Search for Neutrinoless Double Beta Decay : NEMO3 Results and Plans for SuperNEMO

23$^{rd.}$ Rencontres de Blois, May 31, 2011

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on behalf of

SuperNEMO
collaboration

Neutrinos and Double Beta Decay

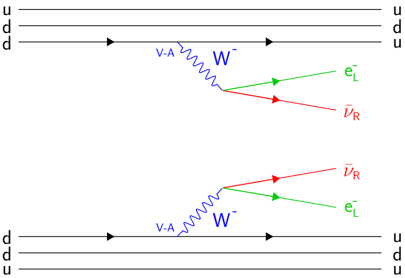
NEMO3 Results

Status and Plans for SuperNEMO

Double Beta Decays

$2\nu2\beta$ Standard Process

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



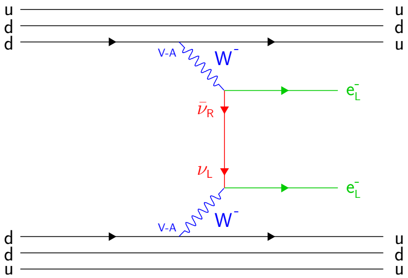
Lepton Number Conservation: $\Delta L = 0$

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

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

$0\nu2\beta$ Non-Standard Process

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



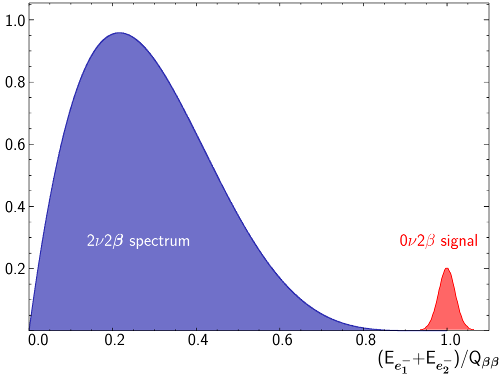
Lepton Number Violation: $\Delta L = 2$

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

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

other mechanisms: V+A, SUSY physics, Majoron $0\nu2\beta[\chi]$

Experimental Principle

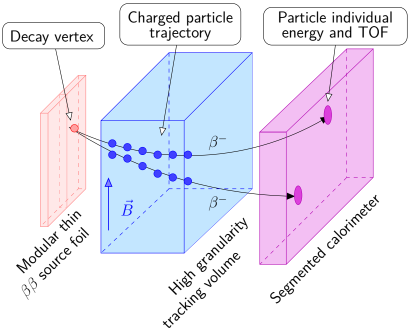


Ideally one $0\nu2\beta$ experiment should:

- measure the energy of the 2 electrons with very good energy resolution
- identify individually the 2 electrons emitted (E_{e_1}, E_{e_2} & $\cos\theta$)

NEMO's Technique : Calorimetry + Tracking

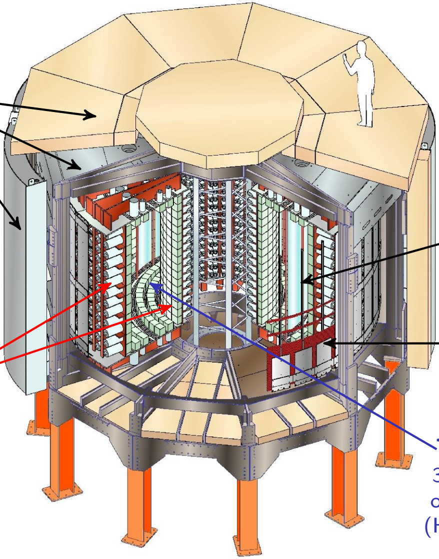
- Reconstruction of final state topology:
  - $e^{\pm}$ individual energy
  - charged particle trajectory
  - time of flight
  - magnetic field curvature
  - angular distribution
  - vertex
- Background rejection and measurement through particle identification: e^-, e^+, γ, α
- Source is separated from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



NEMO3 Experiment (2003 - 2011)

