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

- General remarks about $\beta \beta$ 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

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

The NEMO3 detector
Double beta $\beta\beta 0\nu$ decay: $(A,Z) \rightarrow (A,Z+2) + 2e^-$

Physics beyond the standard model

$\Delta L = 2$ process

$\beta\beta 0\nu$: $2n \rightarrow 2p + 2e^-$

- Majorana neutrino $\nu = \bar{\nu}$ and effective mass $<m_\nu>$
- Right-handed current in weak interaction
- Majoron emission $\beta\beta 0\nu\chi$
- SUSY particle exchange

$\beta\beta 2\nu$ is a conventional 2nd order process in nuclear physics

$2n \rightarrow 2p + 2e^- + 2\nu$

$(T_{1/2}^{0\nu})$

$(Q_{\beta\beta} \sim \text{MeV})$
**Half-life for $\beta\beta 0\nu$ decay**

**Theoretical aspect:**

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

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

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

$m_i$ : mass of $\nu$ eigenstates  
$U_{ei}$ : mixing matrix elements

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

**Experimental aspect:**

**With gaussian background:**

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

$\mathcal{N}$: Avogadro number  
$k_{\text{C.L.}} = 1.6445 \ @ \ 90\% \ C.L.$  
$A$ : atomic mass  
$t$ : measurement duration (year)

Background (year$^{-1}$, g$^{-1}$, keV$^{-1}$)  
FWHM (keV)
Uncertainty on nuclear matrix elements

\[ T_{1/2}^{0\nu} = \frac{1}{\Gamma(Q_{\beta\beta}^5) M^2 \langle m_\nu \rangle^2} \]

- \( \Gamma \): phase-space integral
- \( M \): nuclear matrix element
- \( \langle m_\nu \rangle \): neutrino effective mass

The best way seems to use:

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

Systematic study (pnQRPA, pnRQRPA, full-RQRPA, SQRPA)

QRPA + nucleon currents

Shell Model

\[ 100 \text{ kg} \ 100^{\text{Mo}} \approx 1 \text{ ton} \ 76^{\text{Ge}} \]
### Sensitivity for present experiments

2 techniques of detection

<table>
<thead>
<tr>
<th>Pure Calorimeter</th>
<th>Calorimeter + Tracking Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge</td>
<td>Bolometers</td>
</tr>
<tr>
<td>Mass</td>
<td>~10 kg</td>
</tr>
</tbody>
</table>

#### Efficiency $\beta\beta 0\nu$

- $\text{Efficiency } 50\%$  
- $\text{Efficiency } 100\%$  
- $< 20\%$  

#### Energy Resolution

- $\text{Energy Resolution FWHM (at } Q_{\beta\beta})$  
- $4 \text{ keV}$  
- $8 \text{ keV}$  
- $90 \text{ keV}$  

#### Background

- $\text{N}_{\text{bkg}} /\text{year/kg/FWHM}$  
- $0.24$ (Single Site)  
- $4$  
- $0.045$  

#### Origin of background

- Cosmogenic or External Bkg ?  
- $\alpha$ surface pollution  
- $\beta\beta 2\nu$  

#### Additional Information

- $T_{1/2}^{0\nu} > 10^{25} \text{ years : } \sim 1 \text{ evt } \beta\beta 0\nu \text{ detected / year}$
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 $\sigma_t = 5$ mm, $\sigma_z = 1$ cm
- Calorimeter (1940 plastic scintillators – low radioactivity PMTs) $\sigma_E/E = 3\%$ 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 $\approx 300$ Bq)

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
$e^-$, $e^+$, $\gamma$-rays, delayed-$\alpha$, neutrons

"zero background" experiment
Sources in NEMO3 detector (20 sectors)

Frejus Underground Laboratory (4800 m.w.e.)

