Searching for neutrinoless double beta decay with the SuperNEMO demonstrator

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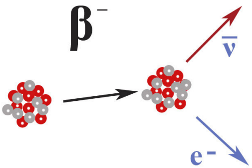
PHENIICS Fest, 28 mai 2018

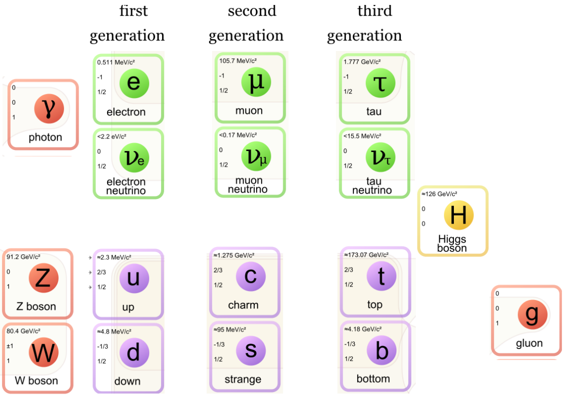


"I have done a terrible thing, I have postulated a particle that cannot be detected."
Pauli, 1930.

- H.Becquerel 1896 : Discovery of radioactivity
  Only electron observed $\rightarrow$ non conservation of total energy
- W.Pauli 1930 : Solution to conserve total energy $\Rightarrow$ "Neutrino"
  - $\rightarrow$ neutral
  - $\rightarrow$ spin $1/2$
  - $\rightarrow$ small or null mass
  - $\rightarrow$ small interaction probability
- E.Fermi 1934 : Effective theory : foundation stone of weak interaction
- C.Cowan & F.Reines 1956 : Neutrino discovery

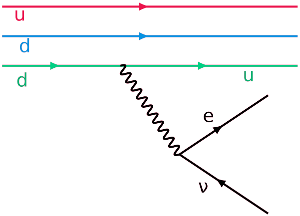
The Standard Model of Particle Physics

Succeeds to describe particles and interactions



Weak interaction

Responsible for quarks and leptons changing flavour $\Rightarrow$ β decay



SM $\longrightarrow$ neutrinos are massless

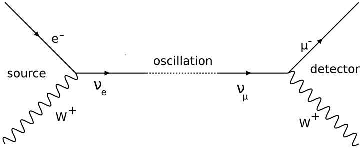
The Standard Model of Particle Physics

Neutrino masses are not described by the SM

Pontecorvo, 1957 : neutrino oscillations ?

Oscillation probability (2 flavours) :

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



- possible only if neutrinos are massive particles

SuperKamiokande, 1998 Observation of neutrino oscillations

- considering three flavours : at least 2 massive neutrinos

Beyond the Standard Model

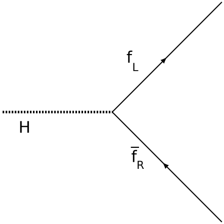
Proof of massive neutrinos lead to extentions of SM

Which mechanism for the mass generation ?

$\rightarrow$ depends on neutrino nature

Dirac particles

Same mass mechanism as other fermions :
Higgs field coupling : $g_{Hf\overline{f}} \propto \frac{m_f}{v}$



Neutrino Dirac mass term in the Lagrangian :

$$\mathcal{L}_l^{mass} = -\frac{v}{\sqrt{2}}\bar{l}_L Y^l l_R + h.c.$$

SM extended with right-handed neutrino

Beyond the Standard Model

Proof of massive neutrinos lead to extentions of SM

Which mechanism for the mass generation ?

