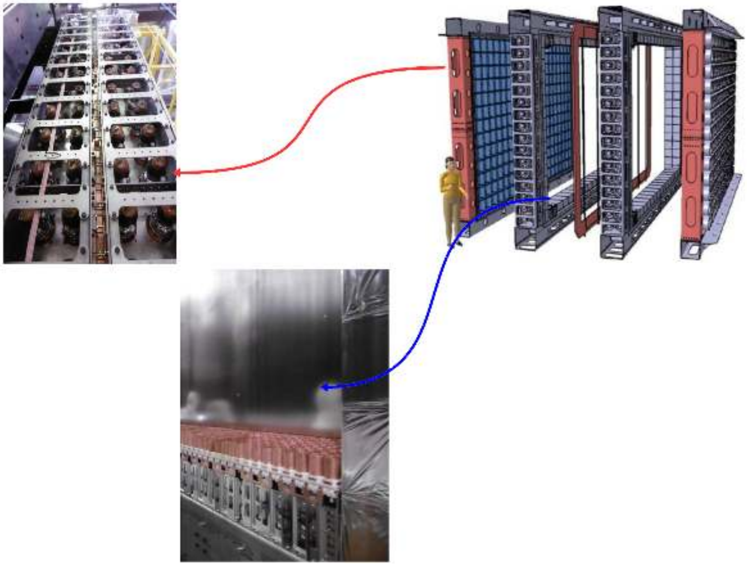

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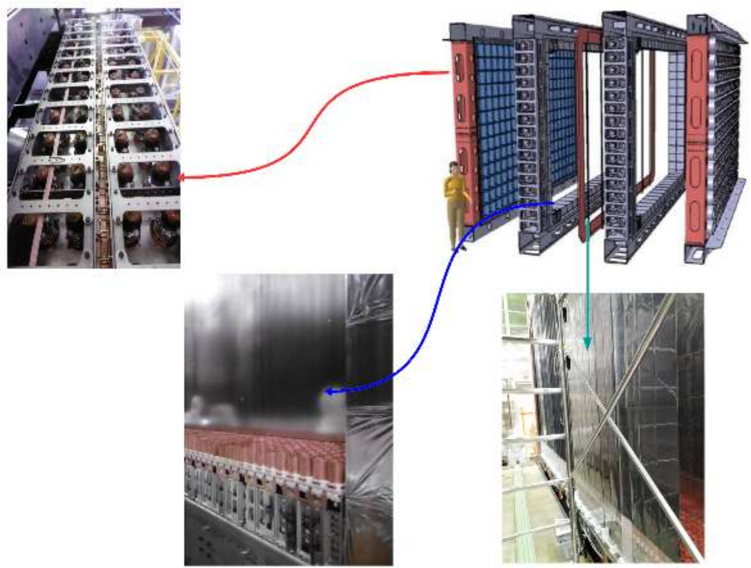

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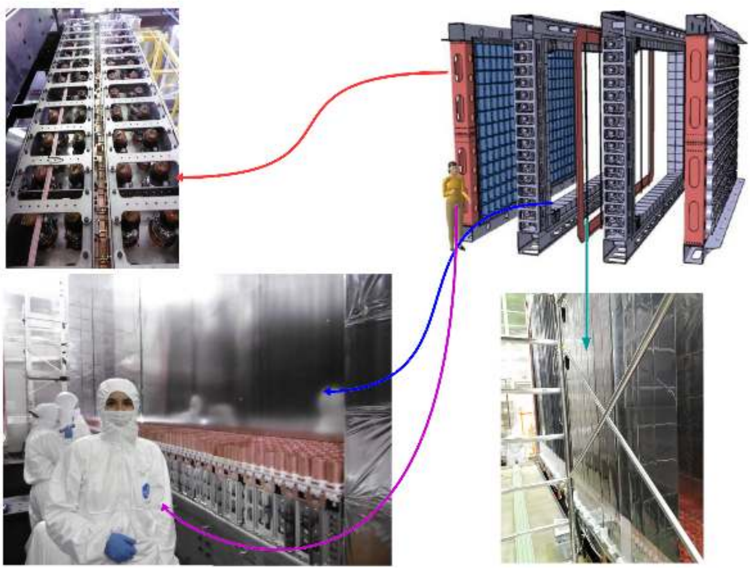
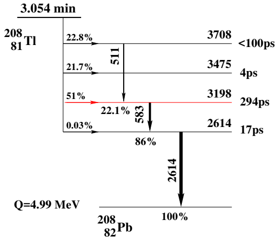
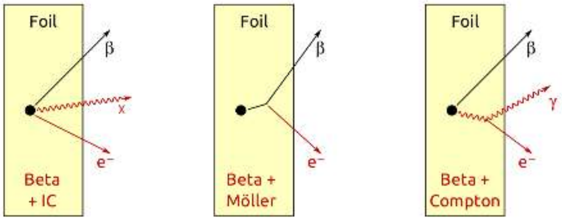


