Nu 02 WP3 : R&D for Neutrinoless Double Beta Decay Experiments

FJPPL
Annecy

Mathieu BONGRAND

LAL Orsay

15/06/2010

- France: M. Bongrand, X. Garrido, S. Jullian, Ch. Marquet, F. Mauger, F. Perrot, F. Piquemal, X. Sarazin & L. Simard

  LAL Orsay, CENBG Bordeaux, LPC Caen & LSM Modane

- Japan: N. Ishihara, Y. Yamada, M. Nomachi, H. Ohsumi, H. Ejiri, K. Fushimi, R. Hazama & Y. Sugaya

  KEK, Osaka U., Saga U., RCNP Osaka, U. Tokushima & Hiroshima U.

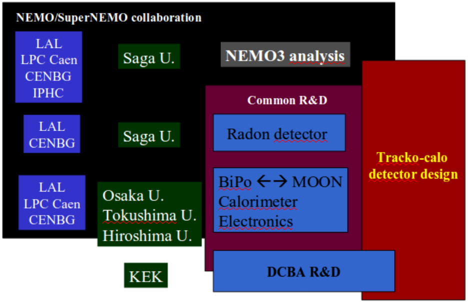
France-Japan Collaboration on DBD

France & Japan have several experiments or projects for double beta decay searches with tracko-calo (e^- identification) or calorimeter detectors

Collaboration started in 2000 on tracko-calo techniques

Common subjects: 2β sources, low background, calorimeter...

- Sources production and purification
- Very low background measurements: BiPo detector
- Radon detectors
- Calorimeter R&D for energy resolution improvement
- Electronics
- Analysis (NEMO3)



Contents

Double Beta Decay

Physics case of double beta decay:

- Lepton Number Violation
- Nature of the Neutrino: *Dirac* ($\nu \neq \overline{\nu}$) or *Majorana* ($\nu \equiv \overline{\nu}$)
- Absolute neutrino mass and mass hierarchy
- CP-violation in the leptonic sector
- Right-handed current interaction
- Search for Supersymmetry and new particles

Majorana neutrinos are fundamental for:

- *Neutrinoless Double Beta Decay*
- *See-Saw Mechanism* to explain the smallness of neutrino masses
- *Leptogenesis* and *Baryon asymmetry* in the Universe

Double Beta Decay: 2 processes

$2\nu2\beta$

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

$$\Delta L = 0$$

$$\nu \;?\; \overline{\nu}$$

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

$0\nu2\beta$

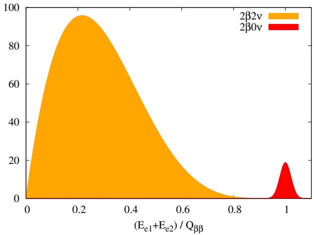
$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$

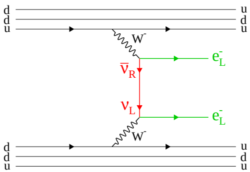
$$\Delta L = 2$$

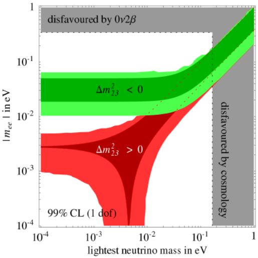
$$\nu \equiv \overline{\nu}$$

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

$$m_{\beta\beta} = c^2_{12}c^2_{13}m_1 + s^2_{12}c^2_{13}e^{2i\eta_2}m_2 + s^2_{13}e^{2i(\eta_3-\delta)}m_3$$







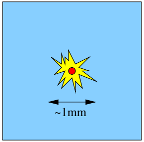
Experimental Principle

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_1, E_2 & $\cos\theta$)
- have a good spatial resolution or segmented sources
- identify the daughter isotope after the decay

Two experimental techniques:

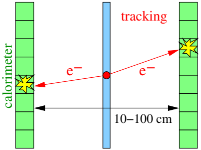
Active sources



semiconductors,
bolometers,
scintillators...

- high efficiency (~90%)
- very good energy resolution (few keV)
- no tracking
- small background rejection

Passive sources



tracko–calo,
TPC...