$\beta\beta$ source foils (thickness $\sim 60$ mg/cm$^2$)

Study of $\beta\beta 2\nu$ process

- $^{116}\text{Cd} (0.40 \text{ kg})$ $Q_{\beta\beta} = 2802$ keV
- $^{130}\text{Te} (0.45 \text{ kg})$ $Q_{\beta\beta} = 2533$ keV
- $^{150}\text{Nd} (36.5 \text{ g})$ $Q_{\beta\beta} = 3367$ keV
- $^{96}\text{Zr} (9.43 \text{ g})$ $Q_{\beta\beta} = 3350$ keV
- $^{48}\text{Ca} (6.99 \text{ g})$ $Q_{\beta\beta} = 4271$ keV

Background study

- $^{nat}\text{Te} (0.61 \text{ kg})$
- Cu (0.62 kg)

Study of $\beta\beta 0\nu$ and $\beta\beta 2\nu$ process

- $^{100}\text{Mo} (6.9 \text{ kg})$ $Q_{\beta\beta} = 3034$ keV
- $^{82}\text{Se} (0.93 \text{ kg})$ $Q_{\beta\beta} = 2995$ keV
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 ($^{90}\text{Sr}$, $^{207}\text{Bi}$, $^{60}\text{Co}$) 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)  
$^{214}\text{Bi} \rightarrow ^{214}\text{Po} \ (164 \ \mu s) \rightarrow ^{210}\text{Pb}$

**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 ($E_\gamma = 2.6$ MeV)
  - $^{212}$Bi $\rightarrow$ $^{212}$Po e(γ)α (300 ns)
- $^{214}$Bi in source foils < 2 µBq/kg
  - Measured by channel e (γ) + α
    - ($^{214}$Bi $\rightarrow$ $^{214}$Po $\rightarrow$ $^{210}$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) $^{214}\text{Bi} \rightarrow ^{214}\text{Po} \rightarrow ^{210}\text{Pb}$

Electron + N γ-rays $^{208}\text{Tl}$ ($E_\gamma = 2.6$ MeV)

Electron – positron pair $\overline{B}$ rejection
Radon in NEMO 3

Air room: ≈ 10 Bq/m³

Two different measurements of radon in the NEMO 3 gas:

• Radon detector:
  sensitivity: 1 count/day for 1 mBq/m³
  Radon measurement ≈ 20 mBq/m³

• (1e⁻ + 1 α) channel in the NEMO-3 data:
  Able to measure Radon every half day
  Radon measurement ≈ 30 mBq/m³

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

NEMO3 trigger: one ββ-like event every 1.5 minute
$^{100}$Mo $\beta\beta^{2}\nu$ - “2003 stable data taking conditions”

650 h analyzed - preliminary results


Background substracted

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

V. Vasiliev (Nemo coll.)

NEMO 3

650 hours
13750 events
$S/B = 40$
$S/B(> 1 \text{ MeV}) \approx 100$
$^{100}$Mo $\beta\beta 2\nu$ angular distribution

650h of data analyzed – no laser correction

Background substracted

NEMO 3

$2\beta 2\nu$ Monte Carlo
Summary for $\beta\beta 2\nu$ analysis - Mo, Se, Cd and Nd

Preliminary results

V. Vasiliev (NEMO Coll.)

<table>
<thead>
<tr>
<th>Element</th>
<th>$T_{1/2}(2\nu)$</th>
<th>(stat)</th>
<th>(syst.)</th>
<th>$10^{19}$ yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{100}$Mo</td>
<td>0.78 $\pm$ 0.009</td>
<td>$\pm$ 0.08</td>
<td>$10^{19}$ yr</td>
<td></td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>9.1 $\pm$ 0.4</td>
<td>$\pm$ 0.9</td>
<td>$10^{19}$ yr</td>
<td></td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>3.1 $\pm$ 0.2</td>
<td>$\pm$ 0.3</td>
<td>$10^{19}$ yr</td>
<td></td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>0.77 $\pm$ 0.07</td>
<td>$\pm$ 0.08</td>
<td>$10^{19}$ yr</td>
<td></td>
</tr>
</tbody>
</table>
100Mo $\beta\beta0\nu$ study using maximum of likelihood method
(A.I. Etienvre PhD thesis - preliminary result)

Motivation: only way to take into account the shape of the $\beta\beta0\nu$ spectrum (E1+E2), the tail of the $\beta\beta2\nu$ 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 $E_{\text{min}} = E_1$ or $E_2$, total energy $E_{\text{tot}}$, 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