- External γ from natural radioactivity
  - Origin : detector PMs
  - $E_\gamma < 2.6$ MeV
- Internal contamination of Radon in the tracker
- **Internal contamination in the source foils**
  - **^{208}Tl from ^{232}Th decay chain**
  - **^{214}Bi from ^{238}U decay chain**





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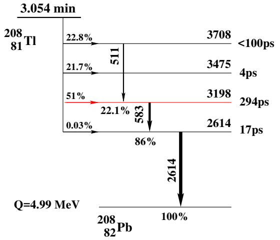

Ultra-low background specifications :

$\mathcal{A}(^{208}\text{Tl})$	$\leq 2\mu$Bq/kg
$\mathcal{A}(^{214}\text{Bi})$	$\leq 10\mu$Bq/kg
$\mathcal{A}(^{222}\text{Rn})$	≤ 0.15 mBq/m^3

Goal

Study the sensitivity of SuperNEMO to the half life of the $0\nu\beta\beta$ decay and influence of internal backgrounds

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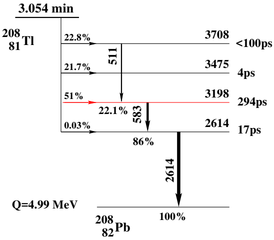

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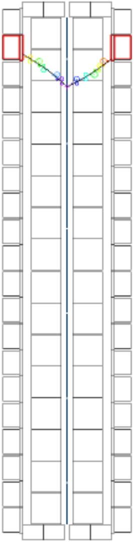
Event simulations & reconstruction with the Falaise software



Event simulation & reconstruction :

- Simulate particles through the detector (GEANT4)
- Record and write informations in an output file
- Reconstruct events (energy and time resolutions, tracker response, ...)

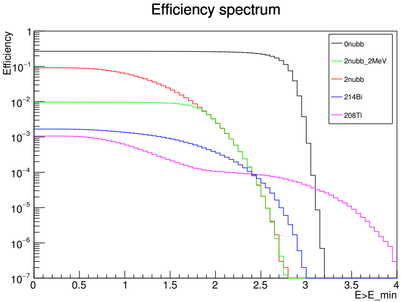
Simulation of internal backgrounds :
$0\nu\beta\beta$, $2\nu\beta\beta$, ^{208}Tl, ^{214}Bi in the source foils

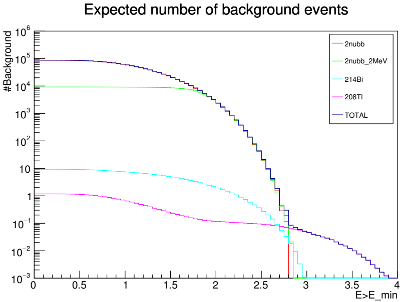
Selection of 2e topologies
1 electron is defined as :

- Vertex on source foil
- 1 calorimeter $+$ 1 tracker trajectory
- 1 negative curve

Sensitivity of SuperNEMO on the half life with E_{inf} and E_{sup}

$$T^{0\nu}_{1/2} > \frac{N_A \ln 2}{W} \times \frac{\epsilon \times M \times T}{N_{exclus}}$$





