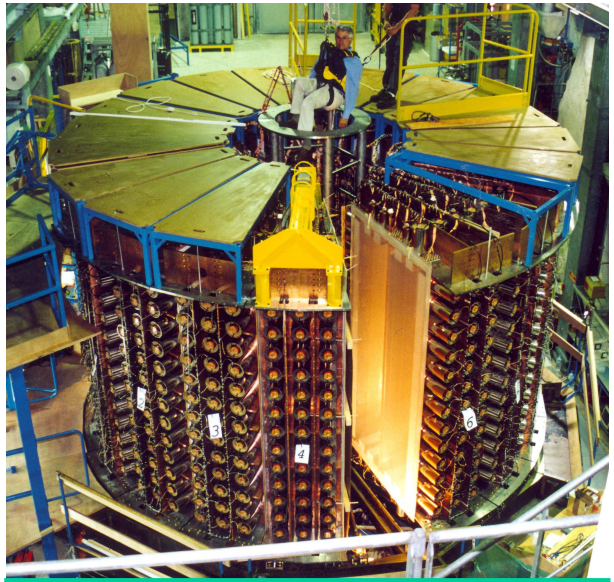
Double Beta Decay Experiments
Present and Future – First results of NEMO3

- **General remarks about ββ experiments – $Q_{\beta\beta}$, half-life and nuclear matrix uncertainty**

- **Present Experiments**
  - ✓ **NEMO3 (tracking+calorimeter – ^{100}Mo) + Future of "à la NEMO"**
  - ✓ **CUORICINO and CUORE (Bolometers – ^{130}Te)**

- **Future projects**
  - ✓ **MAJORANA (Ge detectors)**
  - ✓ **EXO (^{136}Xe + Ba^{++} daughter ion tagging)**

- **Summary**

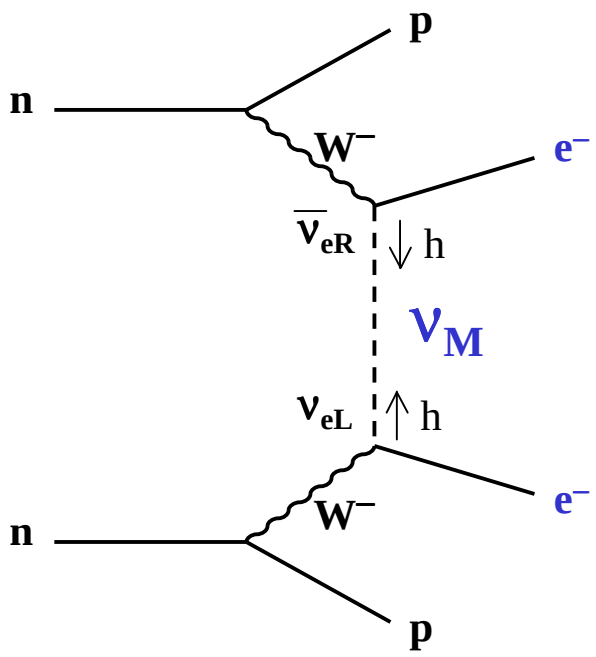


The NEMO3 detector

International Workshop on Weak Interactions in Nuclei and Astrophysics: Standard Model and Beyond - Trento - 19 June 2003
Corinne Augier (NEMO experiment)
LAL-IN2P3&Université Paris-Sud

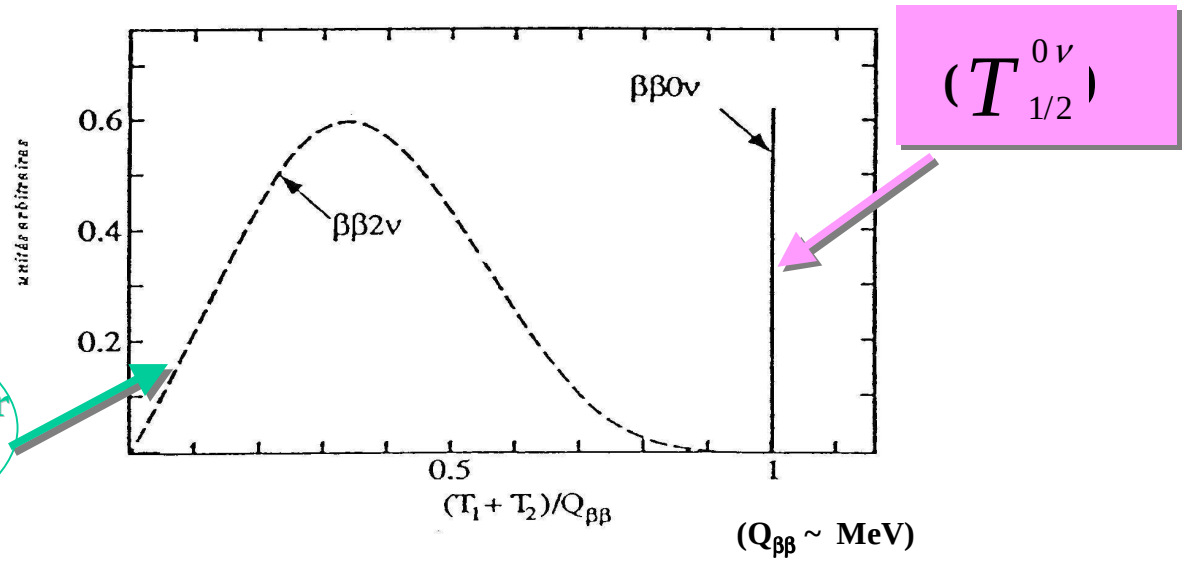
Double beta ββ0ν decay : (A,Z) → (A,Z+2) +2e⁻
Physics beyond the standard model

ββ0ν : 2n → 2p + 2e⁻



ΔL = 2 process

- Majorana neutrino $\nu = \bar{\nu}$ and effective mass $\langle m_\nu \rangle$
- Right-handed current in weak interaction
- Majoron emission ββ0νχ
- SUSY particle exchange



ββ2ν is a conventional 2nd order process in nuclear physics

2n → 2p + 2e⁻ + 2ν

Half-life for ββ0ν decay

Theoretical aspect:

$$T^{0\nu}_{1/2} = \frac{1}{\Gamma(Q^5_{\beta\beta})\ M^2\ \langle m_\nu \rangle^2}$$

Γ : phase-space factor

M : nuclear matrix element

$\langle m_\nu \rangle$: effective neutrino mass

$$\langle m_\nu \rangle = \left| \sum_{i=1}^{3} U_{ei}^2\, m_i \right|$$

m_i : mass of ν eigenstates

U_{ei}: mixing matrix elements

$\langle m_\nu \rangle$ ↔ scale for the neutrino mass

Experimental aspect:

With gaussian background:

$$T^{0\nu}_{1/2}\ (\text{years}) > \frac{\ln 2 \,.\, \mathcal{N}}{k_{C.L.}} \cdot \frac{\varepsilon}{A} \cdot \sqrt{\frac{m\ .\ t}{N_{BDF}\ .\ R}}$$

Detection efficiency → ε

Mass of isotope ββ (g) → m

Background (year^{-1}. g^{-1}. keV^{-1}) → N_{BDF}

FWHM (keV) → R

$\mathcal{N}$: Avogadro number

$k_{C.L.}$ = 1,6445 @ 90% C.L.

A : atomic mass

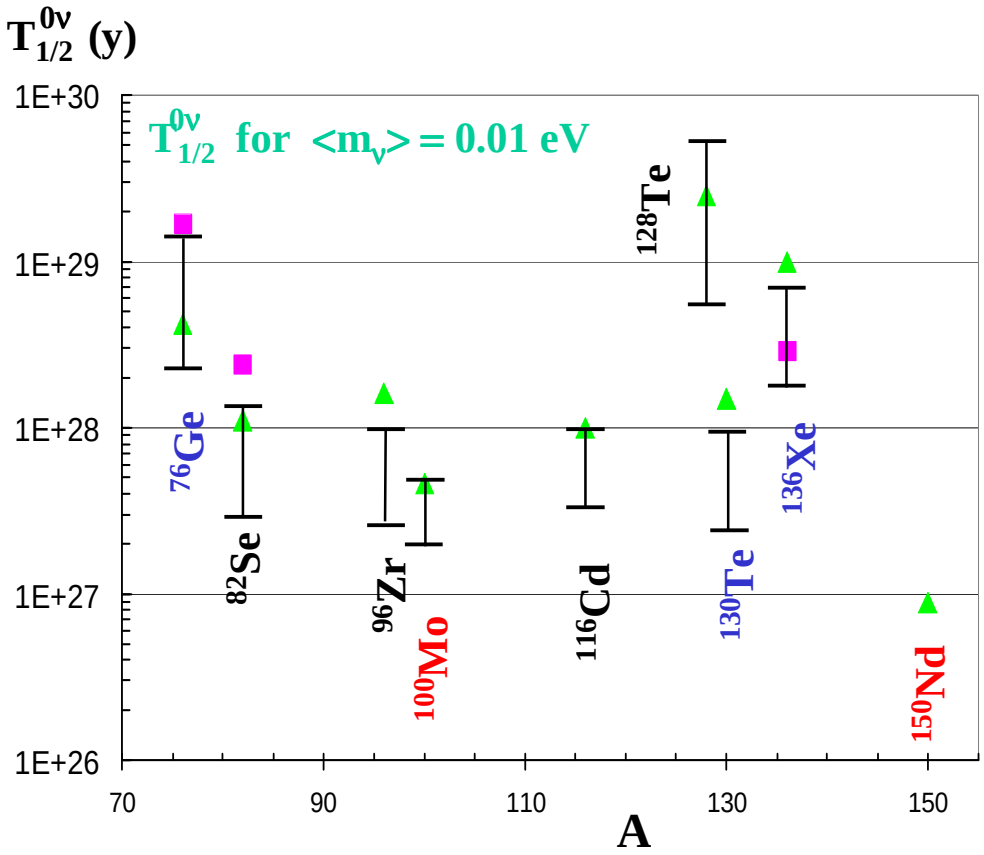
t : measurement duration (year)