$\rightarrow$ depends on neutrino nature

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

Majorana particles : The neutrino is its own antiparticle

Majorana mass term in the Lagrangian with no extra particle

- leads to Lepton Number Violation (LNV) with $\Delta L = 2$ (forbidden in the SM)
  $\rightarrow$ could explain matter/antimatter asymmetry in the universe
- Seesaw mechanisms : heavy ν_R mixes with ν_L and generates light Majorana masses for the observed active neutrinos
  $\rightarrow$ could explain smallness of neurino masses

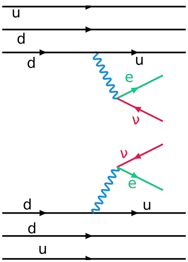
Probe : Neutrinoless double beta decay

Beyond the Standard Model

Probe neutrino nature with neutrinoless double beta decay

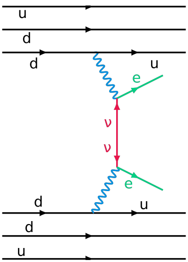
Double beta decay $= 2$ simultaneous neutron decays inside the nucleus

$2\nu\beta\beta$



- Allowed in SM
- Has been observed in several isotopes
- $\tau_{1/2}^{2\nu\beta\beta} \sim 10^{18} - 10^{21}$ years

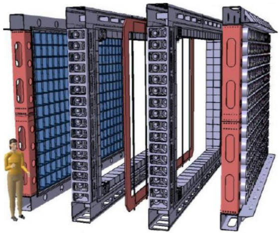
$0\nu\beta\beta$

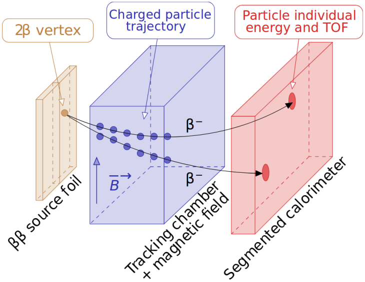


- Forbidden in SM
- Possible only if neutrinos are Majorana partcles
- $\tau_{1/2}^{0\nu\beta\beta} > 10^{24} - 10^{26}$ years

The SuperNEMO experiment

SuperNEMO demonstrator in installation at LSM



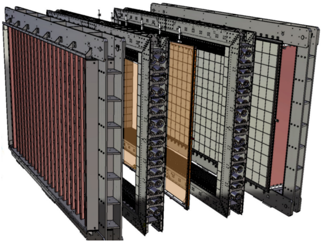


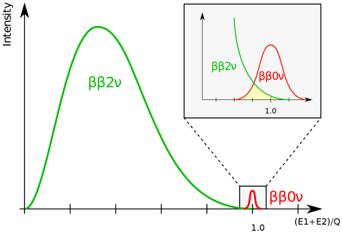
The SuperNEMO demonstrator :

- 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

The SuperNEMO experiment

Selenium source foils



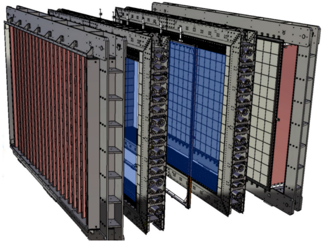


The SuperNEMO demonstrator :

- ^{82}Se source foils : 7 kg
- Released energy $Q_{\beta\beta} = 2.99$ MeV

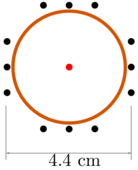
Choice of source material :

- High $Q_{\beta\beta}$ to reduce the contribution of natural radioactivity background
- Find a compromise for the $2\nu\beta\beta$ to not interfere with the $0\nu\beta\beta$ decay



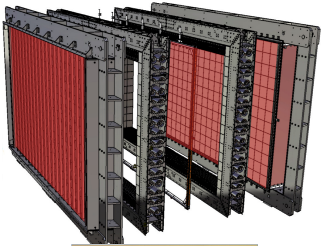
The SuperNEMO demonstrator :

- 2 steel wire chambers on both sides of source foils (14970 wires, 2034 cells)
- Magnetic field 25G
  $\Rightarrow$ particle identification
  $\Rightarrow$ e^+/e^- distinction
- Radial resolution : 0.7 mm
  Vertical resolution : 1 cm
- Gas : 95% He + 4% ethanol + 1% Ar