SuperNEMO collaboration

Neutron/gamma shield
(borated water, wood and pure iron)



Enriched sources:
10 kg of $\beta\beta$ isotopes
($S = 20\,\mathrm{m}^2$, $e = 60\,\mathrm{mg/cm}^2$)

Magnetic field:
$B = 25$ Gauss
$e^{\pm}$ discrimination

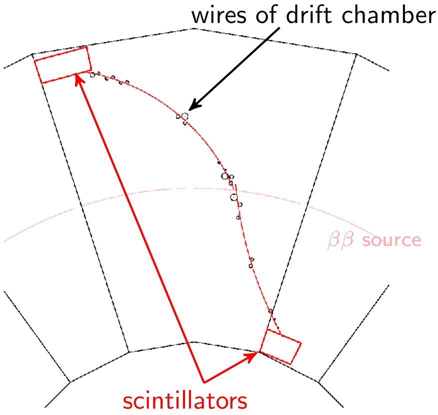
Calorimeter:
1940 plastic scintillators coupled to low radioactivity PMTs

Tracking Detector:
$30\,\mathrm{m}^3$ drift wire chamber operating in Geiger mode
(He + 4% alcool + 1% Ar + 0.1% H_2O)

Laboratoire Souterrain de Modane (4800 m.w.e)

NEMO3 Experiment

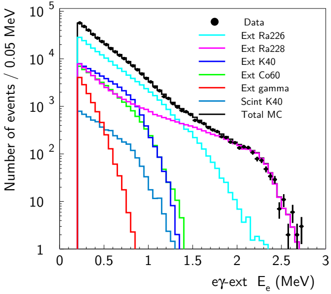
- Measurement of kinematics parameters (E_{e_1}, E_{e_2}, Δt & $\cos\theta$)
- Particle identification e^-, e^+, γ, α using event topology

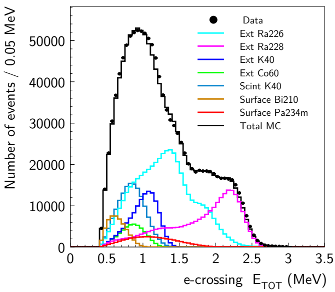


Typical $2\nu2\beta$ candidate event

NEMO3 Experiment

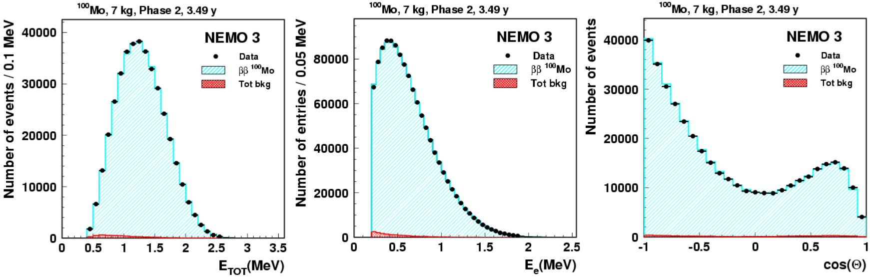
- Measurement of kinematics parameters (E_{e_1}, E_{e_2}, Δt & $\cos\theta$)
- Particle identification e^-, e^+, γ, α using event topology
- Measurement of all background components in independent channels [NIM A606 (2009) 449-465]
  - External backgrounds: $e\gamma_{\text{external}}$, e_{crossing}
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





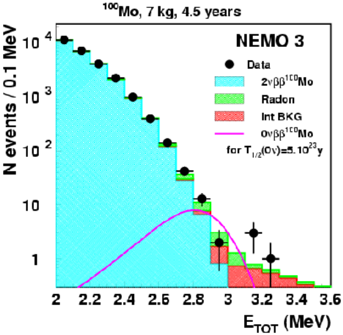
NEMO3 results: $2\nu2\beta$ of ^{100}Mo

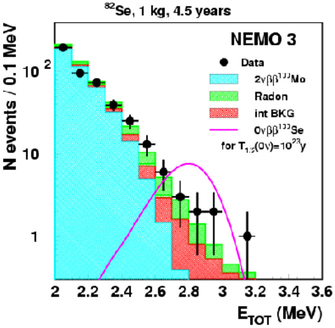
^{100}Mo (6.9 kg): $\sim$ 3.5 yr, $S/B = 76$



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

NEMO3 results: Search for $0\nu2\beta$





$\epsilon_{0\nu}(^{100}\text{Mo}) \sim 13\%$

$\mathcal{T}^{0\nu}_{1/2}(^{100}\text{Mo}) > 1.0\,10^{24}$ yr @ 90 % C.L.

