

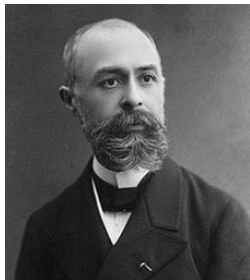
Les expériences NEMO ou la recherche du neutrino de Majorana

Conférence "Entrée en Matière", 30 Octobre 2011

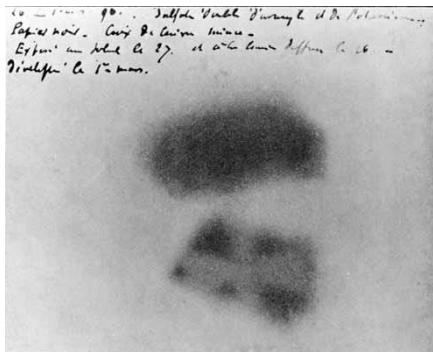
Xavier Garrido

Laboratoire de l'Accélérateur Linéaire, Université Paris Sud, Orsay

Le rayonnement "étrange"



Henri Becquerel 1852 – 1908



1896 : émission naturelle de radiations pénétrantes par l'Uranium

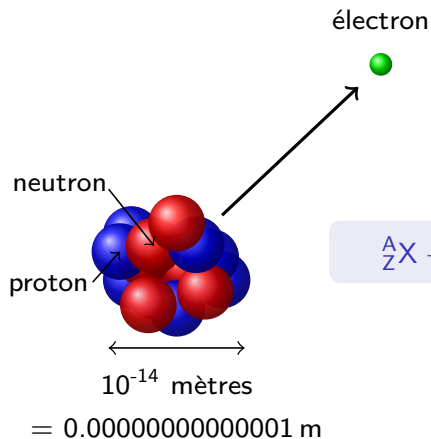
Le rayonnement bêta



Marie Skłodowska 1867 – 1934
Pierre Curie 1859 – 1906

- ▶ Thorium, Polonium et Radium émettent également des rayons U
- Ce rayonnement bêta est la résultante de l'émission d'un électron

La désintégration bêta avant 1930

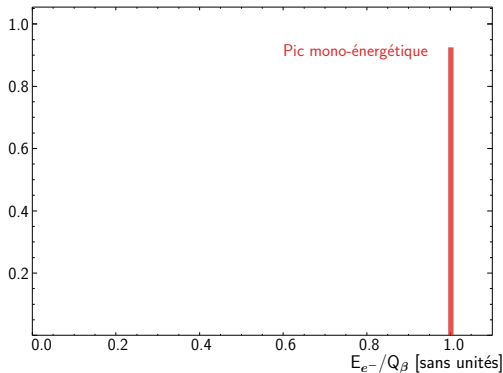


Spectre en énergie de l'électron

1914 : Désintégration $\beta \equiv$ désintégration à 2 corps (noyau lourd + électron)



James Chadwick 1891 – 1974

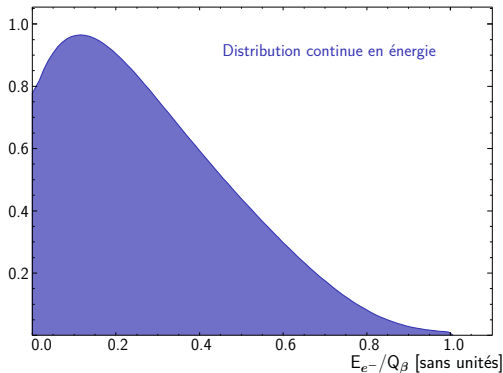


Spectre en énergie de l'électron

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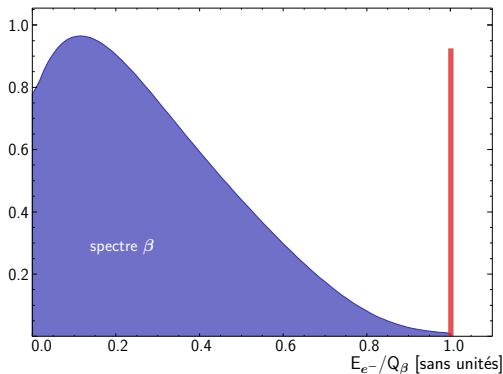
James Chadwick 1891 – 1974



Spectre en énergie de l'électron

1914 – 1930 : crise de l'énergie dans le monde subatomique

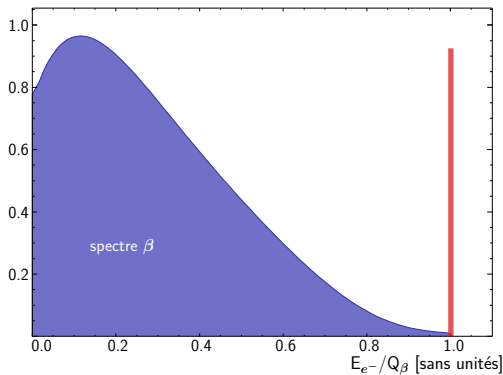
→ conservation de l'énergie ?



Spectre en énergie de l'électron

Explications avancées:

1. plusieurs e^- émis
2. interactions secondaires
3. présence de photon γ



La naissance théorique du neutrino



Wolfgang Pauli 1900 – 1958

1930 : Pauli postule l'existence d'une particule de masse très faible et interagissant très peu

→ naissance théorique du neutrino

La naissance théorique du neutrino

4th December 1930

Dear Radioactive Ladies and Gentlemen,

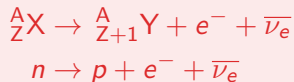
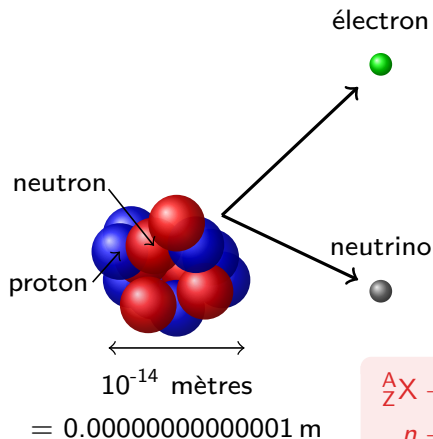
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the “wrong” statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a **desperate remedy to save the “exchange theorem” of statistics and the law of conservation of energy**. Namely, the possibility that there could exist in the nuclei **electrically neutral particles**, that I wish to call **neutrons, which have spin 1/2** and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. **The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...**

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: **“Oh, It’s well better not to think to this at all, like new taxes”**. From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.

Your humble servant

W. Pauli

La désintégration bêta après 1930



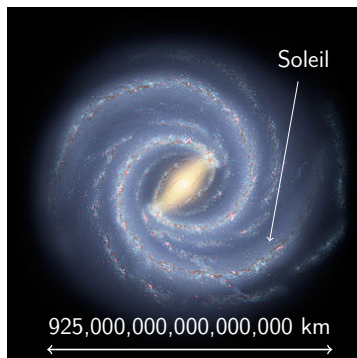
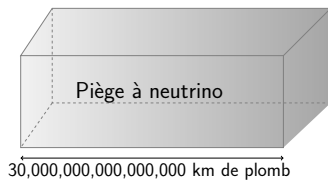
La découverte expérimentale du neutrino



Wolfgang Pauli 1900 – 1958

“I have done something very bad today by proposing a particle that cannot be detected, [. . .] It is something no theorist should ever do.”