The SuperNEMO experiment

The calorimeters walls : measuring energies

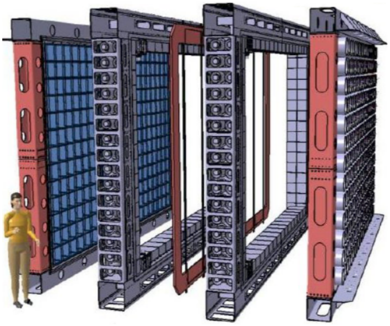


The SuperNEMO demonstrator :

- $520 \times 8"$ PMs $+ 192 \times 5"$ PMs
- Polystyrene scintillators
- Energy resolution : 8% FWHM @1 MeV
- Time resolution : 400 ps @1 MeV

The SuperNEMO experiment

The demonstrator specifications

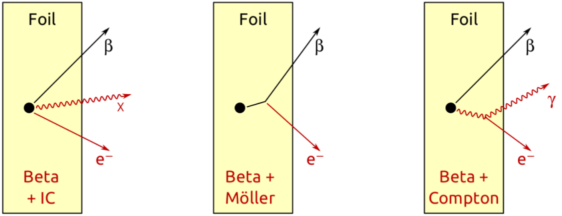


- Expected sensitivity $\tau_{1/2}^{0\nu\beta\beta} > 6.5 \times 10^{24}$ years
- 7 kg of ^{82}Se for 2.5 years taking data $= 17.5$ kg.y exposure

The background for SuperNEMO experiment

Main backgrounds

- External γ from natural radioactivity **Background events for $2\nu\beta\beta$**
  - Origin : detector PMs, laboratory
  - $E_\gamma < 2.6$ MeV
- Internal contamination of Radon in the tracker **Background events for $0\nu\beta\beta$**
- **Internal contamination in the source foils** **Background events for $0\nu\beta\beta$**
  - **^{208}Tl from ^{232}Th decay chain**
  - **^{214}Bi from ^{238}U decay chain**



The background for SuperNEMO experiment

Rejecting backgroung with a time-of-flight criteria

Ultra-low background specifications

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

Goal

Try to improve the internal ^{208}Tl background rejection using a time of flight criteria

Rejecting backgroung with a time-of-flight criteria

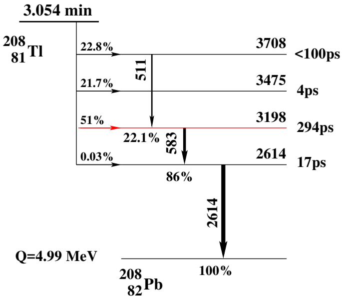
Using IC of 2.615 MeV -γ of ^{208}Tl

Simplified decay chain of ^{208}Tl :

- Significant life-time 294 ps energy level
- Most of the decays pass through this 294 ps level
- ^{208}Tl contributes to $0\nu\beta\beta$

  Most of the time : ^{208}Tl $\rightarrow \beta$ decay $+$ internal conversion of the 2.615 MeV-γ

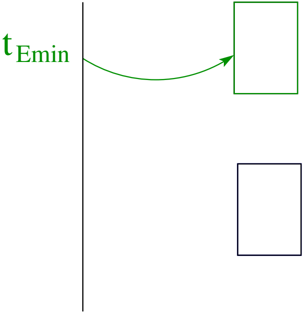
$\Rightarrow$ Two electrons emitted, the one of highest energy is delayed



Delayed electron
$\Rightarrow$ possible rejection of ^{208}Tl background with time of flight