$\langle m_{\beta\beta}\rangle$ <0.47 - 0.96 eV

$\epsilon_{0\nu}(^{82}\text{Se}) \sim 14\%$

$\mathcal{T}^{0\nu}_{1/2}(^{82}\text{Se}) > 3.2\,10^{23}$ yr @ 90 % C.L.

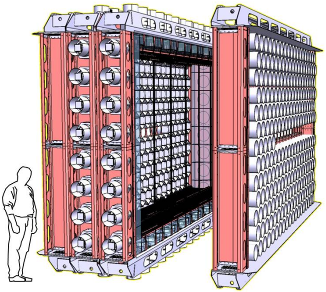
$\langle m_{\beta\beta}\rangle$ <0.94 - 2.5 eV

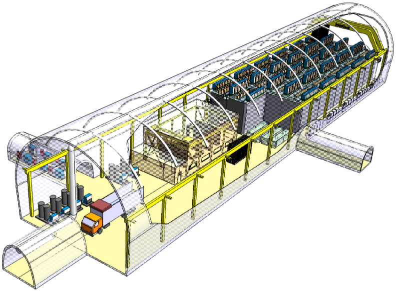
More results available: excited states, $0\nu2\beta$ for others isotopes, processes

V+A: $\mathcal{T}^{0\nu}_{1/2}(^{100}\text{Mo}) > 5.4\,10^{23}$ yr @ 90 % C.L.

Majoron: $\mathcal{T}^{0\nu}_{1/2}(^{100}\text{Mo}) > 2.1\,10^{22}$ yr @ 90 % C.L.

SuperNEMO Experiment





From NEMO3 to SuperNEMO

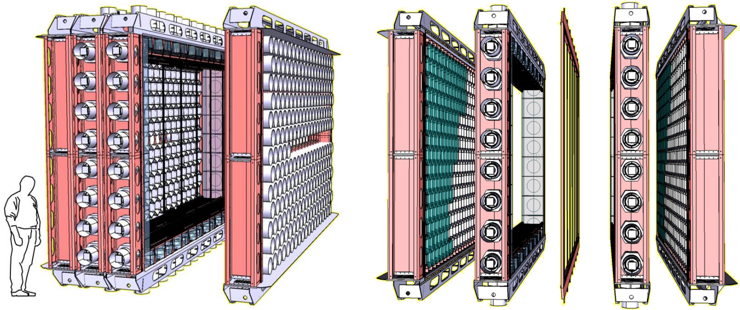
SuperNEMO is the next generation of NEMOs experiment

$\mathcal{T}_{1/2}^{0\nu} \gtrsim 10^{26}$ yr @ 90 % C.L. for $\langle m_{\beta\beta} \rangle < 40$ - 100 meV

	NEMO3	**SuperNEMO**
Mass	7 kg	100 kg
Isotope	^{100}Mo	^{82}Se
Foil density	60 mg/cm^2	40 mg/cm^2
Energy resolution (FWHM)		
@ 1 MeV	15 %	**7 %**
@ 3 MeV	8 %	**4 %**
Sources contaminations		
$\mathcal{A}(^{208}\text{Tl})$	$< 20\ \mu$Bq/kg	**$< 2\ \mu$Bq/kg**
$\mathcal{A}(^{214}\text{Bi})$	$< 300\ \mu$Bq/kg	**$< 10\ \mu$Bq/kg**
Radon (^{222}Rn)	~ 5.0 mBq/m^3	**~ 0.1 mBq/m^3**