La découverte expérimentale du neutrino



La découverte expérimentale du neutrino



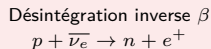
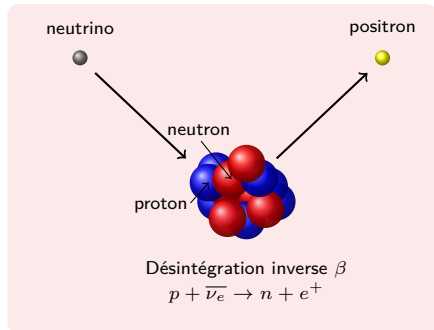
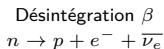
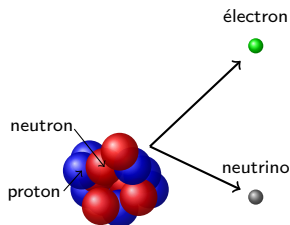
Clyde Cowan 1919 – 1974



Fred Reines 1918 – 1998

La découverte expérimentale du neutrino

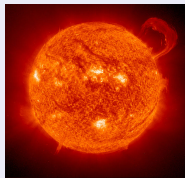
1956 : Expérience de Savannah River



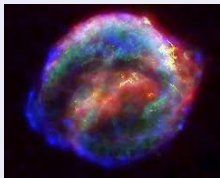
Sources de neutrinos possibles :

- ▶ bombe nucléaire
- ▶ réacteur nucléaire

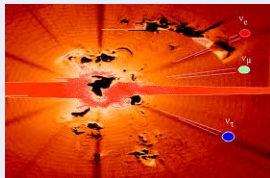
Les sources de neutrino



Fusion au sein du Soleil
64 milliards/cm²/s



Explosion de Supernova
5 milliards/cm²/10s



Big Bang
300 neutrinos/cm³



Réacteur nucléaire
100 000 cm²/s @ 200 km



Corps humain
7000 neutrinos/s



Terre & Atmosphère
6 millions/cm³

Le neutrino & le modèle standard

Quarks



up



down



charm



strange



top



bottom

Leptons



e - neutrino

1956



electron



μ - neutrino

1963



muon



τ - neutrino

2000



tau

matière



\bar{u}



\bar{d}



\bar{c}



\bar{s}



\bar{t}



\bar{b}



$\bar{\nu}_e$

e - neutrino



\bar{e}

electron



$\bar{\nu}_\mu$

μ - neutrino



$\bar{\mu}$

muon



$\bar{\nu}_\tau$

τ - neutrino



$\bar{\tau}$

tau

anti-matière

Le neutrino selon Ettore Majorana



Paul Dirac 1902 – 1984

Paul Dirac propose, aux débuts des années 30, qu'à chaque particule élémentaire correspond une antiparticule de même masse mais de charge opposée

$$\nu \neq \bar{\nu}$$

Les neutrinos étant de charge nulle, Ettore Majorana postule que la notion de matière/antimatière ne s'applique pas aux neutrinos

$$\nu \equiv \bar{\nu}$$



Ettore Majorana 1906 – ?

Le neutrino selon Ettore Majorana

Les neutrinos étant de charge nulle, Ettore Majorana postule que la notion de matière/antimatière ne s'applique pas aux neutrinos

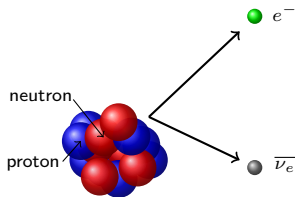
$$\nu \equiv \bar{\nu}$$



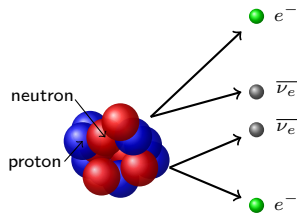
Ettore Majorana 1906 – ?

→ **Expériences NEMO: étudier le neutrino de Majorana : $\nu \equiv \bar{\nu}$?**

La double désintégration bêta

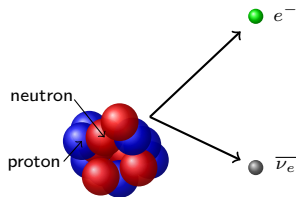


Simple désintégration β
 $n \rightarrow p + e^- + \bar{\nu}_e$

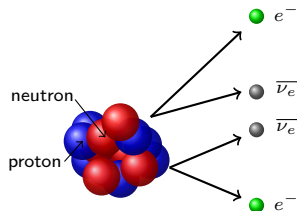


Double désintégration β
 $2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$

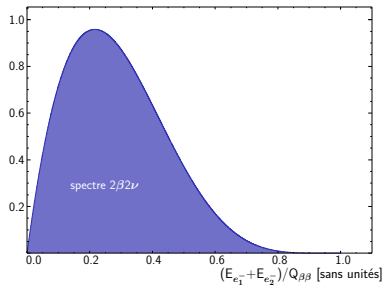
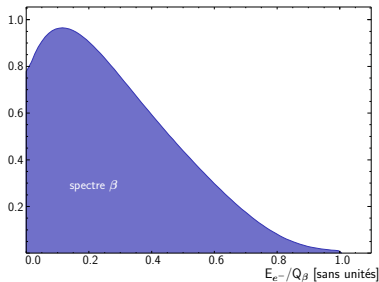
La double désintégration bêta



Simple désintégration β
 $n \rightarrow p + e^- + \bar{\nu}_e$

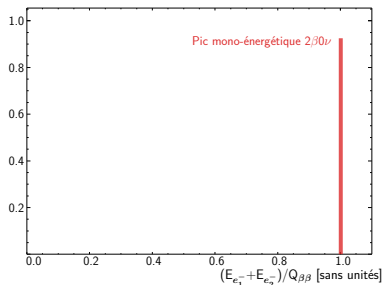
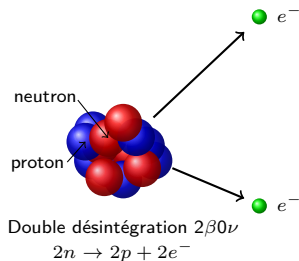


Double désintégration β
 $2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$