- lower efficiency (~30%)
- less good energy resolution (few %)
- tracking & particles identification
- precise backgrounds measurements

Choice of double beta decay isotopes

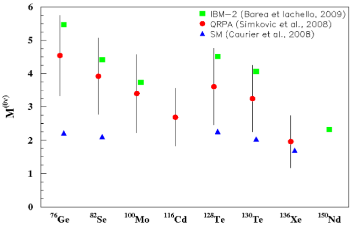
2β isotope for an experiment:

- high $Q_{\beta\beta}$
  - $> E_\gamma(^{208}Tl) = 2.6$ MeV
  - $> Q_\beta(^{214}Bi) = 3.2$ 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 and purification

2β	$Q_{\beta\beta}$ MeV	$G_{0\nu}$ 10^{-25}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

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

$$\mathcal{T}^{0\nu}_{1/2} > \frac{ln\,2\,N_A\,\mathcal{E}_{0\nu}}{1.64\,A}\sqrt{\frac{m\,t}{N_{bdf}\,r}}$$



NEMO3: Neutrino Ettore Majorana Observatory

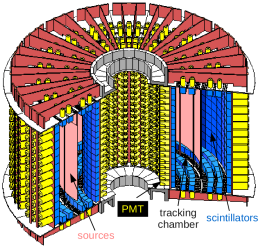
NEMO3 Experiment

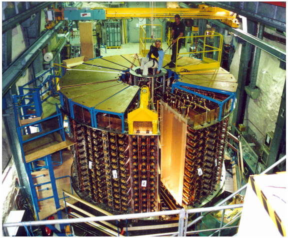
NEMO3 tracko-calo experiment with passive sources running since 2003

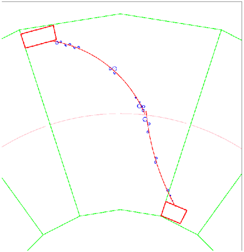
- Many 2β enriched isotopes in thin vertical foils ($60\ \mathrm{mg/cm^2}$):
  - **for $0\nu2\beta$: ^{100}Mo (6.9 kg) & ^{82}Se (932 g)**
  - for $2\nu2\beta$: ^{130}Te (454 g), ^{116}Cd (405 g), ^{150}Nd (37 g), ^{96}Zr (9 g) & ^{48}Ca (7 g)
- Tracking chamber: 6180 drift cells operated in geiger mode + B field
- Calorimeter: 1940 polystyrene scintillators & low radioactivity PMTs
- Shielding: *Laboratoire Souterrain de Modane*, pure iron & borated water

Unique features:

- measurement of all kinematics parameters (E_1, E_2, ToF & $\cos\theta$)
- identification of e^-, e^+, γ & α
- direct background measurements (e^-, $e^-\gamma$, $e^-\alpha$, $e^-\gamma\gamma$, $e^-\gamma\gamma\gamma$, *oce*...)

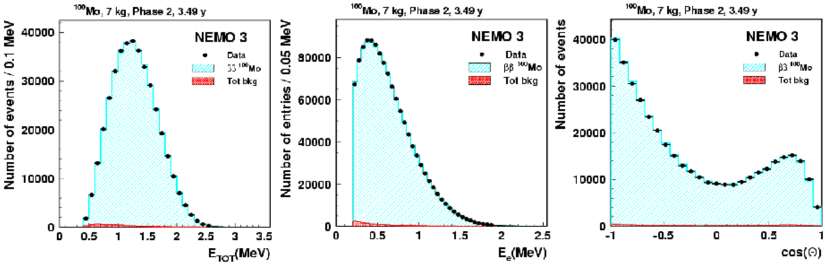






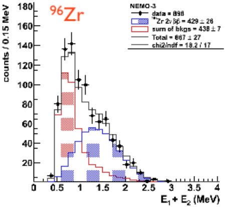
NEMO3 Results: $2\nu2\beta$ of ^{100}Mo

^{100}Mo (6.9 kg): phase 2 data (low radon), $\sim$ 3.5 yr & $S/B = 76$



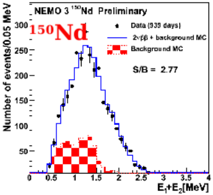
$$\mathcal{T}_{1/2}^{2\nu} = 7.17 \pm 0.01\ \text{(stat)} \pm 0.54\ \text{(syst)}\ 10^{18}\ \text{yr}$$
$$\mathcal{M}^{2\nu} = 0.126 \pm 0.006$$