SuperNEMO Modules

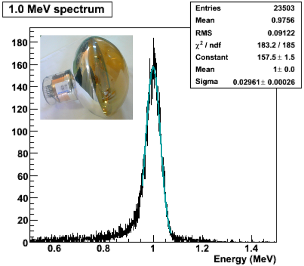
- 20 modules based on NEMO3 principle (about 4.0×5.5 m^2/module)
  - $\sim$ 5 kg of 2β sources
  - $\sim$ 2000 drift cells in geiger mode + B field
  - $\sim$ 700 scintillators with low radioactivity 8" PMTs

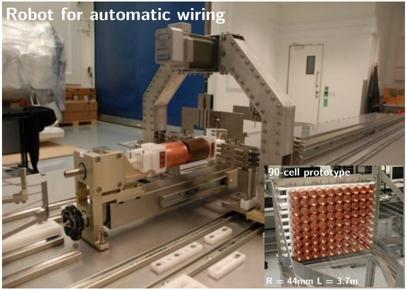


SuperNEMO: 4 years of R&D

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

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





- **Tracker**
  Basic cell design developed and performances demonstrated using cosmic muon data

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

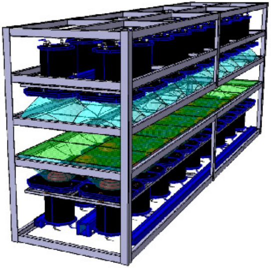
SuperNEMO: 4 years of R&D

- $\beta\beta$ source

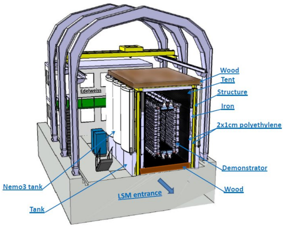
  Enrichement: centrifugation of 100 kg of ^{82}Se is feasible, studies to produce large amount of ^{150}Nd and ^{48}Ca

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

BiPo3 detector



SuperNEMO demonstrator



- Building of one module to:
  - confirm R&D on large scale mass production
  - measure backgrounds especially from Radon
  - produce competitive physics measurement

0.3 expected bkg events in [2.8 - 3.2] MeV with 7 kg of ^{82}Se in 2 years

Sensitivity by 2015 : 6.5 10^{24} year (90% C.L.)

$\langle m_{\beta\beta} \rangle < 200$ - 400 meV

Summary

- NEMO experiments use tracking-calorimeter technique
  - full event reconstruction
  - clear $\beta\beta$ event signature
  - excellent background rejection using event topology
- NEMO3 (2003 - 2011) has run $2\nu2\beta$ factory
  - $\mathcal{T}^{2\nu}_{1/2}(^{100}\mathrm{Mo}) = 7.17 \pm 0.01\ (\mathrm{stat}) \pm 0.54\ (\mathrm{syst})\ 10^{18}$ yr
  - 7 isotopes studied $\rightarrow$ constraints for nuclear matrix elements
- NEMO3 provides competitive $0\nu2\beta$ limits
  - $\mathcal{T}^{0\nu}_{1/2}(^{100}\mathrm{Mo}) \geq 1.0\,10^{24}$ yr @ 90% C.L. ($\langle m_{\beta\beta}\rangle$ <0.47 - 0.96 eV)

Summary

- SuperNEMO is the next generation experiment
  - R&D objectives have been reached
- Demonstrator module
  - tracker already funded by U.K and scientific council of IN2P3 recently approved calorimeter construction
  - sensitive to Klapdor claim by 2015
- SuperNEMO full detector
  - installed inside the new LSM laboratory ?
  - $\mathcal{T}^{0\nu}_{1/2} \gtrsim 10^{26}$ yr @ 90 % C.L., $\langle m_{\beta\beta} \rangle <$40 - 100 meV
  - possibility to probe $0\nu2\beta$ mechanism by 2019