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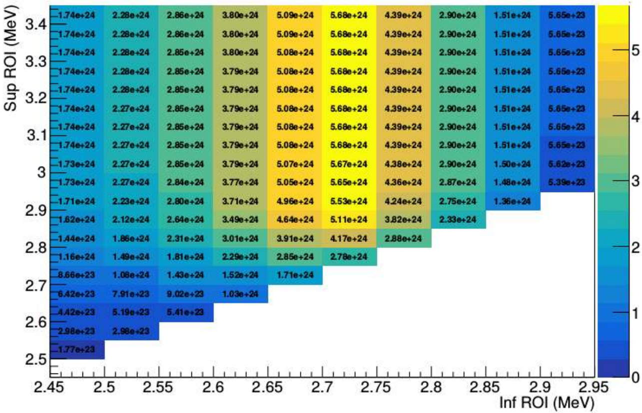
$T^{0\nu}_{1/2}$ depends on $[E_{\text{inf}}, E_{\text{sup}}]$



Conclusion

SuperNEMO in installation at LSM

- Neutrinoless double beta decay is the best known process to probe LNV
- SuperNEMO is a tracko-calorimeter detector searching for $0\nu\beta\beta$
- Source foils installed and tracker closed ! !
- First data early 2019

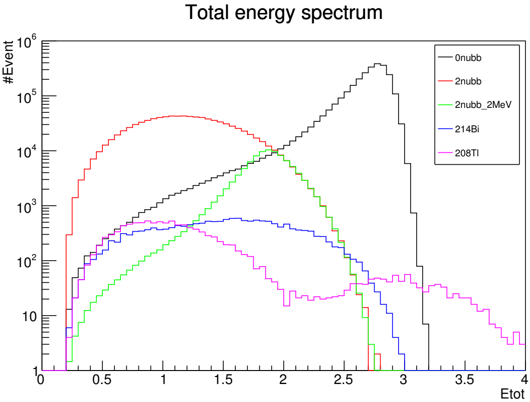
PhD work

- Continue the sensitivity study with 2^{nd} order cuts
- Study influence of external background

Back up

$$T^{0\nu}_{1/2} > \frac{N_A \ln 2}{W} \times \frac{\epsilon \times M \times T}{N_{exclus}}$$

ϵ - selection efficiency of $0\nu\beta\beta$ events
N_{exclus} - number of excluded signal events calculated with $N_{background}$



Selection efficiencies for $0\nu\beta\beta$ and backgrounds :

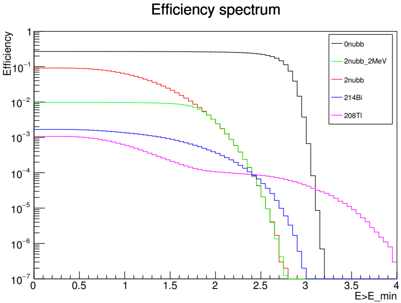
$$\epsilon(E_{\text{inf}}, E_{\text{sup}}) = \frac{1}{N}\int_{E_{\text{inf}}}^{E_{\text{sup}}} \frac{\partial E}{\partial N} dE$$

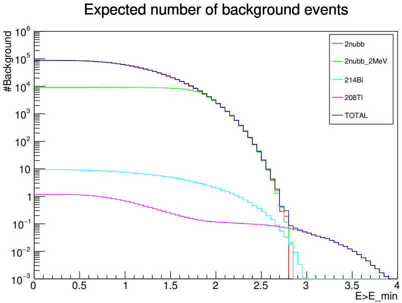
Expected number of background events in the correponding ROI :

$$N_{2\nu} = \frac{N_A \ln 2}{W} \frac{\epsilon_{2\nu} \times M \times T}{T^{2\nu}_{1/2}}$$

$$N_{^{208}\text{Tl}} = A_{^{208}\text{Tl}} \times \epsilon_{^{208}\text{Tl}} \times M \times T$$

$$N_{^{214}\text{Bi}} = A_{^{214}\text{Bi}} \times \epsilon_{^{214}\text{Bi}} \times M \times T$$