Rejecting backgroung with a time-of-flight criteria

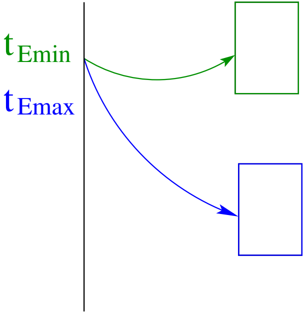
Using IC of 2.615 MeV -γ of ^{208}Tl



- β decay : electron of smallest energy generated at t_{Emin}

Rejecting backgroung with a time-of-flight criteria

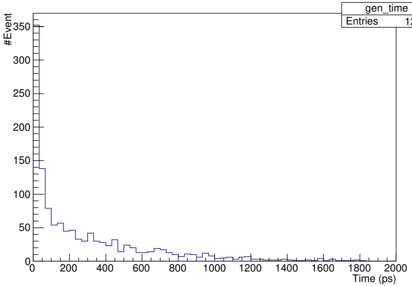
Using IC of 2.615 MeV -γ of ^{208}Tl



- β decay : electron of smallest energy generated at t_{Emin}
- IC : electron of highest energy generated at t_{Emax}

Rejecting backgroung with a time-of-flight criteria

Using IC of 2.615 MeV -γ of ^{208}Tl



- β decay : electron of smallest energy generated at t_{Emin}
- IC : electron of highest energy generated at t_{Emax}
- Simulation of ^{208}Tl events in the source foils : distribution of the difference of the emission times of the electrons *at the source*

$$\Delta t^{gen} = t^{gen}_{Emax} - t^{gen}_{Emin}$$

Delayed IC electron $\Rightarrow$ decreasing exponential $\tau = 294$ ps

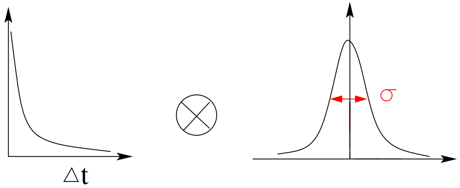
Rejecting backgroung with a time-of-flight criteria

Reconstruct generated times from measured calorimeter times

Reconstruct Δt^{gen} from measured calorimeter times

- Correction from the propagation in the tracker
  $\Delta t^{gen} = (t^{calo} - \frac{L}{\beta c})|_{Emax} - (t^{calo} - \frac{L}{\beta c})|_{Emin}$
- Uncertainties on the time measurement in calorimeters and on the correction : σ_t and $\sigma_{(\frac{L}{\beta c})}$

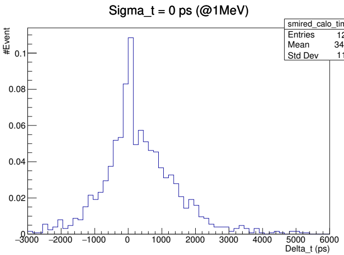
Exponential function ($\tau = 294$ ps) convolued with gaussian function $(\mu = 0, \sigma = \sqrt{\sigma_t^2 + \sigma^2_{(\frac{L}{\beta c})}})$

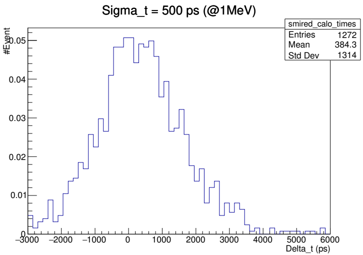


Rejecting backgroung with a time-of-flight criteria

Define the probability to have $\Delta t \geq \Delta t_{event}$

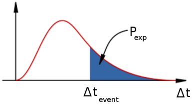
Goal : define a *new* χ^2 to reject internal ^{208}Tl





From exponentially modified gaussian function we define the exponential probability P_{exp} : for each event, we calculate the probability to have

$$\Delta t \geq \Delta t_{event}$$



Conclusion

- Neutrinoless double beta decay is the best known process to probe LNV
- SuperNEMO is a tracko-calorimeter detector searching for $0\nu\beta\beta$
- In installation @Modane underground laboratory, first data early 2019

Outgoings

- Continue this work to reject ^{208}Tl background events
- Study the spacial resolution of SuperNEMO calorimeter
  - Optimise the time determination in calorimeter pulses
  - Estimate precisely the calorimeter time resolution with crossing electrons (data without shielding)