BACKUP Slides

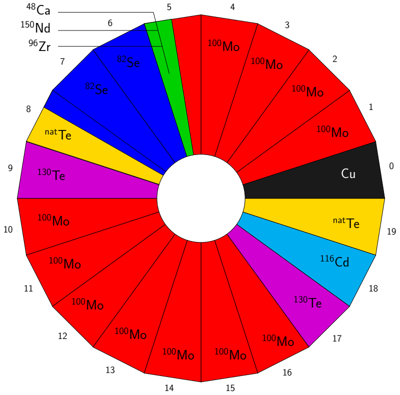
Choice of 2β isotopes

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

- 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 $\mathcal{T}^{0\nu}_{1/2}$)
- high $\mathcal{M}_{0\nu}$ (low $\mathcal{T}^{0\nu}_{1/2}$)
- high $\mathcal{T}^{2\nu}_{1/2}$ (low $2\nu2\beta$)
- high mass:
  - natural abundance
  - low atomic mass A
  - enrichment - purification

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

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



Isotope	Mass (g)	$Q_{\beta\beta}$ (keV)
$0\nu2\beta$ search + $2\nu2\beta$ meas.		
^{100}Mo	6914	3034
^{82}Se	932	2995
$2\nu2\beta$ 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		
^{nat}Te	491	see ^{130}Te
Cu	621	-

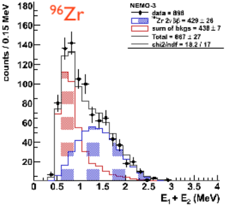
Enriched isotopes produced by centrifugation in Russia

NEMO3 Experiment

NEMO3 Calibrations

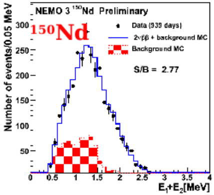
- Relative energy calibration done by laser survey
- Absolute energy calibration was performed using ^{207}Bi (482 and 976 keV CE) and ^{90}Sr ($Q_\beta(^{90}Y) = 2.283$ MeV) sources put inside calibration tubes in source frame
- Time calibration done with ^{60}Co source (2 coincident γ at 1332 keV and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

NEMO3 Results: $2\nu2\beta$ other isotopes



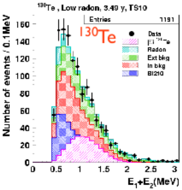
$[2.35 \pm 0.14(stat) \pm 0.16(sys)] \times 10^{19}$ yr

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



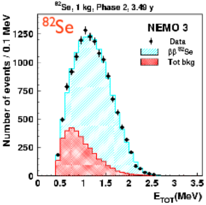
$[9.20 \pm 0.25(stat) \pm 0.63(sys)] \times 10^{18}$ yr

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



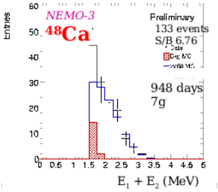
$[7.0^{+1.0}_{-0.8}(stat)\ ^{+1.1}_{-0.9}(sys)] \times 10^{20}$ yr

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



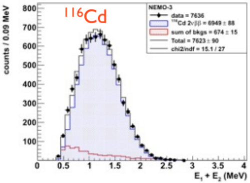
$[9.6 \pm 0.1(stat) \pm 1.0(sys)] \times 10^{19}$ yr