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



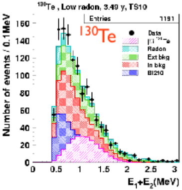
[2.35±0.14(stat)±0.16(sys)]×10^{19} yr

$M^{2\nu}$=0.049±0.002



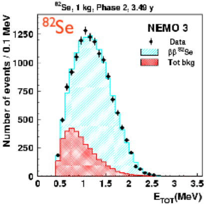
[9.20±0.25(stat)±0.63(sys)]×10^{18} yr

$M^{2\nu}$=0.030±0.002



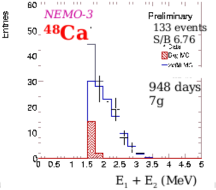
[7.0$^{+1.0}_{-0.8}$(stat) $^{+1.1}_{-0.9}$(sys)]×10^{20} yr

$M^{2\nu}$=0.0173±0.0025



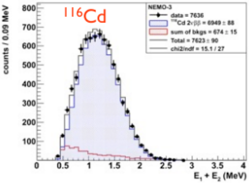
[9.6±0.1(stat)±1.0(sys)]×10^{19} yr

$M^{2\nu}$=0.049±0.004



[4.4$^{+0.5}_{-0.4}$(stat)±0.4(sys)]×10^{19} yr

$M^{2\nu}$=0.0238±0.0015

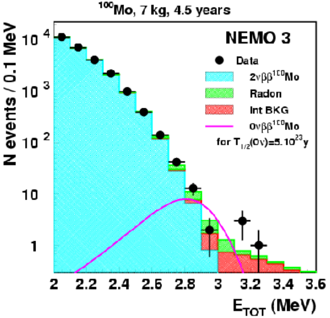


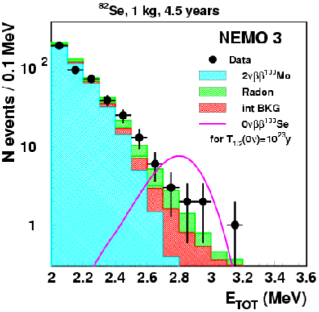
[2.88±0.04(stat)±0.16(sys)]×10^{19} yr

$M^{2\nu}$=0.0685±0.0025

NEMO3 Results: $0\nu2\beta$

^{100}Mo (6.9 kg) & ^{82}Se (932 g): phase 2 data (low radon) & $\sim$ 4.5 yr





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

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

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

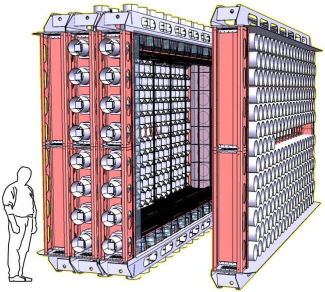
$\epsilon_{0\nu}(^{82}\text{Se}) \sim 14$ %

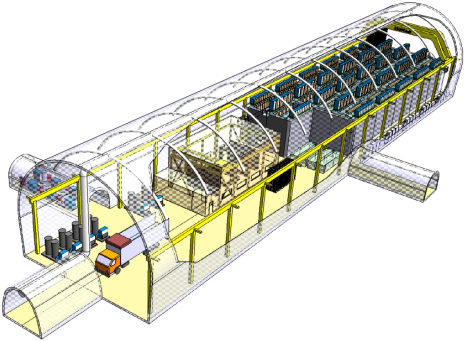
$\mathcal{T}^{0\nu}_{1/2}(^{82}\text{Se}) > 3.2\ 10^{23}$ yr @ 90 % C.L.

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

Many more results available: excited states, $0\nu2\beta$ for all isotopes, different processes...
V+A: $\mathcal{T}^{0\nu}_{1/2} > 5.4\ 10^{23}$ yr @ 90 % C.L. & Majoron: $\mathcal{T}^{0\nu}_{1/2} > 2.1\ 10^{22}$ yr @ 90 % C.L.