Uncertainty on nuclear matrix elements

$$T^{0\nu}_{1/2} = \frac{1}{\Gamma(Q^5_{\beta\beta})\ M^2\ \langle m_\nu \rangle^2}$$

Γ : phase-space integral
M : nuclear matrix element
$\langle m_\nu \rangle$: neutrino effective mass

$^{48}Ca \rightarrow {}^{48}Ti$	$Q_{\beta\beta}$ = 4271 keV
$^{76}Ge \rightarrow {}^{76}Se$	$Q_{\beta\beta}$ = 2039 keV
$^{82}Se \rightarrow {}^{82}Kr$	$Q_{\beta\beta}$ = 2995 keV
$^{96}Zr \rightarrow {}^{96}Mo$	$Q_{\beta\beta}$ = 3350 keV
$^{100}Mo \rightarrow {}^{100}Ru$	$Q_{\beta\beta}$ = 3034 keV
$^{116}Cd \rightarrow {}^{116}Sn$	$Q_{\beta\beta}$ = 2802 keV
$^{128}Te \rightarrow {}^{128}Xe$	$Q_{\beta\beta}$ = 867 keV
$^{130}Te \rightarrow {}^{130}Xe$	$Q_{\beta\beta}$ = 2529 keV
$^{136}Xe \rightarrow {}^{136}Ba$	$Q_{\beta\beta}$ = 2479 keV
$^{150}Nd \rightarrow {}^{150}Sm$	$Q_{\beta\beta}$ = 3367 keV



The best way seems to use:

- Recent calculations
- Calculations with systematic study (several nuclei, different models…)
- Calculations where 2ν experimental measurements were used

Stoica et al., Nucl. Phys. A694, 269 (2001)
Systematic study (pnQRPA, pnRQRPA, full-RQRPA, SQRPA)

Simkovic et al., Phys. Rev. C60, 055502 (1999)
QRPA + nucleon currents

Caurier et al., Phys. Rev. Lett. 77, 1954 (1996)
Shell Model

100 kg $^{100}Mo \approx$ 1 ton ^{76}Ge !!!

Sensitivity for present experiments

2 techniques of detection

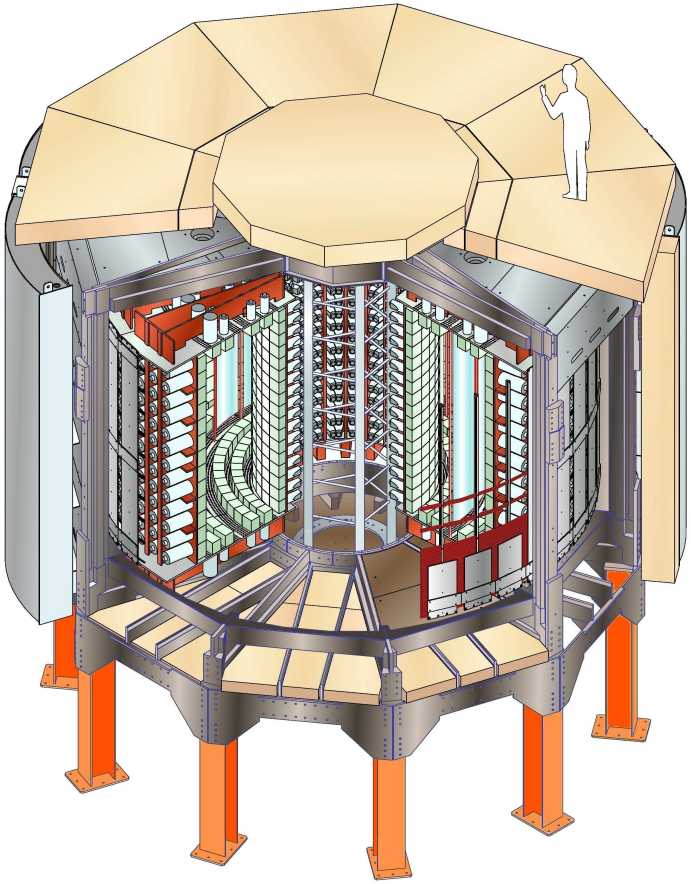
	pure calorimeter		calorimeter + tracking detector
	Ge	**Bolometers**	**TPC & wire chambers (NEMO3)**
mass		**~ 10 kg**	
Efficiency ββ0ν	**50%**	**100%**	**< 20%** ← *- geometrical efficiency; - energy loss in source foils; - scatterings in tracking volume*
Energy Resolution FWHM (at $Q_{\beta\beta}$)	**4 keV**	**8 keV** (5 keV best value)	**90 keV**
N_{bkg} /year/kg/FWHM	**0.24** (Single Site)	**4**	**0.045** ← *localisation and identification of e^-, e^+, γ–rays, delayed-α*
Origin of background	**Cosmogenic or External Bkg ?**	**α surface pollution ext. γ from ^{208}Tl**	ββ2ν

→ $T^{0\nu}_{1/2}$ > ~ 10^{25} years : ~ 1 evt ββ0ν detected / year

NEMO3 : Neutrino Ettore Majorana Observatory

CENBG Bordeaux, Charles Univ. Prague, FNSPE Prague, INEEL, IReS Strasbourg, ITEP Moscow, JINR Dubna, Jyvaskyla Univ., LAL Orsay, LPC Caen, LSCE Gif, Mount Holyoke College, Saga Univ, UCL London

- **Tracking detector** (6180 Geiger cells in He+alcohol): **Vertex σ_t = 5 mm, σ_z = 1 cm**
- **Calorimeter** (1940 plastic scintillators – low radioactivity PMTs) **σ_E/E = 3% at 3 MeV**
- **Iron shield** (20 cm) **+ Neutron shield** (water + wood + paraffin)
- **Magnetic field** B=25 G
- **All materials with low radioactivity** (total activity in ^{208}Tl and ^{214}Bi ≈ 300 Bq)