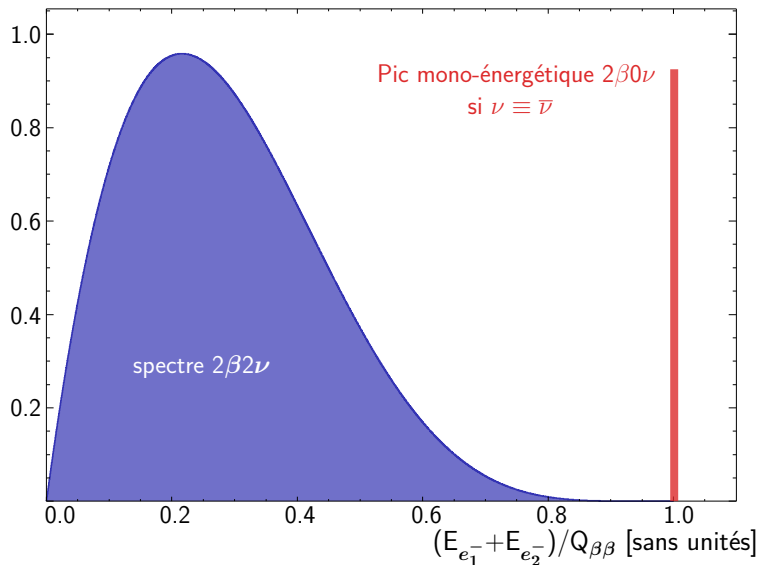


La double désintégration bêta sans émission de neutrino

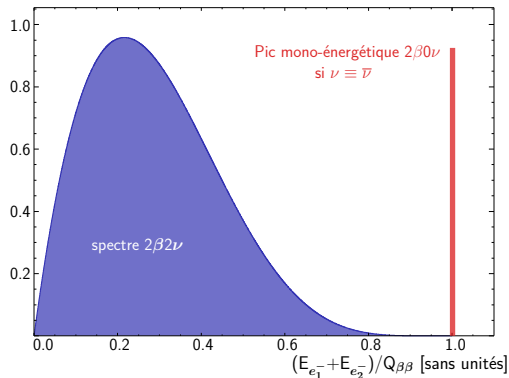
Dans l'hypothèse où le neutrino serait une particule de Majorana :



Signature expérimentale



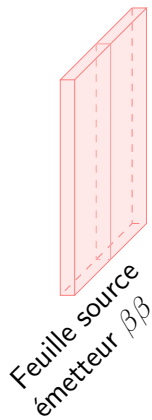
Mesure expérimentale



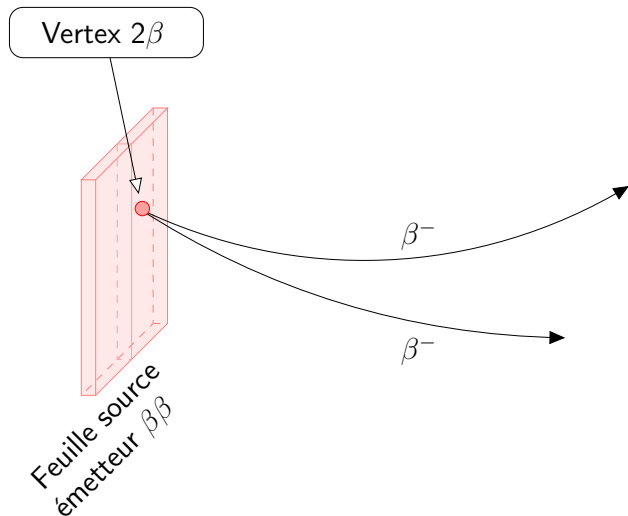
Idéalement, une expérience $2\beta 0\nu$ doit :

- ▶ mesurer précisément l'énergie des électrons émis,
- ▶ identifier individuellement chacune des particules émises.

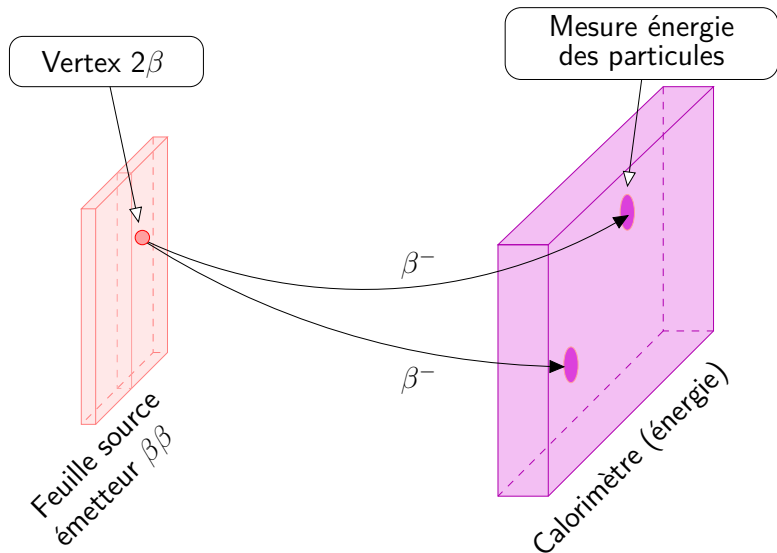
Principe expérimental des expériences NEMO



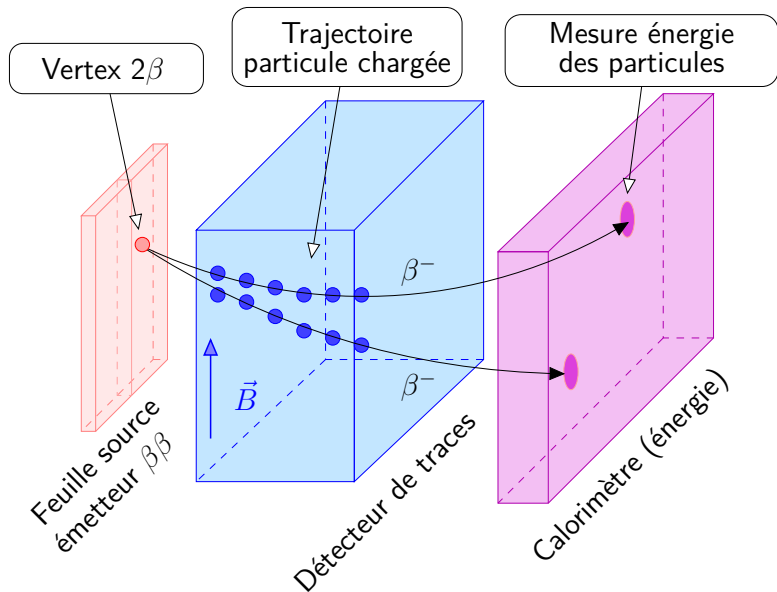
Principe expérimental des expériences NEMO



Principe expérimental des expériences NEMO



Principe expérimental des expériences NEMO



Les expériences NEMO

1988 : NEMO1 (LAL, LLR, CENBG, IPHC)

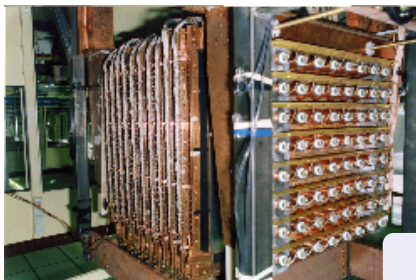


Visible au
Trocadéro

- ▶ pas de feuille source
- ▶ construction chambre à fils (G. Charpak) bas bruit de fond
- ▶ protection contre les neutrons