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



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

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



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

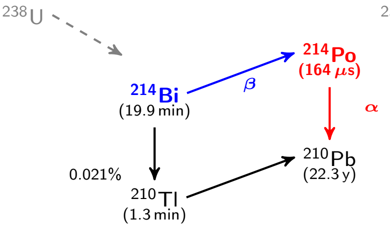
$M^{2\nu} = 0.0685 \pm 0.0025$

NEMO3 Results: $2\nu2\beta$ other isotopes

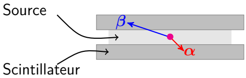
Isotope	$\mathcal{T}_{1/2}^{2\nu2\beta}$ **years**
^{100}Mo	$(7.11 \pm 0.02\ (\text{stat.}) \pm 0.54\ (\text{syst.})) \times 10^{18}$
^{100}Mo(0_1^+)	$(5.7^{+1.3}_{-0.9}\ (\text{stat.}) \pm 0.8\ (\text{syst.})) \times 10^{20}$
^{82}Se	$(9.6 \pm 0.3\ (\text{stat.}) \pm 1.0\ (\text{syst.})) \times 10^{19}$
^{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	$(9.20^{+0.25}_{-0.22}\ (\text{stat.}) \pm 0.73\ (\text{syst.})) \times 10^{18}$
^{96}Zr	$(2.35 \pm 0.14\ (\text{stat.}) \pm 0.19\ (\text{syst.})) \times 10^{19}$
^{48}Ca	$(4.4^{+0.5}_{-0.4}\ (\text{stat.}) \pm 0.4\ (\text{syst.})) \times 10^{19}$

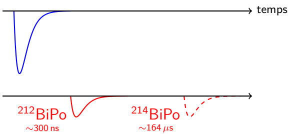
BiPo Detector

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

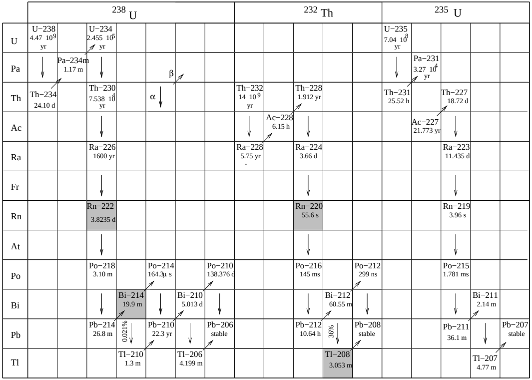


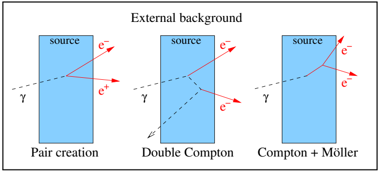
- Experimental principle: detection of "BiPo" coincidences *i.e.* β decay followed by a delayed α particle

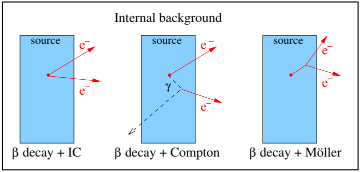




Natural Radioactivity Background





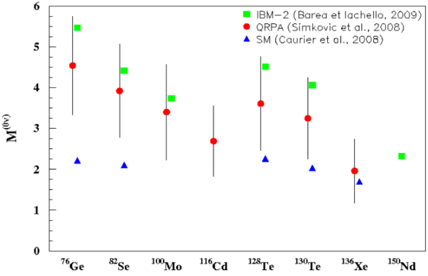


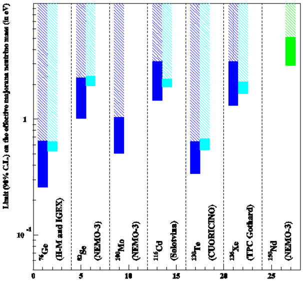
Neutrino Current Limits

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

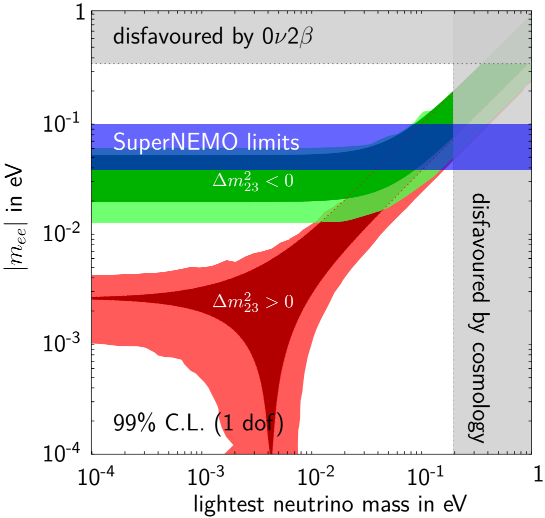
NME & Effective Neutrino Mass

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





SuperNEMO & Neutrino Hierarchy



Overview of DBD Experiments

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