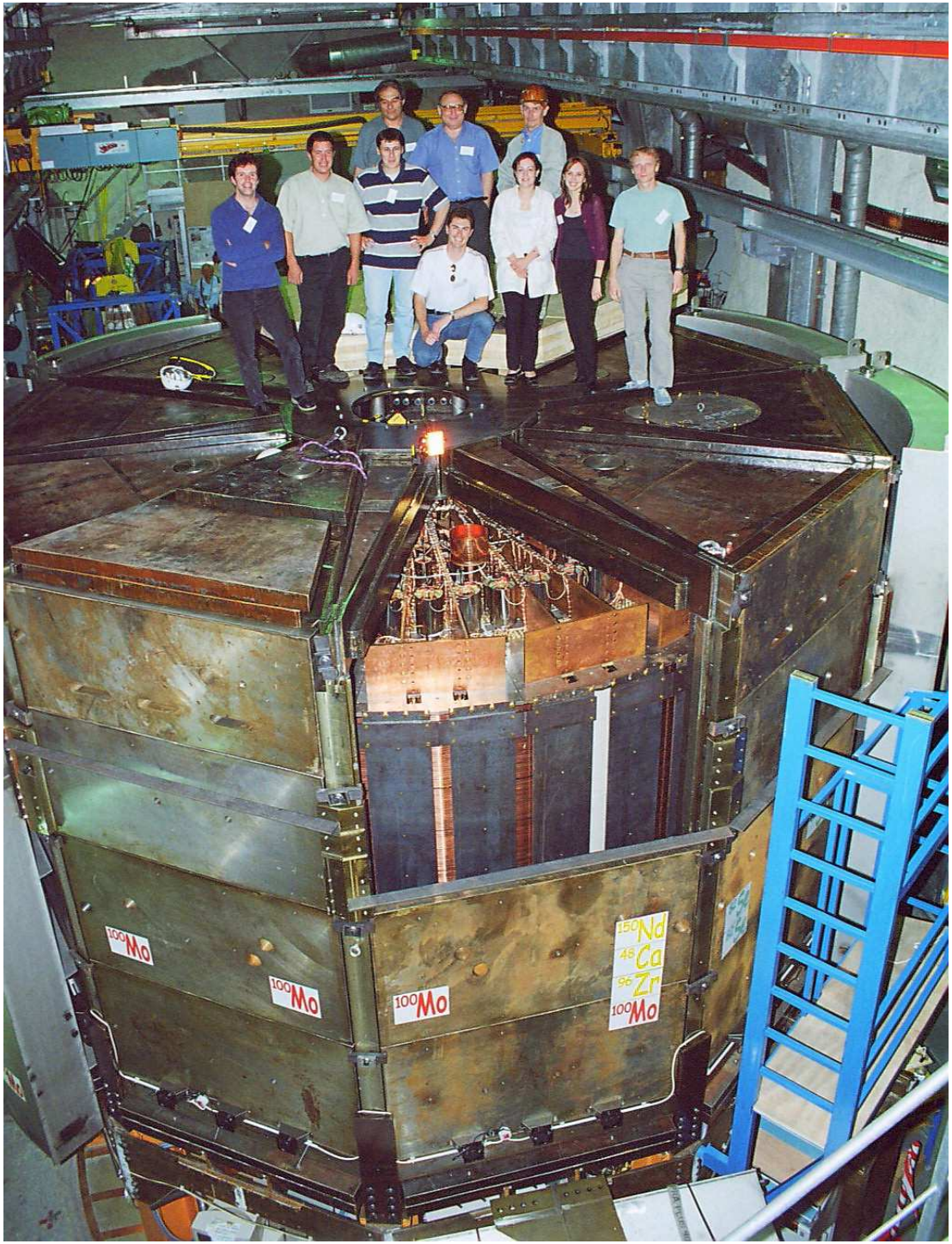


1 sector of NEMO3

general "means" of NEMO

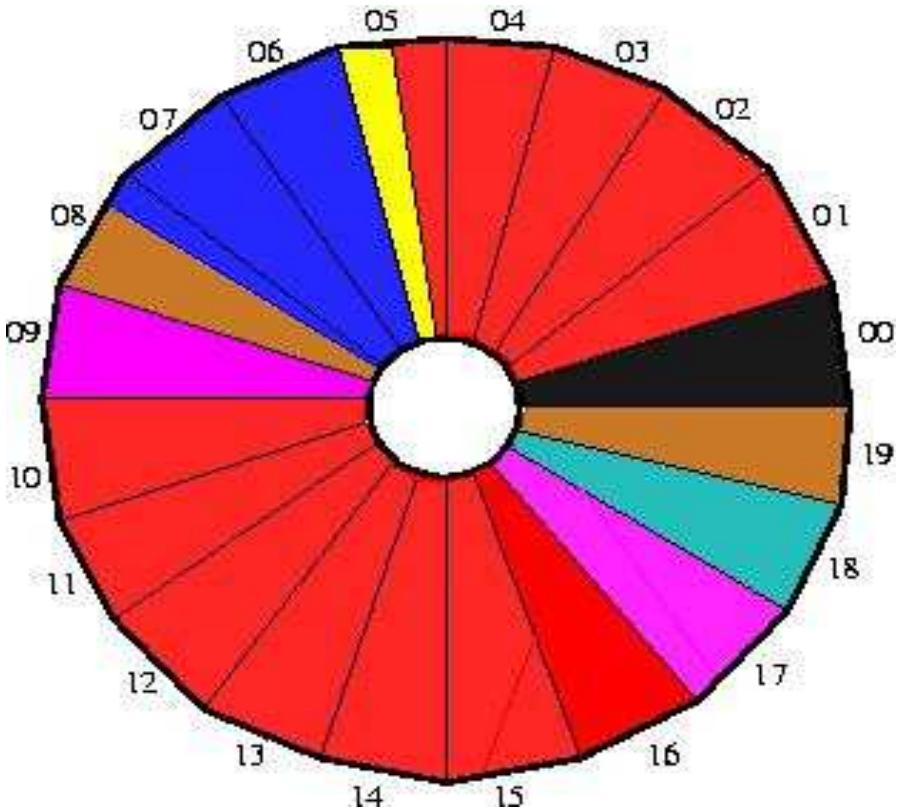
- **Measure several isotopes** ^{100}Mo, ^{82}Se, ^{130}Te, ^{116}Cd, ^{96}Zr, ^{48}Ca, ^{150}Nd
- **Tag and measure all the components of background** e^-, e^+, γ–rays, delayed-α, neutrons

"zero background" experiment


100Mo
100Mo
100Mo
150Nd
48Ca
96Zr
100Mo

Sources in NEMO3 detector (20 sectors)

Frejus Underground Laboratory (4800 m.w.e.)
ββ source foils (thickness ~ 60 mg/cm^2)



Study of ββ2ν process

^{116}Cd (0.40 kg) $Q_{\beta\beta}$ = 2802 keV

^{130}Te (0.45 kg) $Q_{\beta\beta}$ = 2533 keV

^{150}Nd (36.5 g) $Q_{\beta\beta}$ = 3367 keV
^{96}Zr (9.43 g) $Q_{\beta\beta}$ = 3350 keV
^{48}Ca (6.99 g) $Q_{\beta\beta}$ = 4271 keV

^{nat}Te (0.61 kg)
Cu (0.62 kg)

Background study

^{100}Mo (6.9 kg)
$Q_{\beta\beta}$ = 3034 keV

^{82}Se (0.93 kg)
$Q_{\beta\beta}$ = 2995 keV

Study of ββ0ν and ββ2ν process

STATUS of the NEMO3 EXPERIMENT

- Apr. 2000: first events with 3 sectors with no magnetic field and no shield
- Sep. 2001: full detector mounted and assembled
- Dec. 2001: first events with the full detector with no magnetic field and no shield
- Feb. 2002: Coil (magnetic field) mounted
- Mar. 2002: first events with the full detector with magnetic field (no shield)
- Apr. 2002: Iron shield mounted
- Feb. 2003: Neutron shield mounted

- **Jun. 2002 → Dec. 2002: Test runs with iron shield + magnetic field**
- **Dec. 2002 → Feb. 2003: Shutdown for the last tuning**

- **14 February 2003 : START TAKING DATA**

And also:

- **Runs with calibration sources (^{90}Sr, ^{207}Bi, ^{60}Co)**
  for energy and time calibration
- **Runs with neutron source**
  to study tracking vertex resolution
  to test neutron shielding (water + wood)
- **Runs to test iron shield**
  with and without iron shield

Performance of the detector as expected

How NEMO3 tags the background

Electron

Gamma : 50% efficiency at 1 MeV
Energy Threshold = 30 keV

Delayed-α tracks (<700 μs)

$^{214}Bi \rightarrow {}^{214}Po$ (164 μs) $\rightarrow {}^{210}Pb$

Positron : e^+/e^- separation with a magnetic field 25 G
3% confusion @ 1 MeV

Time of Flight : Time Resolution $\approx$ 300 ps at 1 MeV

Sensitivity of NEMO3 to measure sources of background

Design NEMO3 for 10 kg:

^{208}Tl in source foils < 20 μBq/kg

^{214}Bi in source foils < 300 μBq/kg

neutron flux < 10^{-8} n cm^{-2} s^{-1}

Sensitivity NEMO3 after 1 year of data :

⇒ **^{208}Tl in source foils < 2 μBq/kg**

channel eγ 's (Eγ = 2.6 MeV)

^{212}Bi → ^{212}Po e(γ)α (300 ns)

⇒ **^{214}Bi in source foils < 2 μBq/kg**

measured by channel e (γ) + α

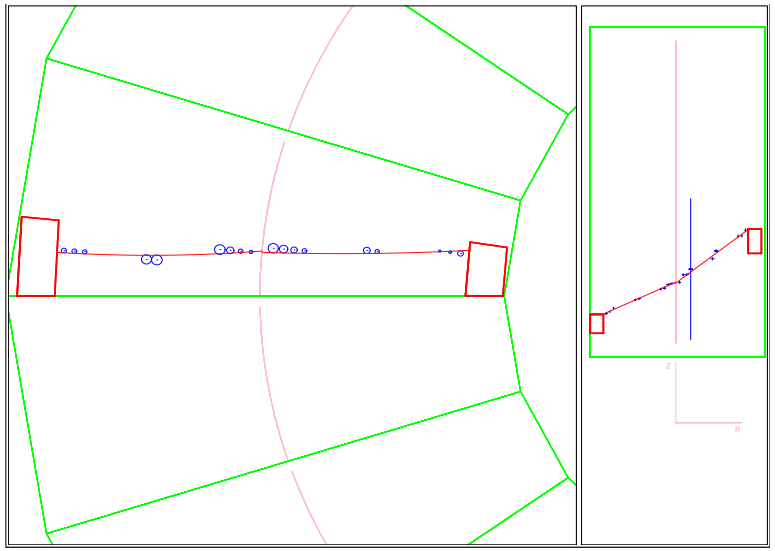
(^{214}Bi → ^{214}Po → ^{210}Pb; $T_{1/2}$ = 164 μs)