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

Likelihood: parameters of the maximisation

- $x_k = \frac{N_k}{N_{\text{tot}}}$, Number of events for $k$ process
- $Q_{\beta\beta}$, Total number of events

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

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

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

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

- **internal** $^{208}\text{Tl}$ : $< 68 \mu\text{Bq/kg} @ 90\% \text{ C.L.}$ using $e^- + N\gamma$-rays channel analysis ($1 \leq N \leq 3$)
- **internal** $^{214}\text{Bi}$ : NEMO3 requirement ($< 300 \mu\text{Bq/kg}$)
- **external** $^{208}\text{Tl}$ : HPGe measurement (18 Bq)
- **external** $^{214}\text{Bi}$ : HPGe measurement (300 Bq)
- **neutrons** : 0.2 event (crossing electrons)
$^{100}\text{Mo } \beta\beta 0\nu$ fit with 900 h of “2002 test data taking” (preliminary result)

$\Rightarrow 865$ events $(E_1 + E_2 > 2 \text{ MeV})$

$Q_{\beta\beta}$ is free parameter

$3.00 \pm 0.04 \text{ MeV}$

$T^{0\nu}_{1/2} > 7.10^{22}$ y (90% C.L.)

$< m_\nu > < 1.7 - 2.7$ eV

- Method to use for NEMO3 analysis of Mo and Se

- New analysis at the end of 2003 using stable data taking conditions
\(^{100}\text{Mo } \beta\beta0\nu \) preliminary result “2003 stable data taking conditions”

650h analyzed - no laser correction - preliminary results

\(\Rightarrow \beta\beta0\nu \) decay

- \(\beta\beta0\nu\) energy region \([2.75,3.2]\) MeV
- 1 \(\beta\beta0\nu\) candidate event
- \(\varepsilon = 10\%\)
- Conservative limit
  \[ T_{1/2}^{0\nu} > 6 \cdot 10^{22} \text{ y. (90\% C.L.)} \]
  \[ < m_\nu > < 1.8 - 2.9 \text{ eV} \]

\(\Rightarrow \beta\beta0\nu\chi \) decay (Majoron)

- Energy region \([2.6,3.2]\) MeV
- 9 candidate events, 5 expected
- \(\varepsilon = 0.7\%\)
- 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 $\beta\beta0\nu = 14\%$

**External background and neutron background negligible**

7 kg of $^{100}\text{Mo}$

**Source contamination**

$^{214}\text{Bi} < 0.3$ mBq/kg
$^{208}\text{Tl} < 0.02$ mBq/kg

**Internal background**

$^{214}\text{Bi} < 0.04$ evts/y/kg
$^{208}\text{Tl} < 0.04$ evts/y/kg
$\beta\beta(2\nu) = 0.11$ evts/y/kg

**Total Bkg < 1.4 event/year**

$T_{1/2}(0\nu) > 5.10^{24}$ yr

$<m_{\nu}> < 0.2 - 0.3$ eV

1 kg of $^{82}\text{Se}$

**Source contamination**

$^{214}\text{Bi} = 1.2 \pm 0.5$ mBq/kg (measured)
$^{208}\text{Tl} = 0.4 \pm 0.1$ mBq/kg

**Internal background**

$\beta\beta(2\nu) = 0.01$ evts/y/kg

**Uniform Contamination:**

$^{214}\text{Bi} = 0.2$ evts/y/kg
$^{208}\text{Tl} = 1.0$ evts/y/kg

**Hot spots:**

Pollution rejected

Bkg ~ 0 event/year

$T_{1/2}(0\nu) > 1.5.10^{24}$ yr

$<m_{\nu}> < 0.45 - 1.3$ eV
Past, Present and Future…

**Calorimeters:**

<table>
<thead>
<tr>
<th>Mibeta</th>
<th>CUORICINO (1 yr)</th>
<th>PRESENT</th>
<th>CUORE (5 yr)</th>
<th>FUTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M=13 kg $^{130}$Te (40 kg)</td>
<td>M= 760 kg TeO$_2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt; 3–7 $10^{24}$ yr</td>
<td>&gt; 2.1$10^{26}$ yr</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt; 0.2 – 0.6 eV</td>
<td>&lt; 0.04 – 0.08 eV</td>
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</tr>
</tbody>
</table>