Les expériences NEMO

1992 : NEMO2 (LAL, LPC, CENBG, IPHC, Kiev, Dubna, Moscou)

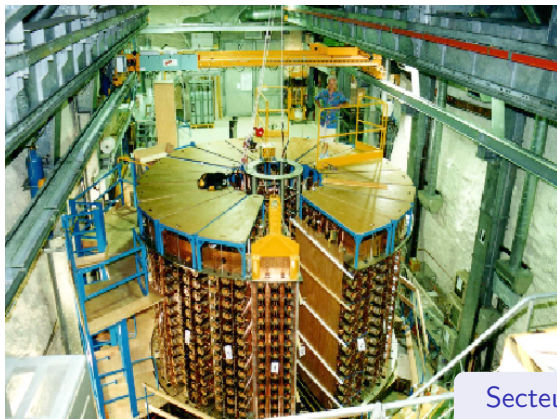


Visible au
LAL

- ▶ double désintégration $2\beta 2\nu$ du ^{100}Mo , ^{82}Se , ^{96}Zr et ^{116}Cd
- ▶ mesure du bruit de fond dans la région du MeV
- ▶ diffusion du Radon dans la chambre à fils

Les expériences NEMO

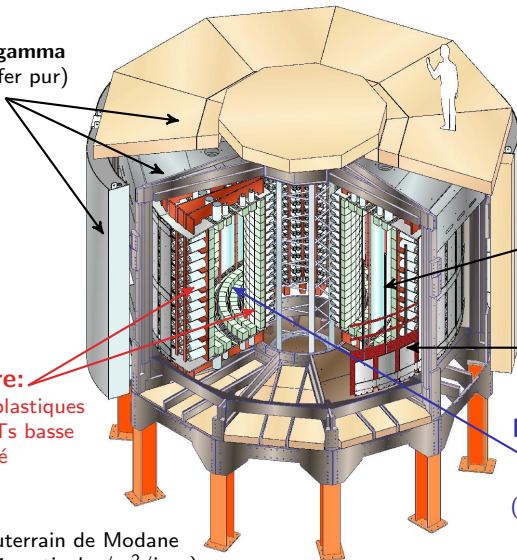
2003 – 2011 : NEMO3 (LAL, LPC, CENBG, IPHC, Kiev, Dubna, Moscou)



Secteur NEMO3
visible au LAL

L'expérience NEMO3

Blindage neutron/gamma
(eau borée, bois et fer pur)



Sources enrichies:
10 kg d'isotopes $\beta\beta$
($S = 20 \text{ m}^2$, $e = 60 \text{ mg/cm}^2$)

Champ magnétique:
 $B = 25 \text{ Gauss}$
discrimination e^\pm

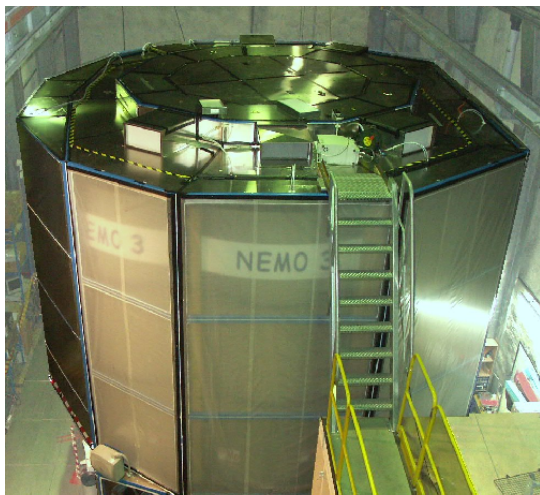
Calorimètre:

1940 scintillateurs plastiques
couplés à des PMTs basse
radioactivité

Détecteur de traces:
 30 m^3 de chambre à fils
opérant en mode Geiger
(He + 4% alcool + 1% Ar
+ 0.1% H₂O)

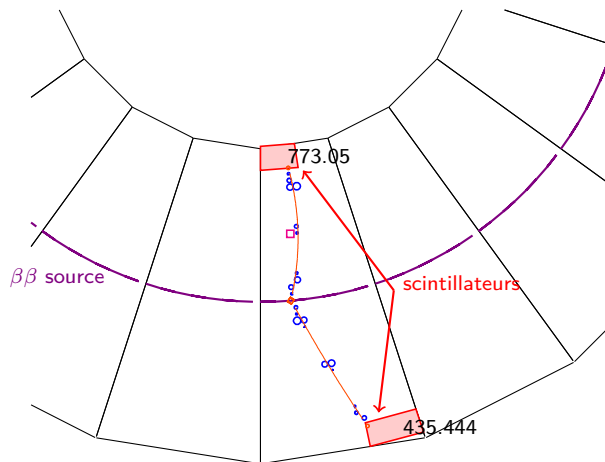
Laboratoire Souterrain de Modane
(4800 m.w.e i.e. $4 \text{ particules/m}^2/\text{jour}$)

L'expérience NEMO3

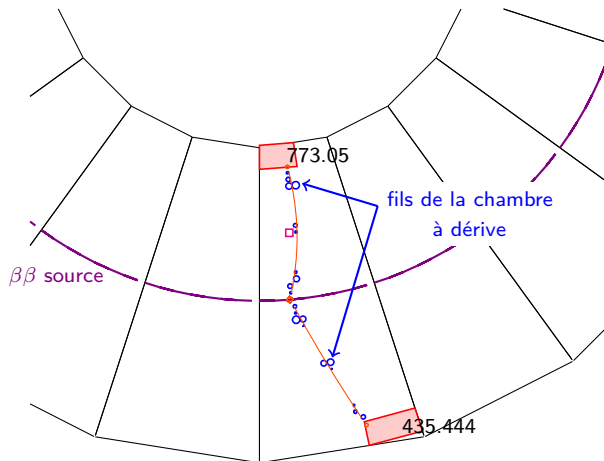


2000 tonnes de matériaux pour une radioactivité
totale de 1000 Bq
(corps humain \sim 7000 Bq)

Événement NEMO3

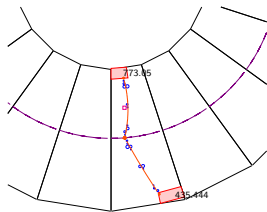


Événement NEMO3

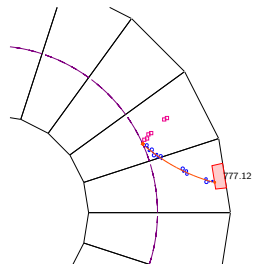
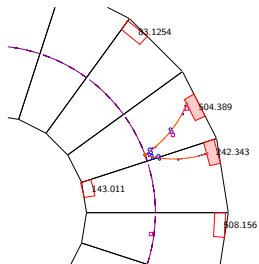
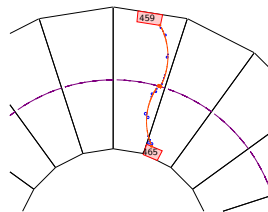