⇒ **neutrons < 10^{-9} n cm^{-2} s^{-1}**

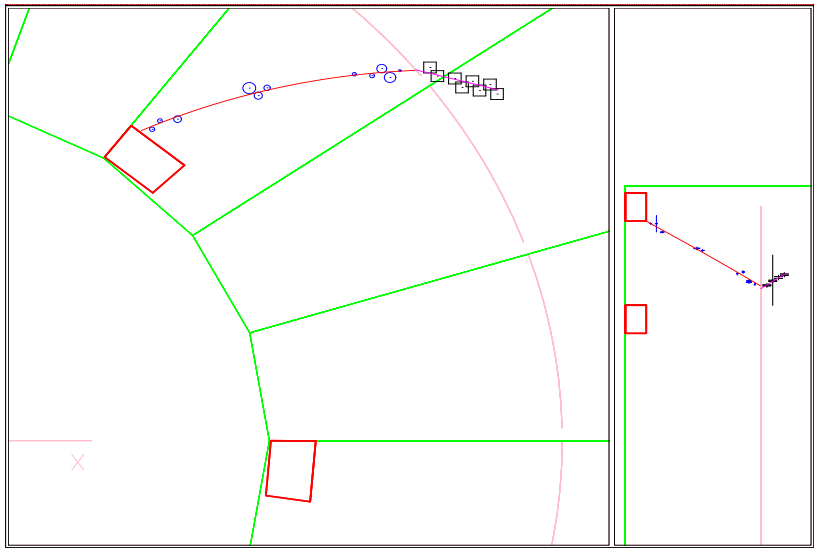
measured by e$^-$ crossing > 4 MeV

Sensitivity to 100 kg of isotopes

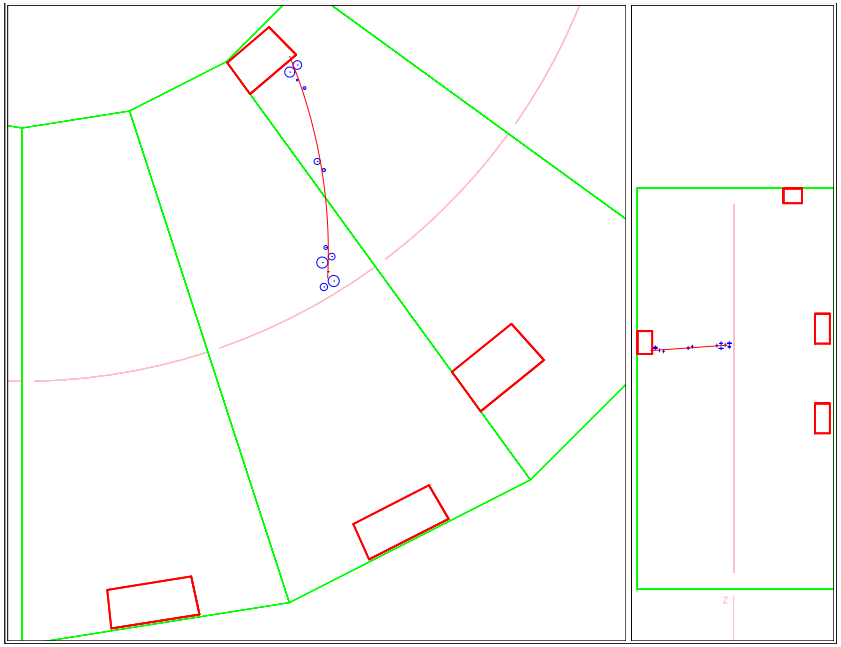
BACKGROUND EVENTS OBSERVED BY NEMO3



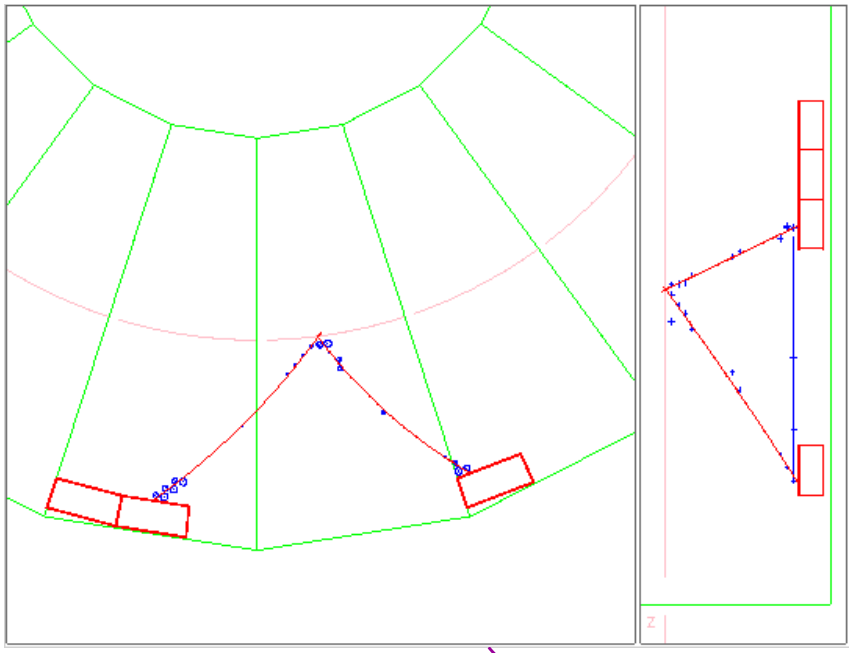
Crossing electron > 4 MeV **Neutron capture in Cu**



Electron + delayed-α track (164 μs) $^{214}Bi \rightarrow {}^{214}Po \rightarrow {}^{210}Pb$



Electron + N γ-rays ^{208}Tl **(Eγ = 2.6 MeV)**



Electron – positron pair $\vec{B}$ **rejection**

Radon in NEMO 3

Air room : ≈ 10 Bq/m^3

Two different measurements of radon in the NEMO 3 gas:

- **Radon detector:**

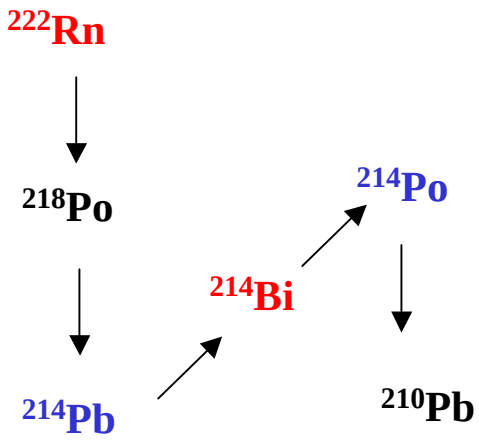
  sensitivity: 1 count/day for 1 mBq/m^3

  Radon measurement ≈ 20 mBq/m^3

- **($1e^- + 1\ \alpha$) channel in the NEMO-3 data:**

  Able to measure Radon every half day

  Radon measurement ≈ 30 mBq/m^3



Expected Background in the ββ0ν energy window for 7 kg ^{100}Mo:

~ 1 event / year

same order than the other backgrounds !!

A free Radon Tent surrounding the NEMO 3 detector in construction:

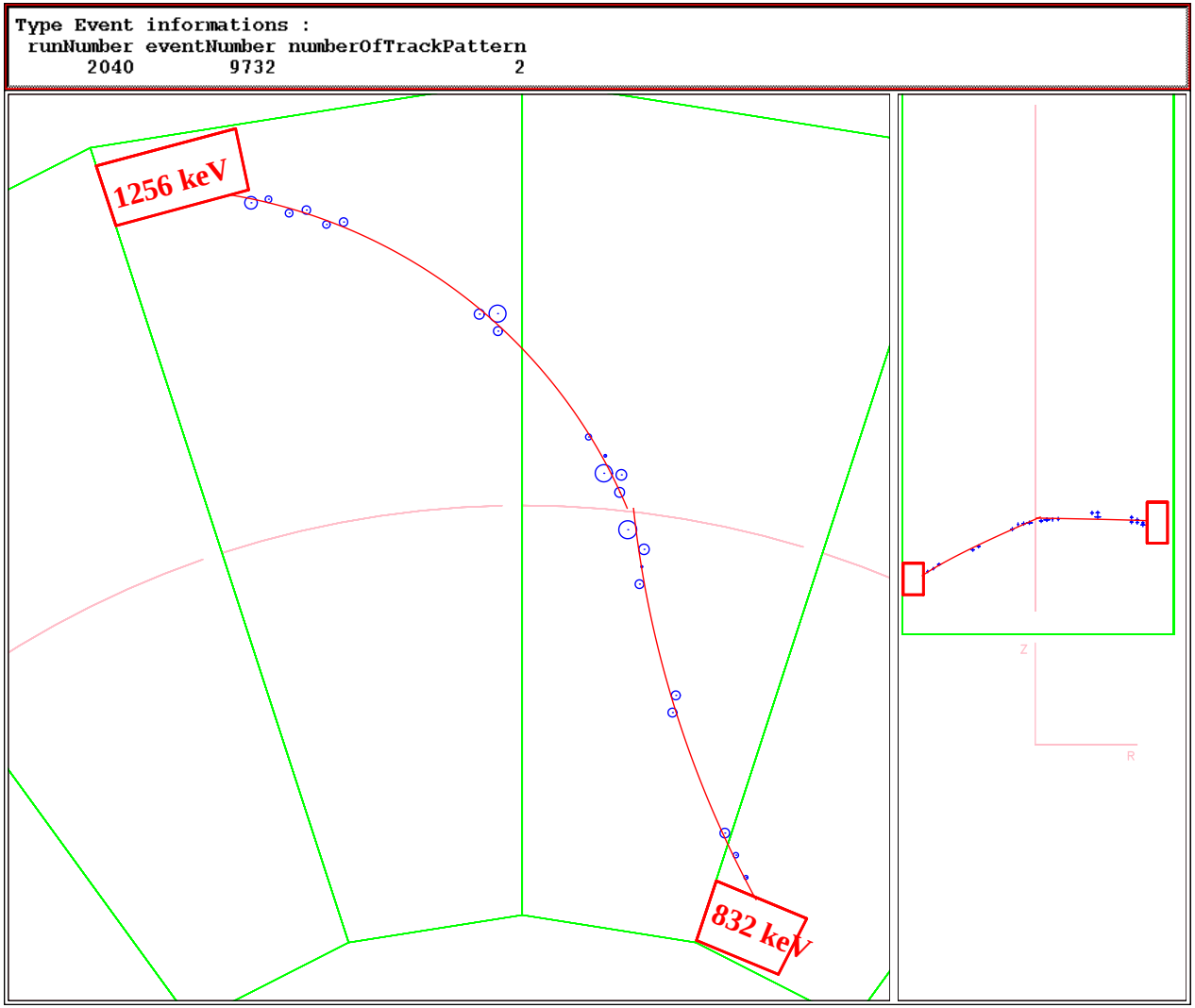
- **Fall 2003: fresh air only**

  Factor ~ 2 for Radon purification

- **Spring 2004: Radon purification system**

  Factor ~ 50

ββ2ν event observed with NEMO3



E_1+E_2= 2088 keV

$(\Delta t)mes - (\Delta t)theo$ = 0.22 ns
$(\Delta vertex)_{\perp}$ = 2.1 mm
$(\Delta vertex)_{//}$ = 5.7 mm

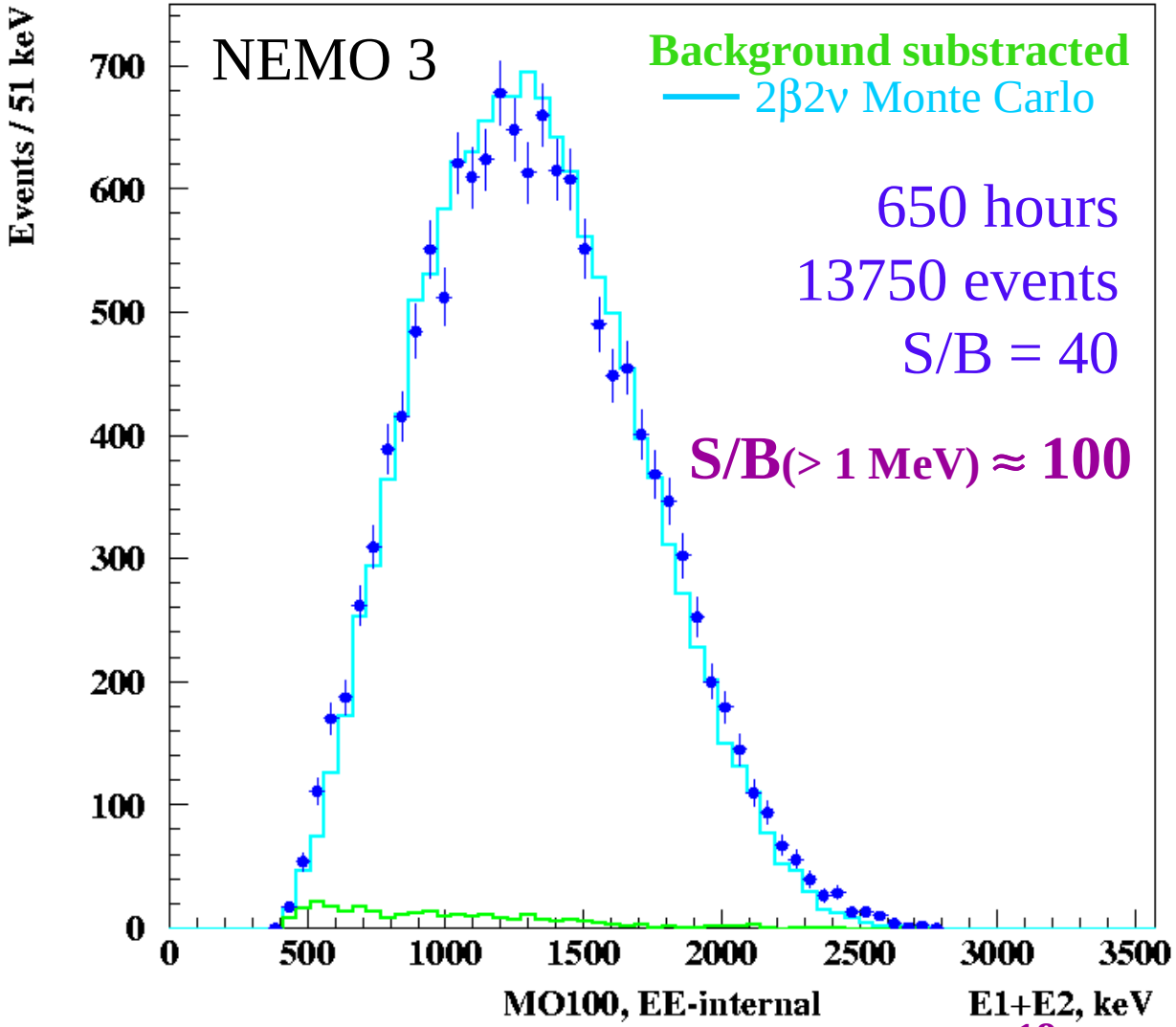
NEMO3 trigger : one ββ-like event every 1.5 minute