**Tracking:**

<table>
<thead>
<tr>
<th>NEMO-1-2</th>
<th>NEMO-3 (5 yr)</th>
<th>“à la NEMO” (5 yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neuchatel TPC Moe</td>
<td>M=7 kg $^{100}$Mo (10 kg)</td>
<td>M=100 kg $^{100}$Mo</td>
</tr>
<tr>
<td>Neuchatel TPC Moe</td>
<td>&gt; 5 $10^{24}$ yr</td>
<td>&gt; 10$^{26}$ yr</td>
</tr>
<tr>
<td>Neuchatel TPC Moe</td>
<td>&lt; 0.2 – 0.3 eV</td>
<td>&lt; 0.04 – 0.07 eV</td>
</tr>
<tr>
<td>Neuchatel TPC Moe</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| M=1 (10) tons $^{136}$Xe | M=1 (10) tons $^{136}$Xe |
| M=1 (10) tons $^{136}$Xe | > 8.1$10^{26}$ yr (1.3 $10^{28}$) | > 8.1$10^{26}$ yr (1.3 $10^{28}$) |
| M=1 (10) tons $^{136}$Xe | < 0.05 – 0.13 (0.013-0.032) eV | < 0.05 – 0.13 (0.013-0.032) eV |

| M=1 (10) tons $^{136}$Xe | MOON |
| M=1 (10) tons $^{136}$Xe |  |  |
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: $<m_\nu> < 0.06 – 0.3 \text{ eV}$

**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 $\beta\beta 0\nu$ and $\beta\beta 2\nu$**
  We need FWHM $\sim 8\%/\sqrt{E}$ (MeV) (instead of 14% for NEMO-3)
  in order to have $\sim 1$ event/year of $\beta\beta 2\nu$ in the $\beta\beta 0\nu$ energy window (like for NEMO3)

  **How to improve $\Delta E/E$ ?**
  - calorimeter: Silicium ($e^-$) + small scintillator ($\gamma$) ?
  - Modular source: bkg rejection + energy loss improvement

**Need to increase the $\beta\beta 0\nu$ 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*

**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

$T \sim 10 \text{ mK} \Rightarrow C \sim 2 \text{ nJ/K} \Rightarrow 1 \text{ MeV/0.1 mK}$

\[13 \text{ kg } ^{130}{Te} \Rightarrow (40 \text{ kg } {TeO}_2) \]

\(Q_{\beta\beta} = 2528 \text{ keV}\)

**1st hypothesis:**
With performances of the 20 crystals of MI-BETA

$\text{FWHM} = 8 \text{ keV}$

$N_{BDF} : 0.5 \text{ event year}^{-1} \text{ keV}^{-1} \text{ kg}^{-1}$

\[T^{0 \nu}_{1/2} > 3.3 \times 10^{24} \text{ years (90\% C.L.)} \]

\(< m_\nu > < 0.3 - 0.6 \text{ eV} \quad \text{(in 1 year)}\)

**2nd hypothesis:**

FWHM = 5 keV  Best value with 760 g crystal

$N_{BDF} : 0.1 \text{ event year}^{-1} \text{ keV}^{-1} \text{ kg}^{-1}$

if bkg dominated by a surface pollution

\[T^{0 \nu}_{1/2} > 7.2 \times 10^{24} \text{ years (90\% C.L.)} \]

\(< m_\nu > < 0.2 - 0.4 \text{ eV} \quad \text{(in 1 year)}\)

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

$$T_{1/2} > 2 \times 10^{26} \text{ yr} \quad <m_{\nu}> < 0.04 - 0.08 \text{ eV}$$

(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 $\alpha$ 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 $\gamma^{208}$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
$N_{\text{Bkg}} = 0.06$ counts $y^{-1}$ kg$^{-1}$ keV$^{-1}$ (SSE)

$T_{1/2}^{0\nu} > 1.9 \times 10^{25}$ y (90% C.L.)