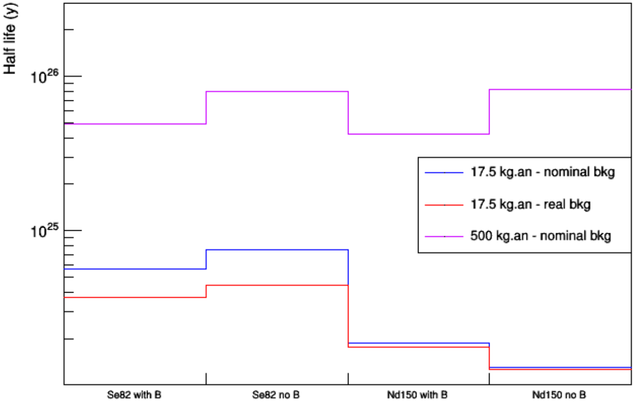
Exposure 17.5 kg.y

Source foils material : ^{82}Se

Background specifications

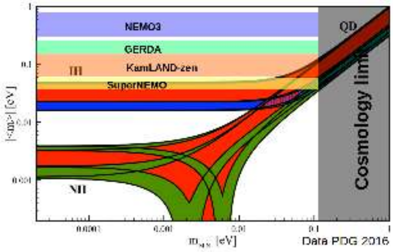
The complete sensitivity study

- Source material : ^{82}Se or ^{150}Nd
- Magnetic field
- Background specifications
- *HyperNEMO* : 500 kg.y



Neutrino effective masses

$$(T^{0\nu}_{1/2})^{-1} = g_A^4 G^{0\nu} |M^{0\nu}|^2 \left| \frac{m_{\beta\beta}}{m_e} \right|^2$$



^{82}Se source foils :

		B = 25 G	B = 0 G
17.5 kg.y	**Nominal background**	[0.23 - 0.46] eV	[0.20 - 0.41] eV
	Measured background	[0.37 - 0.70] eV	[0.28 - 0.52] eV
	No internal background	[0.23 - 0.46] eV	[0.20 - 0.41] eV
500 kg.y	**Nominal background**	[0.08 - 0.16] eV	[0.06 - 0.13] eV

^{150}Nd source foils :

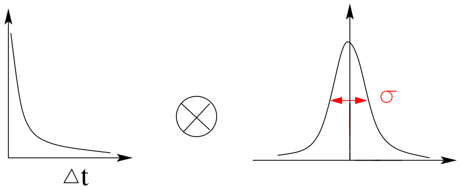
		B = 25 G	B = 0 G
17.5 kg.y	**Nominal background**	[0.15 - 0.50] eV	[0.13 - 0.44] eV
	Measured background	[0.15 - 0.50] eV	[0.20 - 0.65] eV
	No internal background	[0.15 - 0.50] eV	[0.13 - 0.44] eV
500 kg.y	**Nominal background**	[0.046 - 0.15] eV	[0.04 - 0.14] eV

Exponentially modified gaussian

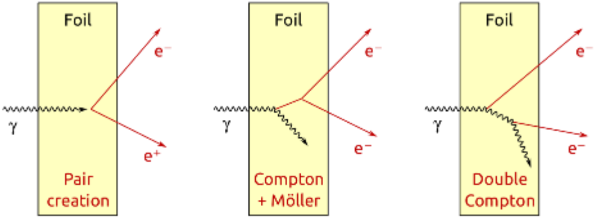
Convolution of an exponential and a gaussian function :

$$f(x,\mu,\sigma) = \frac{\lambda}{2}\exp^{\frac{\lambda}{2}(2\mu+\lambda\sigma^2-2x)}\,\mathrm{erfc}\left(\frac{\mu+\lambda\sigma^2-x}{\sqrt{2}\sigma}\right)$$