^{100}Mo ββ2ν - "2003 stable data taking conditions"

650 h analyzed -preliminary results

(14 Feb. 2003 – 31 Mar. 2003) no laser correction

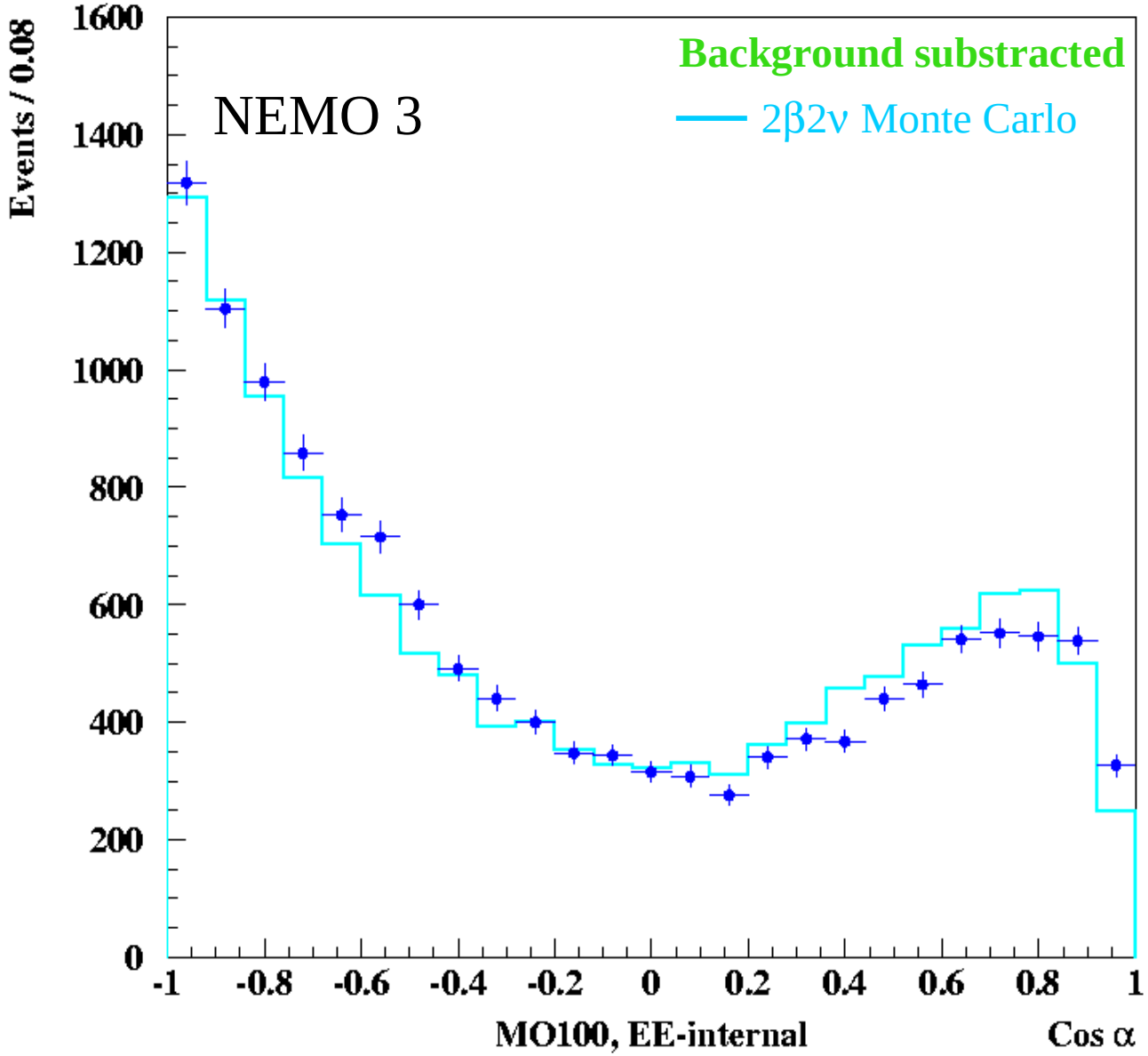
V. Vasiliev (Nemo coll.)



$$T_{1/2} = 7.8 \pm 0.09\ (stat) \pm 0.8\ (syst) \times 10^{18}\ y$$

^{100}Mo ββ2ν angular distribution

650h of data analyzed – no laser correction



Summary for ββ2ν analysis - Mo, Se, Cd and Nd

Preliminary results

V. Vasiliev (NEMO Coll.)

^{100}Mo – $T_{1/2}(2\nu)$ = 0.78	± 0.009 (stat)	± 0.08 (syst.)	10^{19} yr
^{82}Se – $T_{1/2}(2\nu)$ = 9.1	± 0.4 (stat)	± 0.9 (syst.)	10^{19} yr
^{116}Cd – $T_{1/2}(2\nu)$ = 3.1	± 0.2 (stat)	± 0.3 (syst.)	10^{19} yr
^{150}Nd – $T_{1/2}(2\nu)$ = 0.77	± 0.07 (stat)	± 0.08 (syst.)	10^{19} yr

^{100}Mo ββ0ν study using maximum of likelihood method

(A.I. Etienvre PhD thesis - preliminary result)

Motivation: only way to take into account the shape of the ββ0ν spectrum (E1+E2), the tail of the ββ2ν spectrum and to reconstruct the $Q_{\beta\beta}$ value to check the energy scale

Three variables used the differential cross-section: minimal kinetic energies of the two electrons E_{min} = E_1 or E_2, total energy E_{tot}, angle between the two tracks $\cos\theta$.

3-dim probability distribution function P_k^{3D} are build for each of the 7 channels giving 2e-like events

$$P_k^{3D} = P_k(E_{tot})\, P_k(E_{min}/E_{tot})\, P_k(\cos\theta/E_{min})$$

Likelihood: parameters of the maximisation

- $x_k = \dfrac{N_k}{N_{tot}}$ — *Number of events for k process* (N_k); *Total number of events* (N_{tot})
- $Q_{\beta\beta}$

$$L = \prod_{i=1}^{N_{tot}} \left(\sum_{k=1}^{7} x_k P_k^{3D} \right)$$

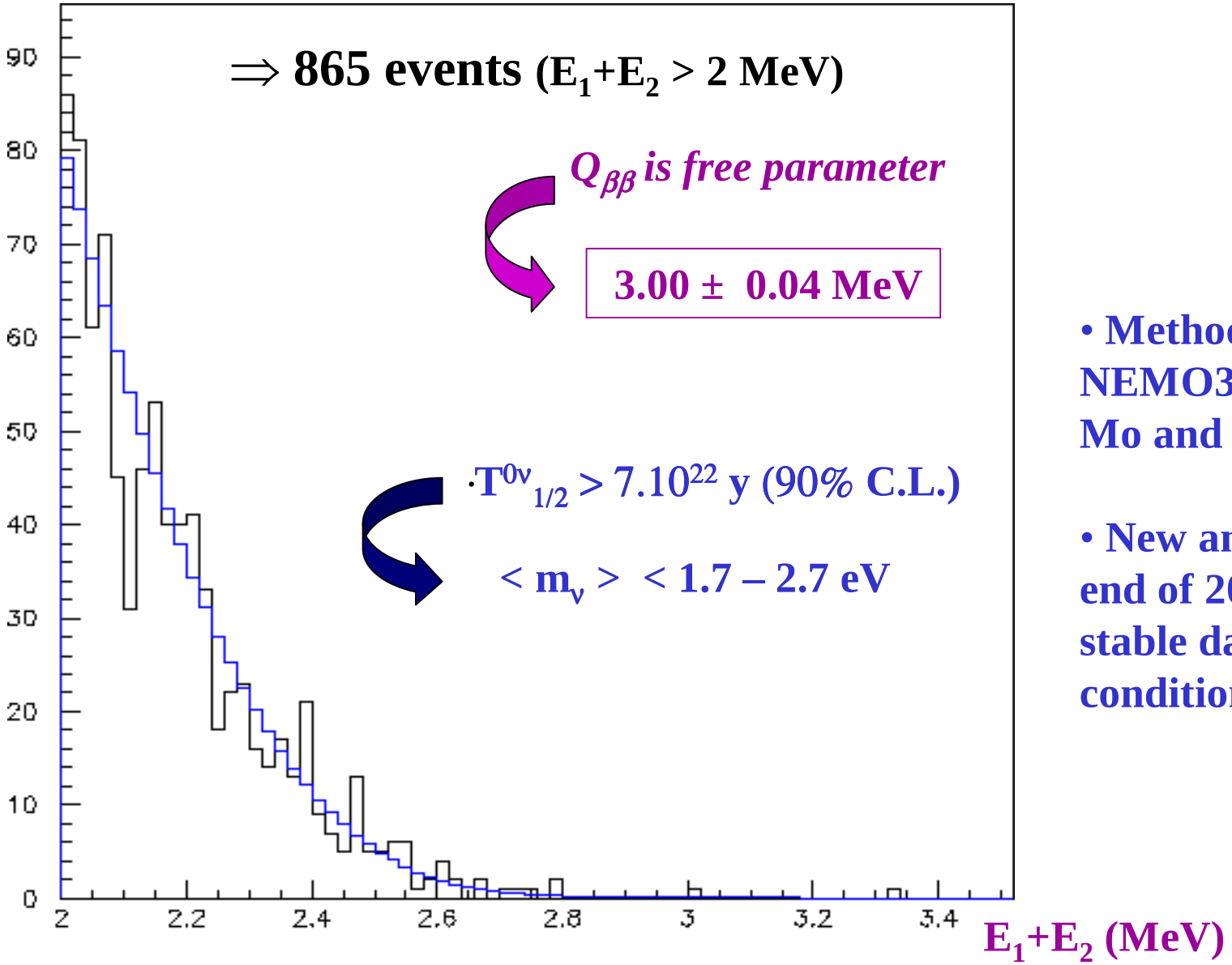
x_k is the contribution of k process (signal or bkg) to the likelihood