Événements NEMO3

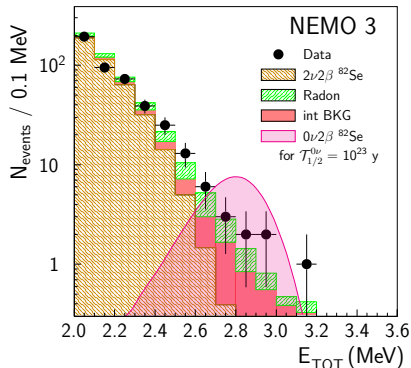
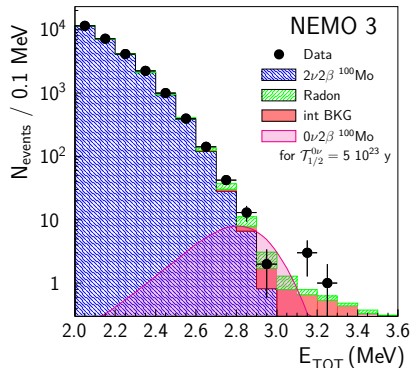
Candidat $2\beta 0\nu$



Candidat $2\beta 0\nu$

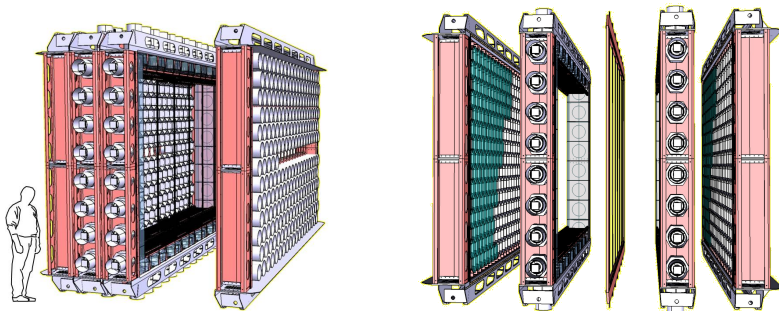


Résultats NEMO3 (2003 – 2011)



→ **Aucun excès significatif d'événement**

Expérience SuperNEMO



NEMO3 → SuperNEMO

SuperNEMO est la prochaine génération d'expérience "NEMO"

	NEMO3	SuperNEMO
Masse	7 kg	100 kg
Isotope	^{100}Mo	^{82}Se
Résolution énergie (FWHM)		
@ 1 MeV	15 %	7 %
@ 3 MeV	8 %	4 %
Contaminations sources		
$A(^{208}\text{Tl})$	< 20 $\mu\text{Bq/kg}$	< 2 $\mu\text{Bq/kg}$
$A(^{214}\text{Bi})$	< 300 $\mu\text{Bq/kg}$	< 10 $\mu\text{Bq/kg}$
Radon (^{222}Rn)	$\sim 5.0 \text{ mBq/m}^3$	\sim 0.1 mBq/m^3

Début de la construction d'un premier module : Janvier 2012

Pendant ce temps ...

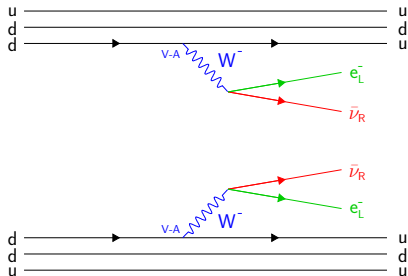
... $10^{21} = 1,000,000,000,000,000,000,000$
neutrinos ont traversé cette pièce

Transparents Additionnels

Double Beta Decays

$2\nu 2\beta$ Standard Process

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



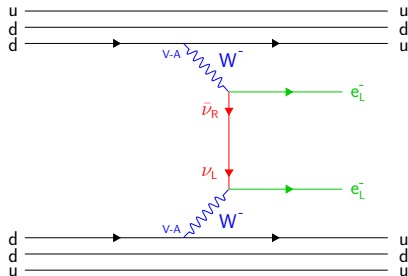
Lepton Number Conservation: $\Delta L = 0$

Neutrino nature: $\nu \neq \bar{\nu}$ or $\nu \equiv \bar{\nu}$

$$(\mathcal{T}_{1/2}^{2\nu})^{-1} = G_{2\nu} |\mathcal{M}_{2\nu}|^2$$

$0\nu 2\beta$ Non-Standard Process

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



Lepton Number Violation: $\Delta L = 2$

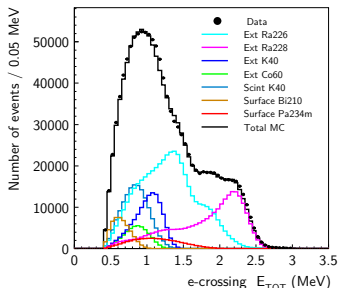
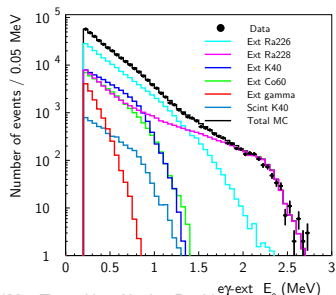
Majorana (massive) neutrino: $\nu \equiv \bar{\nu}$

$$(\mathcal{T}_{1/2}^{0\nu})^{-1} = G_{0\nu} |\mathcal{M}_{0\nu}|^2 |m_{\beta\beta}|^2$$

other mechanisms: V+A, SUSY physics,
Majoron $0\nu 2\beta[\chi]$

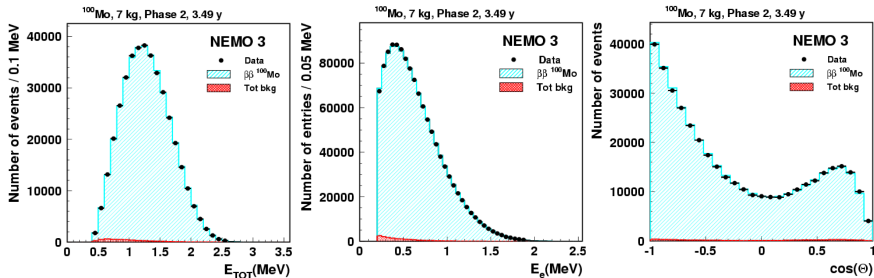
NEMO3 Experiment

- ▶ Measurement of kinematics parameters (E_{e_1} , E_{e_2} , Δt & $\cos\theta$)
- ▶ Particle identification e^- , e^+ , γ , α using event topology
- ▶ Measurement of all background components in independent channels [NIM A606 (2009) 449-465]
 - ▶ External backgrounds: $e\gamma_{\text{external}}$, e_{crossing}
 - ▶ Internal backgrounds in foils: $e\gamma(\gamma\gamma)$, 1 electron topology
 - ▶ Radon daughters deposited on wires and source foils: $e\alpha$ channel