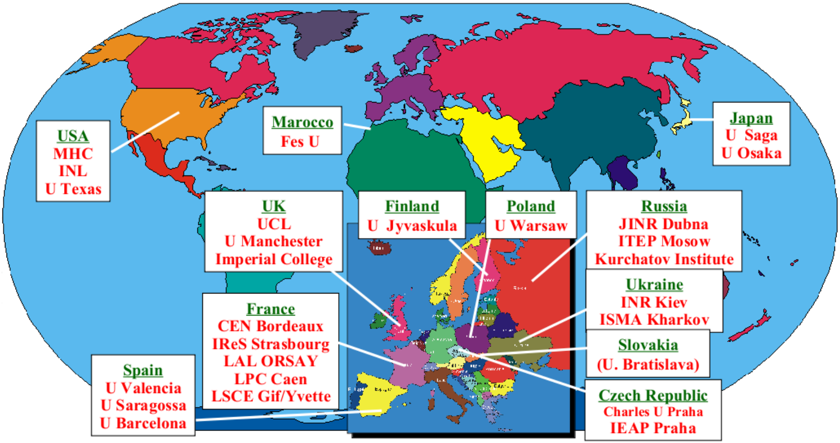
SuperNEMO Project





SuperNEMO Collaboration

$\sim$ 90 Physicists, 12 Countries & 27 Laboratories



From NEMO3 to SuperNEMO

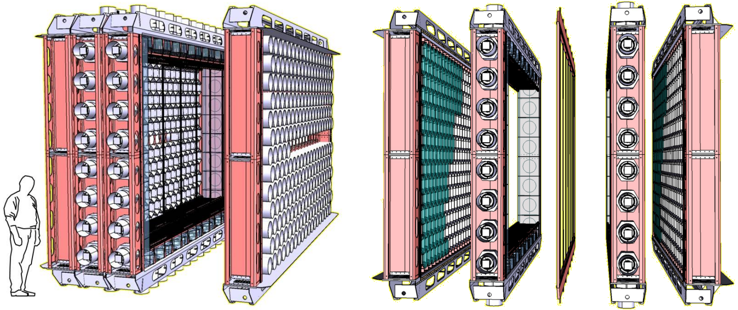
Next generation of the NEMO3 experiment: SuperNEMO with sensitivity
$\mathcal{T}^{0\nu}_{1/2} > 10^{26}$ yr @ 90 % C.L. for $|m_{\beta\beta}| < 50 - 140$ meV

	NEMO3	**SuperNEMO**
Mass	7 kg	100 kg
Isotope	^{100}Mo	^{82}Se or ^{150}Nd
Foil density	60 mg/cm^2	40 mg/cm^2
Energy resolution (FWHM)		
@ 1 MeV	15 %	7 %
@ 3 MeV	8 %	4 %
Sources contaminations		
$\mathcal{A}(^{208}\mathrm{Tl})$	$< 20\ \mu$Bq/kg	$< 2\ \mu$Bq/kg
$\mathcal{A}(^{214}\mathrm{Bi})$	$< 300\ \mu$Bq/kg	$< 10\ \mu$Bq/kg
Radon (^{222}Rn)	~ 5.0 mBq/m^3	~ 0.1 mBq/m^3

SuperNEMO Modules

20 SuperNEMO modules based on NEMO3 principle in 2016
(about 4.0×5.5 m^2 modules)

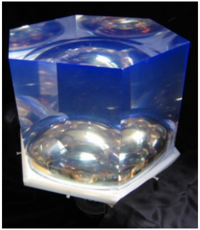
- ~ 5 kg of 2β sources
- ~ 2000 drift cells in geiger mode + B field
- ~ 700 PVT scintillators with low radioactivity 8″ PMTs

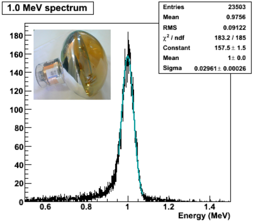


Demonstrator with 7 kg of ^{82}Se (1 kg ^{48}Ca & maybe also ^{150}Nd) in 2013
sensitivity in 1 yr: $\mathcal{T}^{0\nu}_{1/2} > 5\ 10^{24}$ yr @ 90 % C.L. for $|m_{\beta\beta}| < 0.2 - 0.6$ eV