Amplitudes of the 5 background distributions can be constrained or fixed using other measurements

- **internal ^{208}Tl** : < 68 μBq/kg @ 90% C.L. using e^- +Nγ–rays channel analysis ($1 \leq N \leq 3$)
- **internal ^{214}Bi** : NEMO3 requirement (< 300 μBq/kg)
- **external ^{208}Tl** : HPGe measurement (18 Bq)
- **external ^{214}Bi** : HPGe measurement (300 Bq)
- **neutrons** : 0.2 event (crossing electrons)

Minimisation of -ln L ⇒ $x_{0\nu}$, $Q_{\beta\beta}$

^{100}Mo ββ0ν fit with 900 h of "2002 test data taking" *(preliminary result)*



- **Method to use for NEMO3 analysis of Mo and Se**
- **New analysis at the end of 2003 using stable data taking conditions**

^{100}Mo ββ0ν preliminary result "2003 stable data taking conditions"

650h analyzed - no laser correction - preliminary results

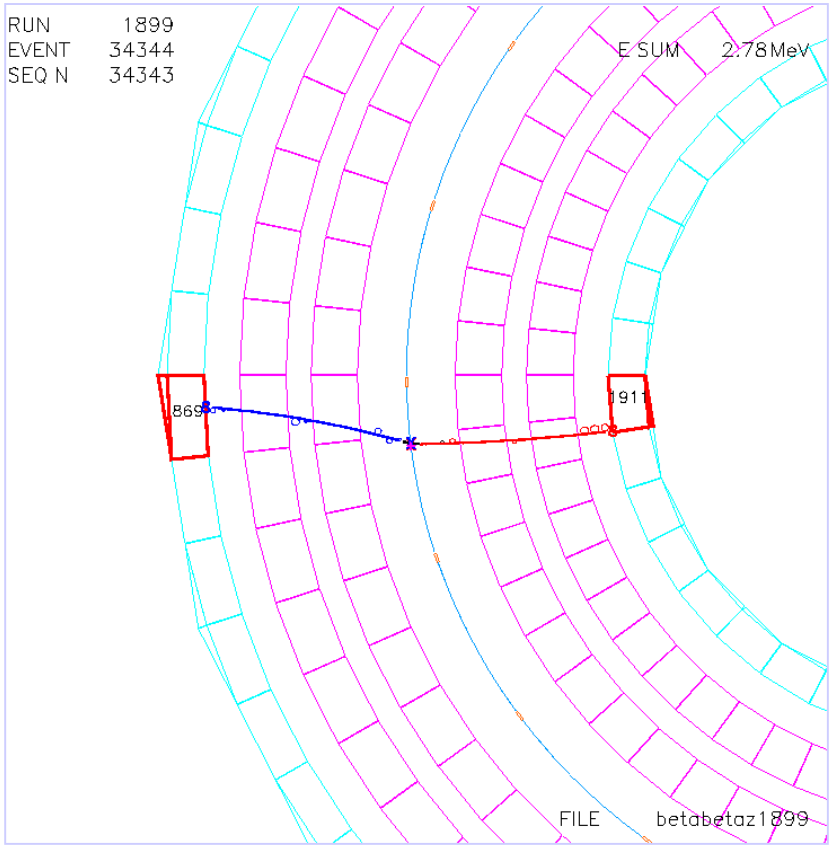
V. Vasiliev (Nemo coll.)

⇒ ββ0ν decay

- ββ0ν energy region [2.75,3.2] MeV
- 1 ββ0ν candidate event
- ε = 10 %
- Conservative limit

$$T_{1/2}^{0\nu} > 6 \cdot 10^{22} \text{ y. (90\% C.L.)}$$

$$< m_\nu > < 1.8 - 2.9 \text{ eV}$$



⇒ ββ0νχ decay (Majoron)

- energy region [2.6,3.2] MeV
- 9 candidate events, 5 expected
- ε = 0.7 %
- Conservative limit

$$T_{1/2}^{0\nu\chi} > 1.8 \cdot 10^{21} \text{ y. (90\% C.L.)}$$

$$g_{ee} < (0.56 - 1.70) \cdot 10^{-4}$$

NEMO3 : Expected background and sensitivity

5 years of data
Energy window: [2.8-3.2] MeV
Efficiency ββ0ν = 14%

External background and neutron background negligible

7 kg of ^{100}Mo

Source contamination : *$A(^{214}Bi) < 0.3$ mBq/kg*
$A(^{208}Tl) < 0.02$ mBq/kg

Internal background : *^{214}Bi < 0.04 evts/y/kg*
^{208}Tl < 0.04 evts/y/kg
ββ(2ν) 0.11 evts/y/kg

Total Bkg < 1.4 event/year
$T_{1/2}(0\nu) > 5.10^{24}$ yr
$\langle m_\nu \rangle < 0.2 – 0.3$ eV

1 kg of ^{82}Se

Source contamination : *$A(^{214}Bi) = 1.2 \pm 0.5$ mBq/kg*
(measured) *$A(^{208}Tl) = 0.4 \pm 0.1$ mBq/kg*

Internal background : *ββ(2ν) 0.01 evts/y/kg*

Uniform Contamination:
^{214}Bi 0.2 evts/y/kg
^{208}Tl 1.0 evts/y/kg

Bkg ~ 1.2 event/year

Hot spots:
Pollution rejected

Bkg ~ 0 event/year
$T_{1/2}(0\nu) > 1.5.10^{24}$ yr
$\langle m_\nu \rangle < 0.45 – 1.3$ eV

Past, Present and Future…

	PRESENT		FUTURE	
Calorimeters:				
Mibeta →	CUORICINO (1 yr)	M=13 kg ^{130}Te (40 kg) > 3–7 10^{24} yr < 0.2 – 0.6 eV	→ CUORE (5 yr)	M= 760 kg TeO_2 > 2.10^{26} yr < 0.04 – 0.08 eV
	^{76}Ge	M=6-11 kg ^{76}Ge > 1.9 10^{25} yr < 0.3 – 1 eV	External Bkg →	GENIUS
			Cosmogenic Bkg →	MAJORANA (10 yr) — M=500 kg enr. Ge > 4.10^{27} yr < 0.02 – 0.07 eV
Tracking:				
NEMO-1-2 →	NEMO-3 (5 yr)	M=7 kg ^{100}Mo (10 kg) > 5 10^{24} yr < 0.2 – 0.3 eV	→ "à la NEMO" (5 yr)	M=100 kg ^{100}Mo > 10^{26} yr < 0.04 – 0.07 eV
Neuchatel TPC Moe			→ EXO 5 (10 yr)	M=1 (10) tons ^{136}Xe > 8.10^{26} yr (1.3 10^{28}) < 0.05 – 0.13 (0.013-0.032) eV
ELEGANT-I-V			→ MOON	

Future of "à la NEMO"

NEMO3, Phase-2: 10 kg of ^{82}Se or even better: 10 kg of ^{150}Nd

D.O.E. starts purification of Se and Nd (INEEL, Idaho Falls, USA)

10 kg ^{150}Nd, 5 years of data: $\langle m_\nu \rangle < 0.06 - 0.3$ eV

Next step would be 100 kg enriched source: ^{100}Mo (or ^{82}Se or ^{150}Nd)

Background rejection:

NEMO3 after 1 year of data will validate ^{208}Tl and ^{214}Bi purification processes and neutron rejection at the level required for 100 kg of ^{100}Mo

Need to improve Energy Resolution to separate ββ0ν and ββ2ν

We need FWHM ~ 8%/$\sqrt{E}$ (MeV) (instead of 14% for NEMO-3)

in order to have ~ 1 event/year of ββ2ν in the ββ0ν energy window (like for NEMO3)

How to improve ΔE/E ?