NEMO3 results: $2\nu 2\beta$ of ^{100}Mo

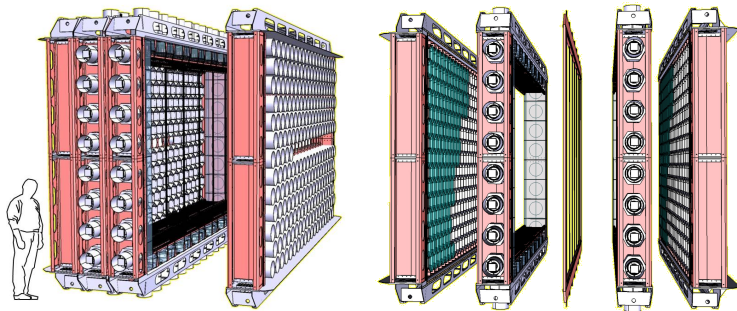
^{100}Mo (6.9 kg): ~ 3.5 yr, $S/B = 76$



$$\mathcal{T}_{1/2}^{2\nu} = 7.17 \pm 0.01 \text{ (stat)} \pm 0.54 \text{ (syst)} 10^{18} \text{ yr}$$
$$\mathcal{M}^{2\nu} = 0.126 \pm 0.006$$

SuperNEMO Modules

- ▶ 20 modules based on NEMO3 principle (about 4.0×5.5 m²/module)
 - ▶ ~ 5 kg of 2β sources
 - ▶ ~ 2000 drift cells in geiger mode + B field
 - ▶ ~ 700 scintillators with low radioactivity 8" PMTs

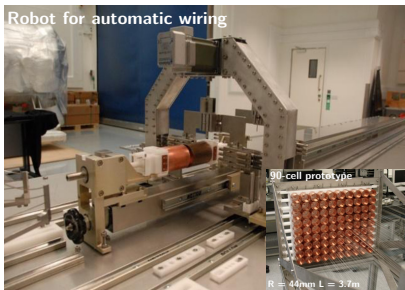
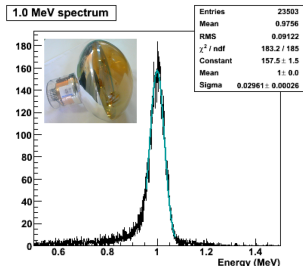


SuperNEMO: 4 years of R&D

► Calorimeter

Required resolution demonstrated with cubic PVT block coupled to 8" PMT

$$\text{FWHM} = 7\% @ Q_{\beta\beta} = 1 \text{ MeV}$$



► Tracker

Basic cell design developed and performances demonstrated using cosmic muon data

$$\sigma_T \simeq 0.7 \text{ mm} \quad \sigma_L \simeq 1 \text{ cm} \quad \epsilon > 98\%$$

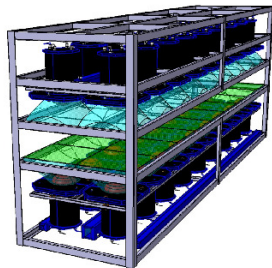
SuperNEMO: 4 years of R&D

► $\beta\beta$ source

Enrichment: centrifugation of 100 kg of ^{82}Se is feasible, studies to produce large amount of ^{150}Nd and ^{48}Ca

Radiopurity: Chemical and physical purification at a level of $^{208}\text{Tl} \leq 2 \mu\text{Bq/kg}$, $^{214}\text{Bi} \leq 10 \mu\text{Bq/kg}$ and will be measured with BiPo3 detector

BiPo3 detector



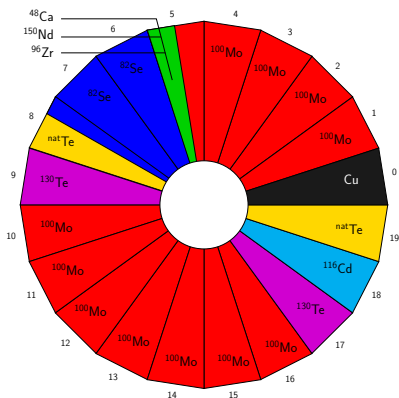
Choice of 2β isotopes

$$(\mathcal{T}_{1/2}^{0\nu})^{-1} = G_{0\nu} |\mathcal{M}_{0\nu}|^2 |m_{\beta\beta}|^2 \quad \mathcal{T}_{1/2}^{0\nu} > \frac{\ln 2 N_A \mathcal{E}_{0\nu}}{1.64 A} \sqrt{\frac{m t}{N_{\text{bkg}} r}}$$

- ▶ high $Q_{\beta\beta}$
 - ▶ $E_\gamma(^{208}\text{Tl}) = 2.6 \text{ MeV}$
 - ▶ $Q_\beta(^{214}\text{Bi}) = 3.3 \text{ MeV}$
- ▶ high $G_{0\nu}$ (low $\mathcal{T}_{1/2}^{0\nu}$)
- ▶ high $\mathcal{M}_{0\nu}$ (low $\mathcal{T}_{1/2}^{0\nu}$)
- ▶ high $\mathcal{T}_{1/2}^{2\nu}$ (low $2\nu 2\beta$)
- ▶ high mass:
 - ▶ natural abundance
 - ▶ low atomic mass A
 - ▶ enrichment - purification

2β	$Q_{\beta\beta}$ MeV	$G_{0\nu}$ 10^{-25} y^{-1}	$\mathcal{T}_{1/2}^{2\nu}$ y	NA %
^{48}Ca	4.272	2.44	$4.3 \cdot 10^{19}$	0.19
^{76}Ge	2.039	0.24	$1.3 \cdot 10^{21}$	7.61
^{82}Se	2.995	1.08	$9.2 \cdot 10^{19}$	8.73
^{96}Zr	3.350	2.24	$2.0 \cdot 10^{19}$	2.8
^{100}Mo	3.034	1.75	$7.0 \cdot 10^{18}$	9.63
^{116}Cd	2.805	1.89	$3.0 \cdot 10^{19}$	7.49
^{130}Te	2.529	1.70	$6.1 \cdot 10^{20}$	33.8
^{136}Xe	2.479	1.81	$\geq 8.5 \cdot 10^{21}$	8.9
^{150}Nd	3.368	8.00	$7.9 \cdot 10^{18}$	5.6

The NEMO-3 detector: $\beta\beta$ sources



Isotope	Mass (g)	$Q_{\beta\beta}$ (keV)
---------	----------	------------------------

$0\nu 2\beta$ search + $2\nu 2\beta$ meas.