SuperNEMO: 4 years of R&D

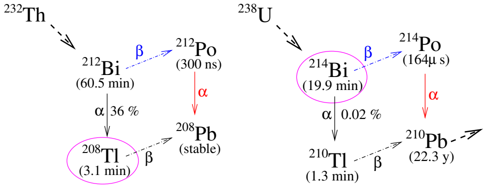
- Calorimeter: FWHM 7 % @ 1 MeV with PVT hexagonal scintillators directly coupled to Photonis or Hamamatsu 8″ HQE and low background PMTs, light injection to monitor PMT gain @ 1 %
- Tracker: efficiency, energy loss, wiring robot, radon emanation & gas radiopurity, radon protection films...
- Sources: enrichment of ^{82}Se, ^{150}Nd & ^{48}Ca, purification, foil production and control of radiopurity





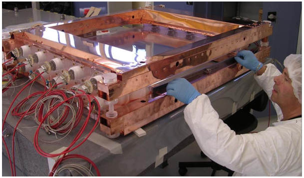
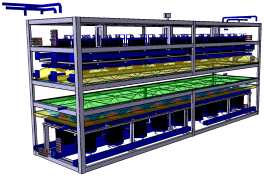
Source Radiopurity: BiPo Detector

The SuperNEMO Collaboration and DBD tracko-calo experiments need a detector with sensitivity of 2 μBq/kg in ^{208}Tl and 10 μBq/kg in ^{214}Bi



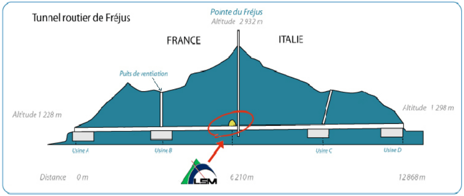
2 BiPo prototypes have been build (2007-2008) in collaboration with Japan still running in LSM: actual sensitivity is $\sim$4 μBq/kg in ^{208}Tl in 1 month

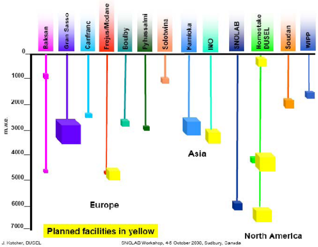
BiPo3 detector is under construction (LSC Canfranc in 2011)

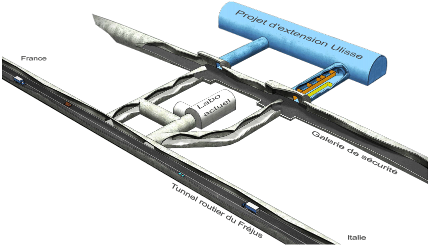




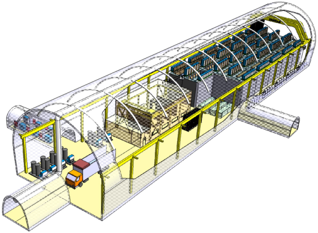
LSM Extension

A safety galery is under construction along the existing road tunnel
This is an opportunity to build a new underground laboratory