- **calorimeter: Silicium (e^-) + small scintillator (γ) ?**
- **Modular source: bkg rejection + energy loss improvement**

4 modules

e = 60 mg/cm^2

Need to increase the ββ0ν efficiency

Energy resolution

Geometrical acceptance

Energy loss of electrons

But NEMO collaboration is now working with first NEMO3 data…
Wait and see !…

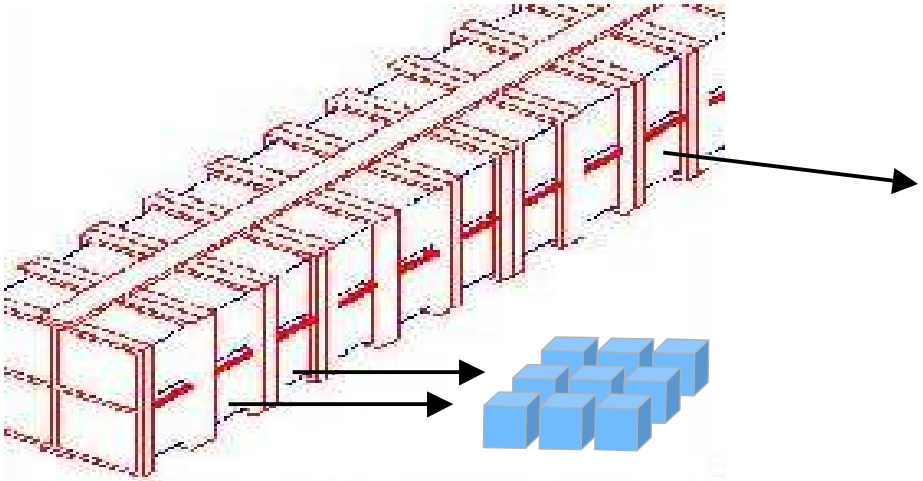
CUORICINO : "little" Cryogenic Underground Observatory for Rare Events

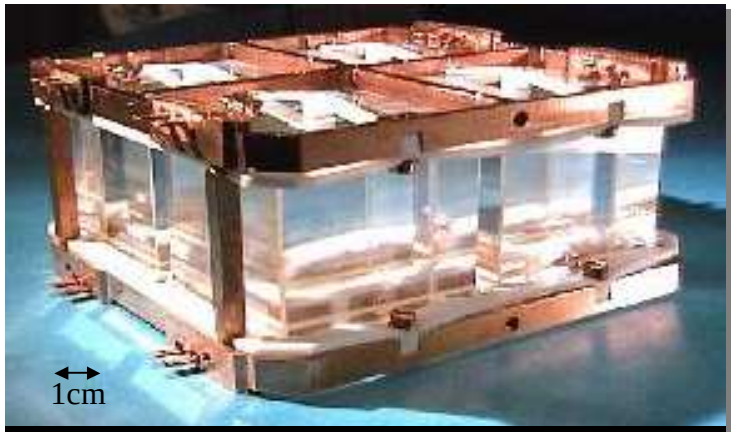
Firenze, Gran Sasso, Insubria, LBNL, Leiden, Milano, Neuchatel, South Carolina, Zaragoza
Begin operation : 2003 Gran Sasso Underground Laboratory

^{130}Te – 2615 keV

Bolometers : 1 tower with - 11 modules of 4 crystals $^{nat}TeO_2$ of 760 g
- 2 modules of 9 crystals $^{nat}TeO_2$ of 340 g
T ~ 10 mK => C ~ 2 nJ/K => 1 MeV/0,1 mK

⇒13 kg ^{130}Te (40 kg TeO_2)
$Q_{\beta\beta}$=2528 keV





One module with 4 TeO_2 crystals of 750 g

1st hypothesis :

With performances of the 20 crystals of MI-BETA
FWHM = 8 keV
N_{BDF} : 0.5 event year^{-1} keV^{-1} kg^{-1}

$T^{0\nu}_{1/2}$ **> 3.3 10^{24} years (90% C.L.)**
< m_ν> < 0.3 – 0.6 eV (in 1 year)

2nd hypothesis :

FWHM = 5 keV Best value with 760 g crystal

N_{BDF} : 0.1 event year^{-1} keV^{-1} kg^{-1}
if bkg dominated by a surface pollution

$T^{0\nu}_{1/2}$ **> 7.2 10^{24} years (90% C.L.)**
< m_ν> < 0.2 – 0.4 eV (in 1 year)

CUORICINO Tower is now in operation in the MI-BETA cryostat

CUORE PROJECT

hep-ex/0212053, submitted to N.I.M

1000 TeO_2 bolometers
Total mass = 760 kg TeO_2 ---> m = 260 kg ^{130}Te

Expected sensitivity:
FWHM = 5 keV
Bkg = 0.01 events/keV/kg/yr at $Q_{\beta\beta}$=2528 keV
46 events/yr in the 5 keV energy window

$T_{1/2} > 2\ 10^{26}$ y **$\langle m_\nu \rangle < 0.04 - 0.08$ eV**
(in 5 years)

ADVANTAGES

Natural abundance of Te^{130} = 34%

$\varepsilon \approx 100\%$

R = 5 keV

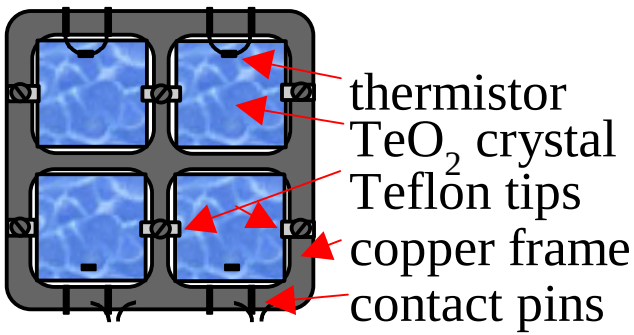
CUORE = N modules of Cuoricino crystals

DISADVANTAGES

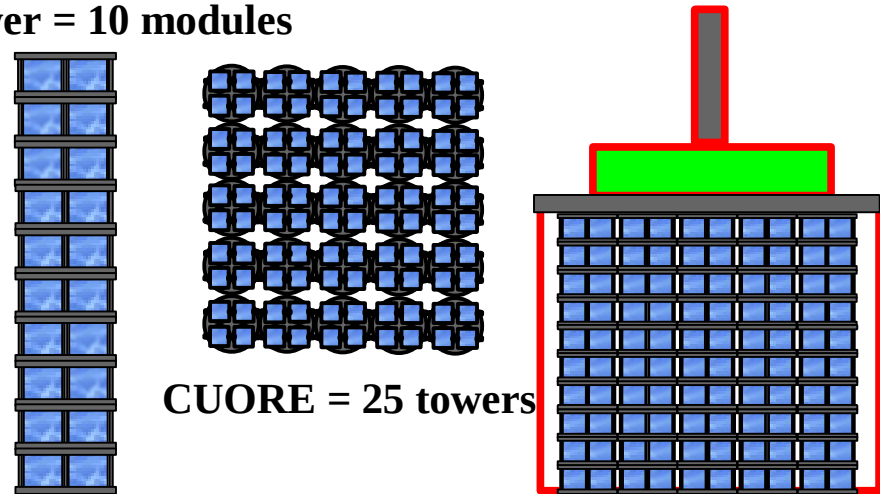
Bkg : ≈ 0.2 events/year/kg/keV for last plane tested
Mostly α surface pollution
Goal for Cuore: 0.01 events/year/kg/keV

Crystal mounts and cryostat
= significant mass close to the bolometers
Cryostat shielded by Roman lead
But copper and Teflon close to the crystals
$\Rightarrow$ source of cosmogenic activities or γ ^{208}Tl ?

1 module = 1 plane of 4 crystals, 760 g each



1 tower = 10 modules



CUORE = 25 towers

Best Limits Today obtained with Ge diodes:

experiments Heidelberg-Moscow & IGEX

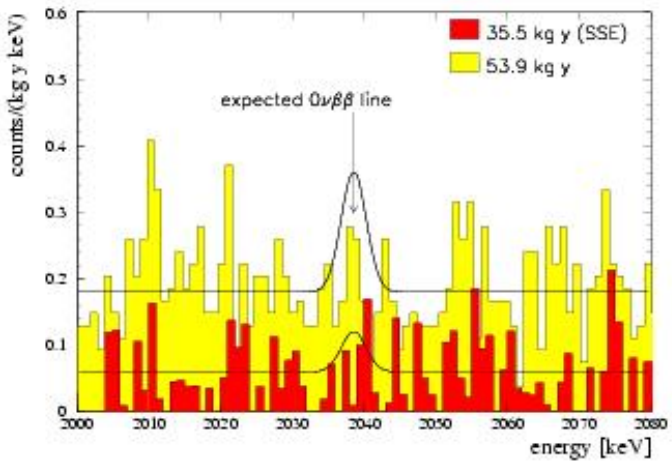
Enriched Germanium diodes (86% in ^{76}Ge, $Q_{\beta\beta}$=2038,5 keV)

Heidelberg-Moscow

1990-2000 Gran Sasso Underground Laboratory

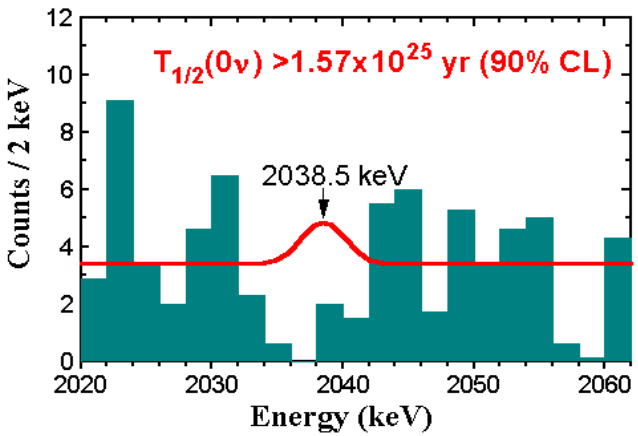
5 detectors Ge (total mass = 10,9 kg)
FWHM = 3,85 keV
N_{Bkg} = 0,06 counts y^{-1} kg^{-1} keV^{-1} (SSE)

$$T_{1/2}^{0\nu} > 1.9\ 10^{25}\ y\ (90\%\ C.L.)$$
$$< m_\nu > < 0.3 - 1.0\ eV$$



Klapdor et al. Eur Phys. J. 12 (2001) 147

IGEX (International Ge EXperiment)



Gonzales et al. Nucl. Phys. B (Proc. Suppl.) 87 (2000) 278

1994-2000 Baksan – Canfranc Underground Laboratories

3 detectors Ge (total mass = 6 kg)
FWHM = 4 keV
N_{BDF} = 0,07 counts y^{-1} kg^{-1} keV^{-1} (SSE)

$$T_{1/2}^{0\nu} > 1.57\ 10^{25}\ y\ (90\%\ C.L.)$$
$$< m_\nu > < 0.36 - 1.07\ eV$$