^{100}Mo	6914	3034
^{82}Se	932	2995

$2\nu 2\beta$ 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

natTe	491	see ^{130}Te
Cu	621	-

Enriched isotopes produced by centrifugation in Russia

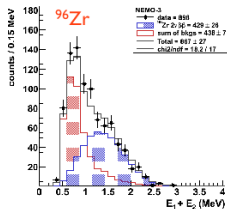
NEMO3 Experiment



NEMO3 Calibrations

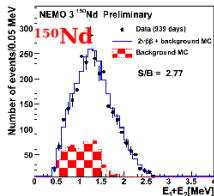
- ▶ Relative energy calibration done by laser survey
- ▶ Absolute energy calibration was performed using ^{207}Bi (482 and 976 keV CE) and ^{90}Sr ($Q_{\beta}(^{90}\text{Y}) = 2.283\text{ MeV}$) sources put inside calibration tubes in source frame
- ▶ Time calibration done with ^{60}Co source (2 coincident γ at 1332 keV and 1173 keV respectively)

NEMO3 Results: $2\nu 2\beta$ other isotopes



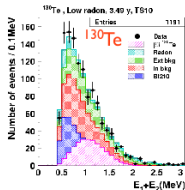
$$[2.35 \pm 0.14(\text{stat}) \pm 0.16(\text{sys})] \times 10^{19} \text{ yr}$$

$$M^{2\nu} = 0.049 \pm 0.002$$



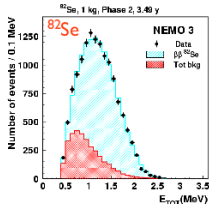
$$[9.20 \pm 0.25(\text{stat}) \pm 0.63(\text{sys})] \times 10^{18} \text{ yr}$$

$$M^{2\nu} = 0.030 \pm 0.002$$



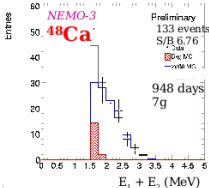
$$[7.0^{+1.0}_{-0.8}(\text{stat}) + {}^{+1.1}_{-0.9}(\text{sys})] \times 10^{20} \text{ yr}$$

$$M^{2\nu} = 0.0173 \pm 0.0025$$



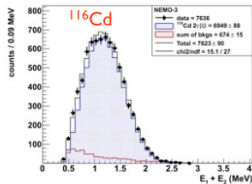
$$[9.6 \pm 0.1(\text{stat}) \pm 1.0(\text{sys})] \times 10^{19} \text{ yr}$$

$$M^{2\nu} = 0.049 \pm 0.004$$



$$[4.4^{+0.5}_{-0.4}(\text{stat}) \pm 0.4(\text{sys})] \times 10^{19} \text{ yr}$$

$$M^{2\nu} = 0.0238 \pm 0.0015$$



$$[2.88 \pm 0.04(\text{stat}) \pm 0.16(\text{sys})] \times 10^{19} \text{ yr}$$

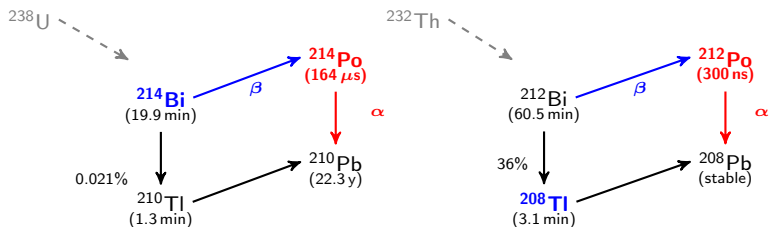
$$M^{2\nu} = 0.0685 \pm 0.0025$$

NEMO3 Results: $2\nu 2\beta$ other isotopes

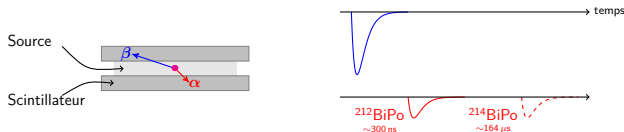
Isotope	$\mathcal{T}_{1/2}^{2\nu 2\beta}$ years
^{100}Mo	$(7.11 \pm 0.02 \text{ (stat.)} \pm 0.54 \text{ (syst.)}) \times 10^{18}$
$^{100}\text{Mo}(0_1^+)$	$(5.7_{-0.9}^{+1.3} \text{ (stat.)} \pm 0.8 \text{ (syst.)}) \times 10^{20}$
^{82}Se	$(9.6 \pm 0.3 \text{ (stat.)} \pm 1.0 \text{ (syst.)}) \times 10^{19}$
^{116}Cd	$(2.8 \pm 0.1 \text{ (stat.)} \pm 0.3 \text{ (syst.)}) \times 10^{19}$
^{130}Te	$(6.9 \pm 0.9 \text{ (stat.)} \pm 1.0 \text{ (syst.)}) \times 10^{20}$
^{150}Nd	$(9.20_{-0.22}^{+0.25} \text{ (stat.)} \pm 0.73 \text{ (syst.)}) \times 10^{18}$
^{96}Zr	$(2.35 \pm 0.14 \text{ (stat.)} \pm 0.19 \text{ (syst.)}) \times 10^{19}$
^{48}Ca	$(4.4_{-0.4}^{+0.5} \text{ (stat.)} \pm 0.4 \text{ (syst.)}) \times 10^{19}$

BiPo Detector

- ▶ Measure ^{208}Tl and ^{214}Bi contamination of source foils

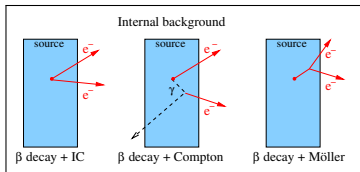
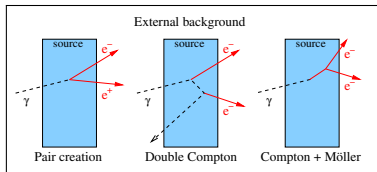


- ▶ Experimental principle: detection of “BiPo” coincidences *i.e.* β decay followed by a delayed α particle



Natural Radioactivity Background

	²³⁸ U			²³² Th			²³⁵ U			
U	U-238 4.47 10 ⁹ yr	U-234 2.45 10 ⁵ yr						U-235 7.04 10 ⁸ yr		
Pa	↓ Pa-234m 1.17 m	↓ Pa-234						↓ Pa-231 3.27 10 ⁴ yr		
Th	Th-234 24.10 d	Th-230 7.538 10 ⁴ yr	β ↗		Th-232 14 10 ⁹ yr	Th-228 1.912 yr		Th-231 25.52 h	Th-227 18.72 d	
Ac			α ↓		Ac-228 6.15 h			Ac-227 21.773 yr		
Ra		Ra-226 1600 yr			Ra-226 5.75 yr	Ra-224 3.66 d			Ra-223 11.435 d	
Fr										
Rn		Rn-222 3.8235 d				Rn-220 55.6 s			Rn-219 3.96 s	
At										
Po		Po-218 3.10 m	Po-214 164.3s s	Po-210 138.376 d		Po-216 145 ms	Po-212 299 ms		Po-215 1.781 ms	
Bi		Bi-214 19.9 m	Bi-210 5.013 d			Bi-212 60.55 m			Bi-211 2.14 m	
Pb		Pb-214 26.8 m	Pb-210 22.3 yr	Pb-206 stable		Pb-212 10.64 h	Pb-208 stable		Pb-211 36.1 m	Pb-207 stable
Tl		Tl-210 1.3 m	Tl-206 4.199 m			Tl-208 3.053 m			Tl-207 4.77 m	