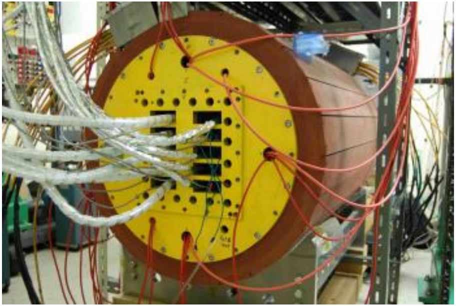




Final decision by France should be known in November 2010

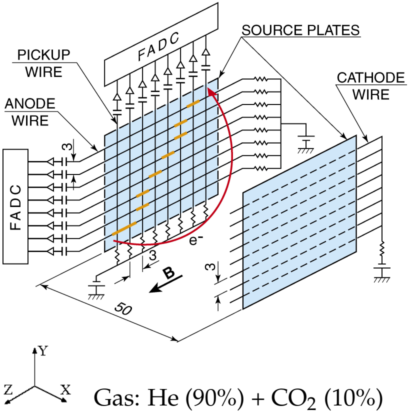
Status of DCBA at KEK

Status of Drift Chamber Beta-ray Analyzer (DCBA) at KEK



DCBA-T2

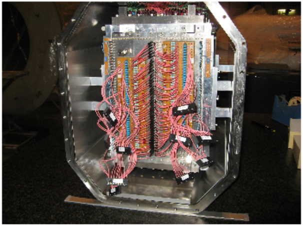
Detection Principle in DCBA

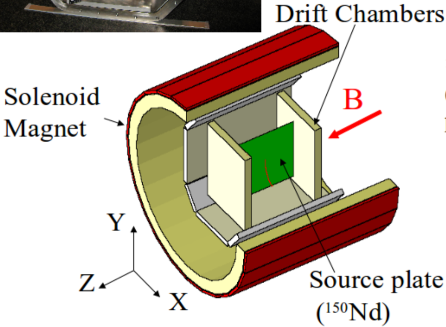


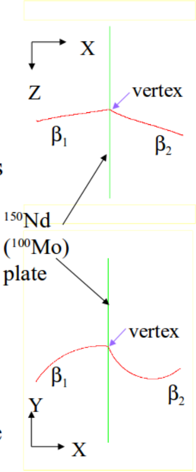
Gas: He (90%) + CO_2 (10%)

- electrons: helical track
  p (MeV/c) $= 0.3\, r$ (cm) B (kG)
  $B \sim 2$ kG & 2 cm $< r_e < 5$ cm
  $\Rightarrow 0.8$ MeV $< T_e < 2.5$ MeV
- alphas: automatically rejected
  $T_\alpha = 1$ MeV $\Leftrightarrow p_\alpha \approx 87$ MeV
  $\rightarrow$ no track curvature by the magnetic field
- gammas: automatically rejected
  $\rightarrow$ no track

DCBA-T2 Prototype







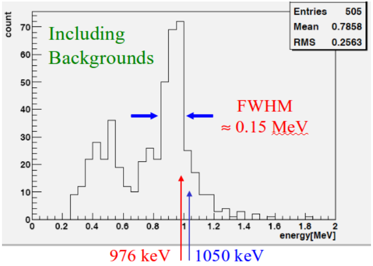
Energy Resolution of DCBA-T2 Prototype

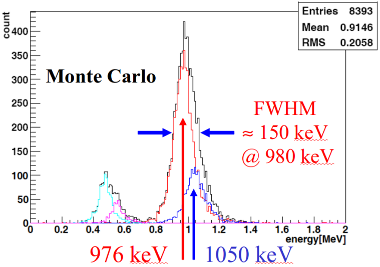
Chamber conditions:

- Gas: He (90%) + CO_2 (10%)
- Magnetic field $B = 0.8$ kG
- Wire pitch $d = 6$ mm