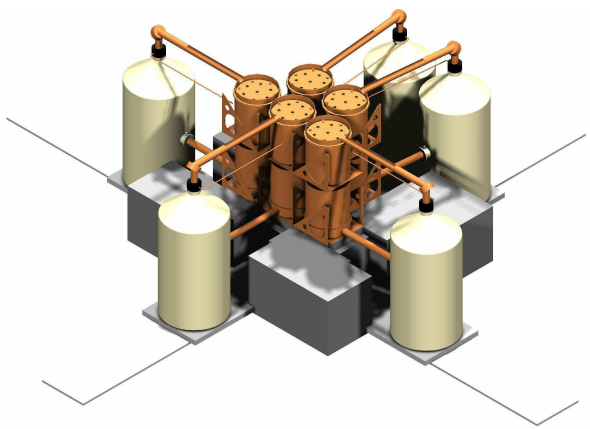
MAJORANA PROJECT

hep-ex/0201021 – 11 jan 2002

Dubna, ITEP, JINR, New Mexico State, Pacific Northwest Natl Lab, South Carolina, TUNL, University of Washington

210 enriched (84%) Ge detectors, 2.4 kg each: total mass = 500 kg (420 kg ^{76}Ge)

Long project: ~ 10 years of R&D and construction + 10 years of data tacking



Cosmogenic activity (^{68}Ge and ^{60}Co) was the limiting bkg for IGEX

➔ IGEX without Pulse Shape Discri.: 0.2 counts/keV/kg/y

- **Fabrication of detectors at an underground facility**

  ^{68}Ge decay ($T_{1/2}$=271 days) : Reduction Factor = 10

  ^{60}Co decay ($T_{1/2}$=5.7 years) : Reduction Factor = 2

- **New Pulse Shape Discrimination (PNNL/USC)**

  Demonstrated Reduction Factor = 3.8

- **Detectors Segmentation 6-axial + 2-azimuthal**

  Monte-Carlo Reduction Factor = 7.2

Total expected background at 2039 keV

in the energy window 3.57 keV (2.8 σ) = 6.5 events

➔ 1.1 10^{-3} counts/FWHM/kg/y

Expected sensitivity:
efficiency = 73%
FWHM = 3 keV
$T^{0\nu}$ = 4.0 10^{27} y
$\langle m_\nu \rangle$ = 0.02 – 0.07 eV

MAJORANA/ GENIUS :
Need common approach to a large Ge DBD Experiment ???

EXO (^{136}Xe) : Enriched Xenon Observatory

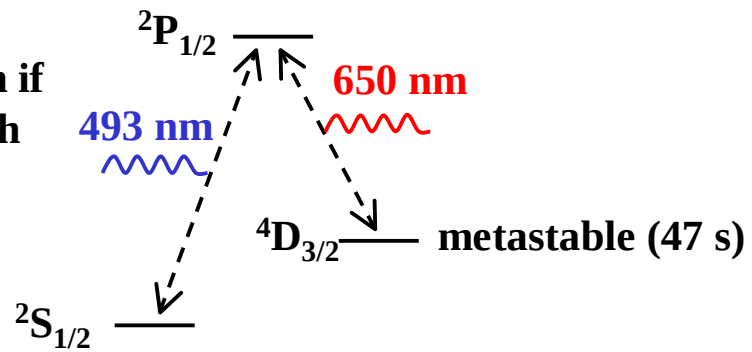
Phys. Lett., B480, 12 (2000)

Univ. of Alabama, Caltech, IBM Almaden, UC Irvine, ITEP Moscow, Neuchatel, Stanford, Torino, Trieste

Up to 10 tons of 80% enriched ^{136}Xe (world production ~30 tons/year)
Detect the $^{136}Ba^{+}$ daughter ion correlated with the ββ decay ($^{136}Xe \rightarrow {}^{136}Ba^{++}\, e^{-}\, e^{-}$) using optical spectroscopy (Moe, Phys. Rev. C44, 931, 1991)

Should eliminate all backgrounds except ββ2ν

Possible real time optical detection if the ion is localized and probed with laser
Single ions can be detected from a photon rate of 10^7/s



Expected sensitivity:

Mass (ton)	Enrich. (%)	Eff. (%)	Measur. Time (yr)	Background	$T_{1/2}(0\nu)$	$\langle m_\nu \rangle$ (eV)
1	80	70	5	0 + 1.8 events	$8.3\ 10^{26}$	0.05 – 0.13
10	80	70	10	0 + 5.5 events	$1.3\ 10^{28}$	0.012 – 0.032

Both Liquid Xe and Gas Xe options open

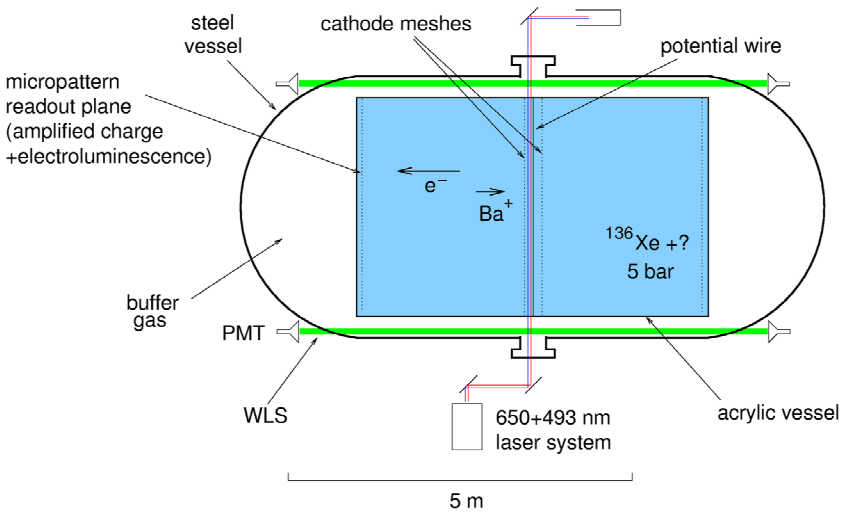
Advantage of TPC Gas Xe:

- **Information from tracking can resolve 2 blobs**
- **Can optically detect the Ba^+ in-situ**

First 100 kg test production completed in April 2002

Caltech-Neuchâtel-PSI, Gotthard und.lab. (3000 mwe)
TPC, 62.5 % enriched ^{236}Xe at 5 bar (180 l fiducial, 5.3 kg)
E_0=2.48 MeV $T_{1/2}^{0\nu} > 4.4 \cdot 10^{23}$ yr
High pressure (5 bars) 1t Xe gas TPC with laser tagging
Energy Resolution obtained by Gotthard 5 bar xenon :
$\sigma(E)/E$= 2.7 % at 2.48 MeV for electrons (^{232}Th)

Some R&D to improve energy resolution and efficiency
Micromegas Readout to amplify charge
Light detection (electroluminescence) in xenon (+ CF4 ?)



Advantages of Liquid Xe:

- **very small detector (3m^3 for 10 tons)**
- **No high pressure**
- **Ba^{++} neutralization easier**

Unknowns for Liquid Xe:

- **Is energy resolution sufficient ?**
- **Ba extraction with good efficiency ?**

(via a cold finger electrode coated in frozen Xe)

- **Ba ion is electrostatically attracted to the cold finger**
- **Later the cold finger can be heated to evaporate the Xe and release the Ba ion into a radio frequency quadrupole trap.**
- **Then the Ba^+ is optically detected.**

First test of L-Xe ionization chamber (1 liter) to test energy resolution:

Good acceptance to scintillation AND ionization

Best resolution obtained by linear combination of the scintillation and ionization signals

Resolution ~ 2%, sufficient for EXO experiment

Test UHV/High Pressure Ba ion trap: initial test successful

Initial prototype with 200 kg enriched Xe without Ba tagging will operate at the Waste Isolation Pilot Plant (WIPP, New Mexico)

SUMMARY

Experiments	Mass (enr. mass)	FWHM (at $Q_{\beta\beta}$)	N_{BKG} /kg/yr/FWHM	$T_{1/2}(0\nu)$ (in year)	$\langle m_\nu \rangle$ (in eV)	Counts /year/FWHM
Heidelberg-Moscow IGEX 10 yr	11 kg	4 keV	0.24	$1.9\ 10^{25}$	0.3 – 1	2.4
NEMO-3 5 yr	7 kg	90 keV	0.045	$5.\ 10^{24}$	0.2 - 0.3	1.4
CUORICINO 1 yr	40 kg (13)	8 keV 5 keV	0.5 0.1	$3.\ 10^{24}$ $7.\ 10^{24}$	0.3 - 0.6 0.2 - 0.4	20 4
CUORE 5 yr	760 kg(260)	5 keV	0.035	$2.\ 10^{26}$	0.04 – 0.08	25
MAJORANA *(GENIUS)* 10 yr	500 kg(420)	4 keV	$1.1\ 10^{-3}$	$4.\ 10^{27}$	0.02 - 0.07	0.75
EXO - 5 yr 10 yr	1 ton 10 tons	120 keV	$3.5\ 10^{-4}$	$8.\ 10^{26}$ $1.3\ 10^{28}$	0.05 - 0.13 0.012 - 0.032	0.35 0.55
MOON	*34 tons* *(3.3 tons)*	*200 keV*	*$4.5\ 10^{-4}$*		*0.05*	*~ 15*
NEMO-Next	*100 kg*	*50 keV*	*$1.7\ 10^{-3}$*	*10^{26}*	*0.04 - 0.07*	*0.17*

CONCLUSION

Many ambitious and exciting projects

A mass sensitivity of 30-100 meV is reachable !

Need serious R&D to reduce background

Need 100 kg step with 2 experiments → **1 calorimeter** / → **1 tracking detector + calorimeter**

using several isotopes

=> double beta international group since summer 2002

Need a big effort on nuclear matrix element calculations (DATABASE?)

CUORICINO starts to be in operation

NEMO-3 starts taking data with stable conditions

Tracking chamber and calorimeter performance as expected

Preliminary results for $\beta\beta2\nu$ decay of Mo, Se, Cd and Nd were obtained
Analysis for others isotopes (Ca, Zr, Te) are in progress
Mo decay on the excited states will be available soon
Search for neutrinoless and majorana $\beta\beta$ decay is in progress