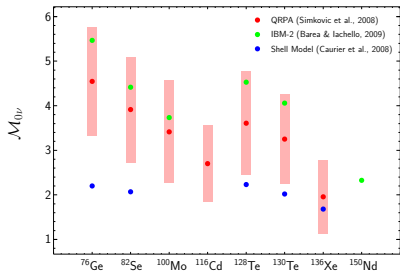


Neutrino Current Limits

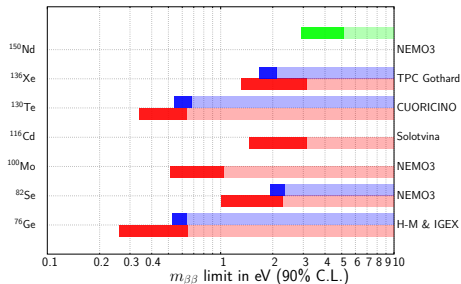
Isotope	Experiment	Technique	Mass	$T_{1/2}^{0\nu}$ [year] 90% C.L.	$ m_{\beta\beta} $ [eV]	
					QRPA	Shell Model
^{48}Ca	NEMO3	Tracko-calo	7 g	$\geq 1.3 \cdot 10^{22}$	–	21 – 29
^{76}Ge	Heidel. - Mosc.	Semi cond. Germanium	11 kg	$\geq 1.5 \cdot 10^{25}$	0.26 – 0.65	0.53 – 0.64
^{82}Se	NEMO3	Tracko-calo	1 kg	$\geq 3.6 \cdot 10^{23}$	1.01 – 2.28	1.94 – 2.36
^{100}Mo	NEMO3	Tracko-calo	7 kg	$\geq 1.1 \cdot 10^{24}$	0.51 – 1.04	–
^{116}Cd	Solotvina	Scintillator crystals CdWO_4	80 g	$\geq 1.7 \cdot 10^{23}$	1.45 – 3.13	2.06
^{130}Te	CUORICINO	Bolometers	10 kg	$\geq 3.0 \cdot 10^{24}$	0.34 – 0.64	0.54 – 0.68
^{136}Xe	TPC Gothard	TPC Gaz Xe	3.4 kg	$\geq 4.4 \cdot 10^{23}$	1.31 – 3.15	1.67 – 2.10
^{150}Nd	NEMO3	Tracko-calo	37 g	$\geq 1.8 \cdot 10^{22}$	IBM : 2.9 – 5.1	

NME & Effective Neutrino Mass

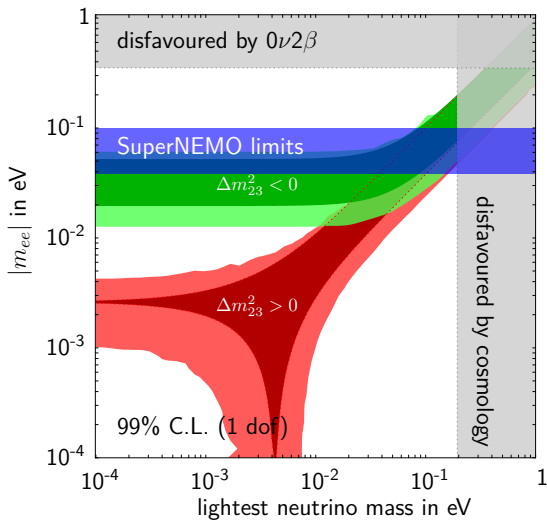
Actual calculation of Nuclear Matrix Elements and limit on effective neutrino mass $m_{\beta\beta}$



QRPA (Šimkovic et al., 2008) IBM-2 (Barea & Iachello, 2009) SM (Caurier et al., 2008)



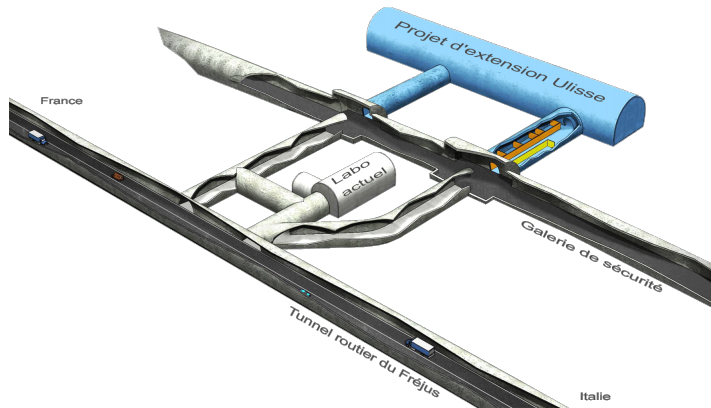
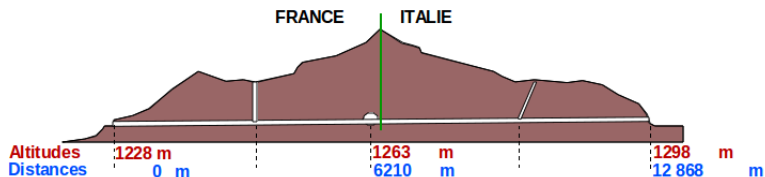
SuperNEMO & Neutrino Hierarchy



Overview of DBD Experiments

Experiment	Isotope	Mass [kg]	FWHM @ $Q_{\beta\beta}$	Bkg cts [keV.kg.yr]	Bkg cts [FWHM.year]	$\mathcal{T}_{1/2}^{0\nu}$ limit	$ m_{\beta\beta} $ [meV]	Timescale Start - Results
Construction / Commissioning								
GERDA I	^{76}Ge	18		10^{-2}	0.7	$3 \cdot 10^{25}$	200 – 500	2010 – 2011
GERDA II		40	4 keV	10^{-3}	0.2	$2 \cdot 10^{26}$	80 – 200	2011 – 2013
GERDA III		100		10^{-3}	0.4	$2 \cdot 10^{27}$	25 – 65	?
CUORE	^{130}Te	200	5 keV	10^{-2}	37	$2 \cdot 10^{26}$	40 – 85	2012 – 2017
EXO-200	^{136}Xe	200	40 keV	$2.5 \cdot 10^{-3}$	20	$6 \cdot 10^{25}$	110 – 260	2010 – 2012
SNO+	^{150}Nd	56	~ 200 keV	–	~ 80	–	~ 100	2011 – 2013
R&D Funding / Prototype								
CANDLE 3	^{48}Ca	0.35	210 keV	–	–	–	–	2010 – ?
SuperNEMO	^{82}Se	100	210 keV	10^{-4}	~ 2	10^{26}	60 – 140	2013 – 2020
NEXT-100	^{136}Xe	100	25 keV	–	–	$6 \cdot 10^{25}$	110 – 260	2014 – 2019
R&D								
Scintillating bolometers	^{82}Se	19				10^{26}	60 – 140	
	^{116}Cd	15	10 keV	$\leq 10^{-3}$	≤ 0.3	$6 \cdot 10^{25}$	75 – 165	?
	^{100}Mo	12				$6 \cdot 10^{25}$	65 – 130	

Extension du Laboratoire Souterrain de Modane



Vitesse des neutrinos : l'expérience OPERA