Conversion electrons from ^{207}Bi point source at the center of the chamber

$E_e = 0.48$ (1.6 %), 0.55 (0.4 %), 0.96 (6.1 %) & 1.05 (2.0 %) MeV

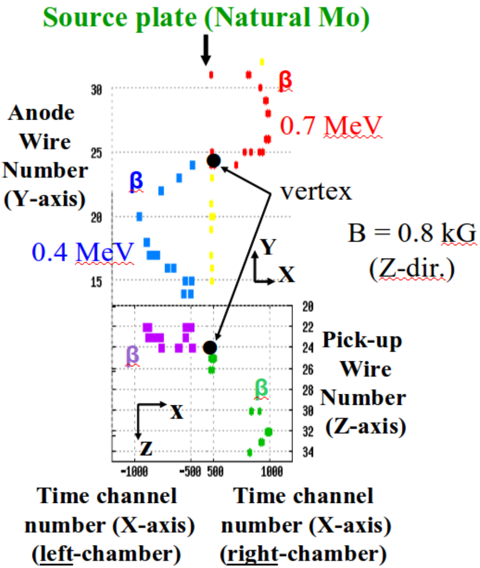




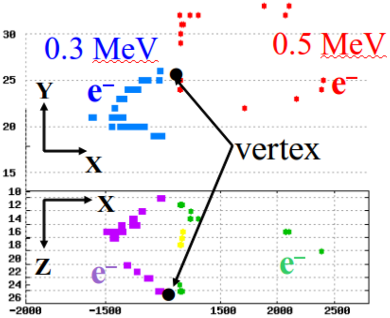
FWHM = 150 keV @ 1 MeV

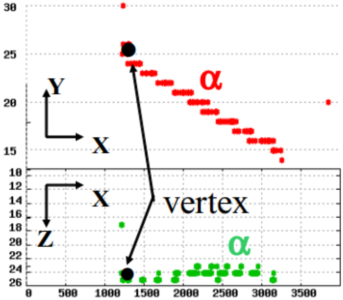
→ **expected $\Delta E/E$ = 6.3 % (FWHM) @ $Q_{\beta\beta}(^{150}\text{Nd})$ = 3.37 MeV**

DCBA-T2 2β Event Candidate



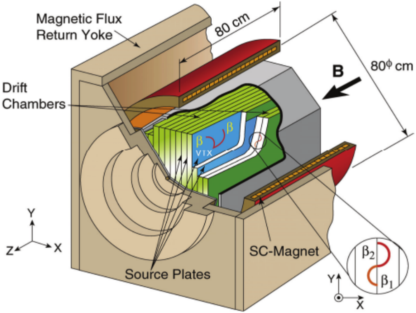
DCBA-T2 BiPo Event

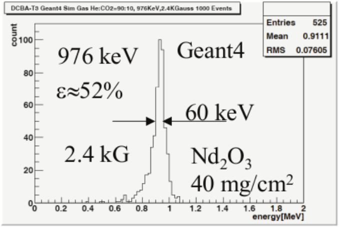


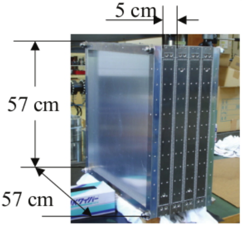


^{214}Bi β decay to ^{214}Po + Compton e⁻ **186 μs later** → ^{214}Po α decay from same decay point (vertex)

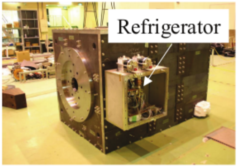
DCBA-T3 Under Construction



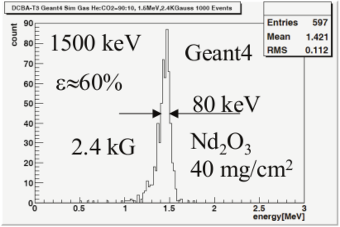




Drift chambers



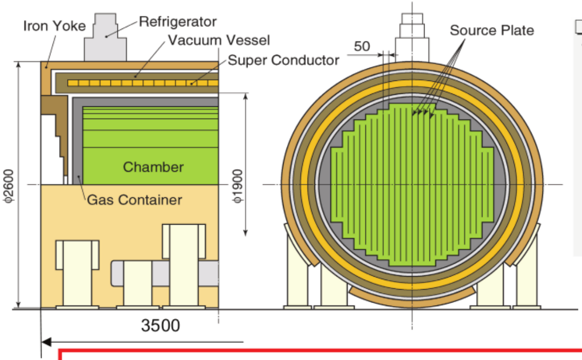
SC-magnet

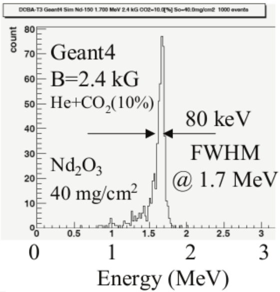


Expected energy resolutions

Magnetic Tracking Detector (MTD)

Project after DCBA: Magnetic Tracking Detector (MTD temporary name)
Chamber cell : the same as DCBA-T3, Source plate: 80 m^2/module
Thickness: 40 mg/cm^2, Source weight: 32 kg/module, B: 3kG (Max)





Expected Energy Resolution $\dfrac{\mathrm{FWHM}(E_{sum}) = \sqrt{2} \times 80\mathrm{keV}}{Q_{\mathrm{Nd\text{-}150}}(3370\mathrm{keV})} \approx 3.4\%$