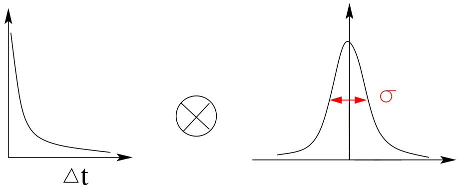
Back up

Exponentially modified gaussian

Convolution of an exponential and a gaussian function :

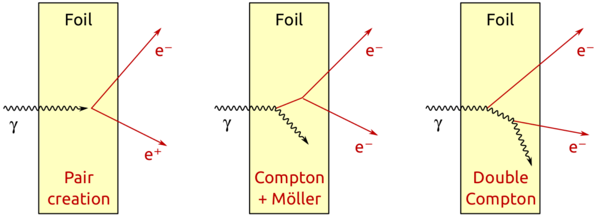
$$f(x,\mu,\sigma) = \frac{\lambda}{2}\exp^{\frac{\lambda}{2}(2\mu+\lambda\sigma^2-2x)}\,\mathrm{erfc}\left(\frac{\mu+\lambda\sigma^2-x}{\sqrt{2}\sigma}\right)$$

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

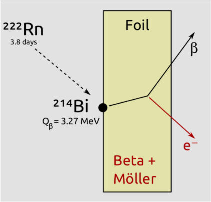


Background scheme for external gammas and Radon

External gamma background :

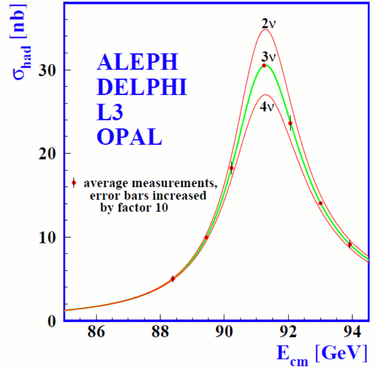


Internal Radon background :



Active light neutrino number with the total Z width

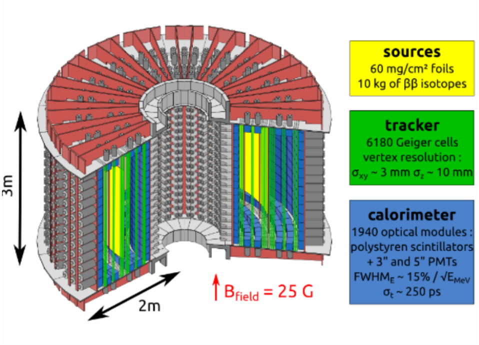
The most precise measurements of the number of light neutrino types come from studies of Z production in e^+e^- collisioners.

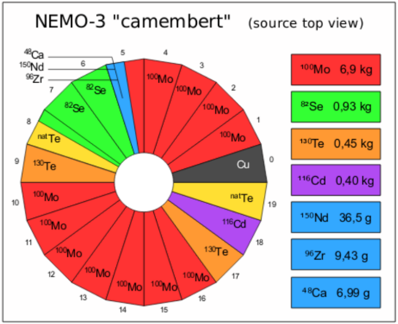


$N_\nu = 2,984 \pm 0,012$ light neutrinos

From NEMO3 to SuperNEMO

(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 :

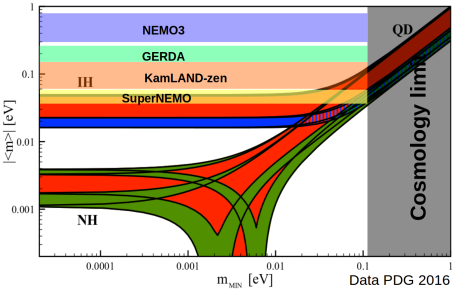
$$\tau_{1/2}^{0\nu\beta\beta} \propto \frac{a\epsilon}{m_{\text{mol}}}\sqrt{\frac{M \times t}{N_{bkg} \times \Delta E}}$$

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

Double beta decay and mass hierarchy



SuperNEMO gas composition

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