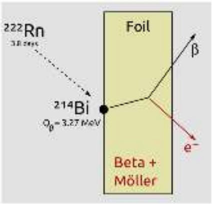
with $\mu = 0, \sigma = \sqrt{\sigma_t^2 + \sigma^2_{(\frac{L}{\beta c})} + \sigma_T^2}$ and $\tau = 294$ps



External gamma background :

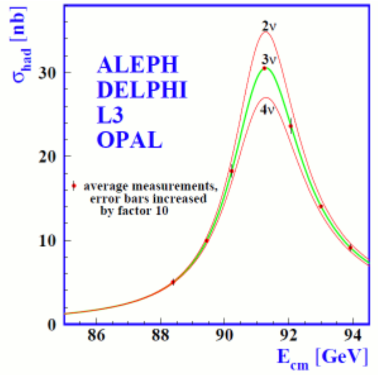


Internal Radon background :



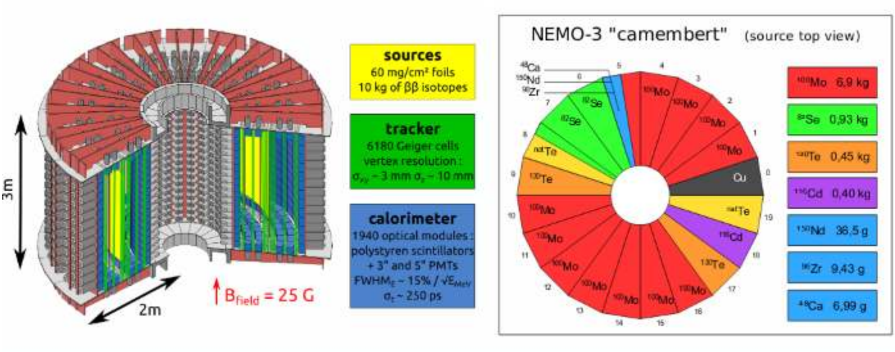
Active light neutrino number with the total Z width

The most precise measurements of the number of light neutrino types come from studies of Z production in e^+e^- collisioners.



$N_\nu = 2,984 \pm 0,012$ light neutrinos

(Pour Laurent : je voudrais mettre ici un tableau comparatif NEMO3/SuperNEMO, est-ce que tu aurais ça quelque part en stock ?)



$0\nu\beta\beta$ sensitivity

Neutrinoless double beta decay sensitivity :

$$\tau_{1/2}^{0\nu\beta\beta} \propto \frac{a\epsilon}{m_{\text{mol}}}\sqrt{\frac{M \times t}{N_{bkg} \times \Delta E}}$$

a - abundance of isotope
ϵ - efficiency of the detector
$M \times t$ - exposure
N_{bkg} - the background rate (counts.keV^{-1}.kg^{-1}.y^{-1})
ΔE - energy resolution

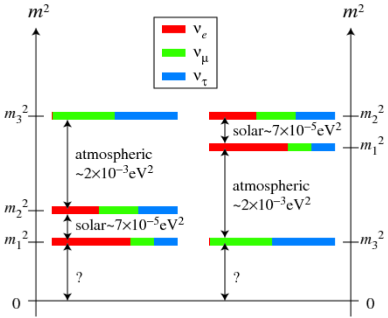
To have a better sensitivity :

- High detection efficiency
- Long period data taking
- Big quantity of isotope
- Low background level

Gas proportions chosen to have the wire chamber functioning at optimal performances

- 95% He : low atomic number $\Rightarrow$ low energy losses for incoming particles (1 MeV electron : 50 keV energy loss)
- 4% ethanol : absorption of UV photons generated by Geiger plasma
- 1% Ar : ionisable $\Rightarrow$ ease the Geiger plasma propagation

Neutrino mass ordering



Majorana mass term

Weinberg operator :

$$\mathcal{L}_W = \frac{1}{2}\frac{g_{eff}v^2}{\mathcal{M}}\bar{\nu}_L^c\nu_L + \text{h.c.}$$

with $m_\nu = \frac{g_{eff}v^2}{\mathcal{M}}$

New physics