Summary

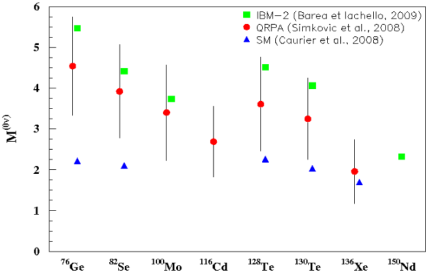
France-Japan double beta decay collaboration started in 2000 on tracko-calo techniques with e^- identification:

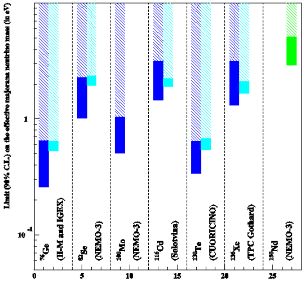
- NEMO3 data analysis & running
- 2β sources (enrichment of isotopes, purification & foil production)
- Control of sources radiopurity (running & analysis of BiPo1 & BiPo2 + construction of BiPo3)
- Calorimeter R&D (energy resolution: scintillators & PMTs)
- Radon detectors (goal sensitivity < 1 mBq/m^3)
- Low radioactive techniques

Backup

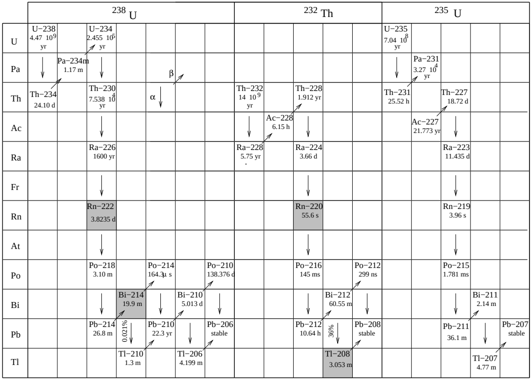
NME & Effective Neutrino Mass

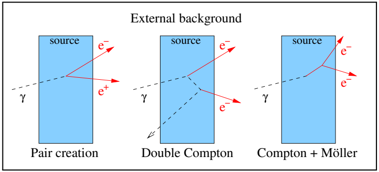
Actual calculation of Nuclear Matrix Elements and limit on effective neutrino mass $m_{\beta\beta}$

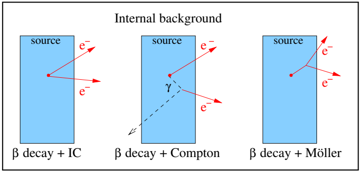




Natural Radioactivity Background







Overview of DBD Experiments

Name	Nucleus	Mass*	Method	Location	Time line
Operational & recently completed experiments					
CUORICINO	Te-130	11 kg	bolometric	LNGS	2003-2008
NEMO-3	Mo-100/Se-82	6.9/0.9 kg	tracko-calo	LSM	until 2010
Construction funding					
CUORE	Te-130	200 kg	bolometric	LNGS	2012
EXO-200	Xe-136	160 kg	liquid TPC	WIPP	2009 (comiss.)
GERDA I/II	Ge-76	35 kg	ionization	LNGS	2009 (comiss.)
SNO+	Nd-150	56 kg	scintillation	SNOlab	2011
Substantial R&D funding / prototyping					
CANDLES	Ca-48	0.35 kg	scintillation	Kamioka	2009
Majorana	Ge-76	26 kg	ionization	SUSL	2012
NEXT	Xe-136	80 kg	gas TPC	Canfranc	2013
SuperNEMO	Se-82 or Nd-150	100 kg	tracko-calo	LSM	2012 (first mod.)
R&D and/or conceptual design					
CARVEL	Ca-48	tbd	scintillation	Solotvina	
COBRA	Cd-116, Te-130	tbd	ionization	LNGS	
DCBA	Nd-150	tbd	drift chamber	Kamioka	
EXO gas	Xe-136	tbd	gas TPC	SNOlab	
MOON	Mo-100	tbd	tracking	Oto	
Other decay modes					
TGV	Cd-106		ionization	LSM	operational