$< m_\nu > < 0.3 - 1.0$ eV

**IGEX (International Ge EXperiment)**

1994-2000 Baksan – Canfranc Underground Laboratories

3 detectors Ge (total mass = 6 kg)
FWHM = 4 keV
$N_{\text{BDF}} = 0.07$ counts $y^{-1}$ kg$^{-1}$ keV$^{-1}$ (SSE)

$T_{1/2}^{0\nu} > 1.57 \times 10^{25}$ y (90% C.L.)

$< m_\nu > < 0.36 - 1.07$ eV
MAJORANA PROJECT

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 $^{76}\text{Ge}$)
Long project: ~ 10 years of R&D and construction + 10 years of data taking

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

- IGEX without Pulse Shape Discri.: 0.2 counts/keV/kg/y
- Fabrication of detectors at an underground facility
  - $^{68}\text{Ge}$ decay ($T_{1/2}=271$ days) : Reduction Factor = 10
  - $^{60}\text{Co}$ 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 $\sigma$) = 6.5 events

$\Rightarrow$ 1.1 $10^{-3}$ counts/FWHM/kg/y

Expected sensitivity:
- efficiency = 73%
- FWHM = 3 keV
- $T^{0\nu} = 4.0 \times 10^{27}$ y
- $<m_{\nu}> = 0.02 - 0.07$ eV

MAJORANA/ GENIUS:
Need common approach to a large Ge DBD Experiment ???
EXO $^{136}\text{Xe}$: Enriched Xenon Observatory

Up to 10 tons of 80% enriched $^{136}\text{Xe}$ (world production ~30 tons/year)
Detect the $^{136}\text{Ba}^+$ daughter ion correlated with the $\beta\beta$ decay ($^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{2+} e^- e^-$) using optical spectroscopy (Moe, Phys. Rev. C44, 931, 1991)

Should eliminate all backgrounds except $\beta\beta 2\nu$

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:

<table>
<thead>
<tr>
<th>Mass (ton)</th>
<th>Enrich. (%)</th>
<th>Eff. (%)</th>
<th>Measur. Time (yr)</th>
<th>Background</th>
<th>$T_{1/2}(0\nu)$</th>
<th>$\langle m_\nu \rangle$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>70</td>
<td>5</td>
<td>0 + 1.8 events</td>
<td>$8.3 \times 10^{26}$</td>
<td>0.05 – 0.13</td>
</tr>
<tr>
<td>10</td>
<td>80</td>
<td>70</td>
<td>10</td>
<td>0 + 5.5 events</td>
<td>$1.3 \times 10^{28}$</td>
<td>0.012 – 0.032</td>
</tr>
</tbody>
</table>
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.label. (3000 mwe)
TPC, 62.5 % enriched \(^{236}\text{Xe}\) at 5 bar (180 l fiducial, 5.3 kg)
\(E_0=2.48\ \text{MeV}\) \(T_{1/2}^{0'} > 4.4 \times 10^{23}\ \text{yr}\)
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 (\(^{232}\text{Th}\))

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)**
<table>
<thead>
<tr>
<th>Experiments</th>
<th>Mass (enr. mass)</th>
<th>FWHM (at Q_{ββ})</th>
<th>N_{BKG} /kg/yr/FWHM</th>
<th>T_{1/2}(0ν) (in year)</th>
<th>&lt;m_{ν}&gt; (in eV)</th>
<th>Counts/year/FWHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heidelberg-Moscow IGEX 10 yr</td>
<td>11 kg</td>
<td>4 keV</td>
<td>0.24</td>
<td>1.9 \times 10^{25}</td>
<td>0.3 – 1</td>
<td>2.4</td>
</tr>
<tr>
<td>NEMO-3 5 yr</td>
<td>7 kg</td>
<td>90 keV</td>
<td>0.045</td>
<td>5. \times 10^{24}</td>
<td>0.2 - 0.3</td>
<td>1.4</td>
</tr>
<tr>
<td>CUORICINO 1 yr</td>
<td>40 kg (13)</td>
<td>8 keV</td>
<td>0.5</td>
<td>3. \times 10^{24}</td>
<td>0.3 - 0.6</td>
<td>20</td>
</tr>
<tr>
<td>CUORE 5 yr</td>
<td>760 kg(260)</td>
<td>5 keV</td>
<td>0.035</td>
<td>2. \times 10^{26}</td>
<td>0.04 – 0.08</td>
<td>25</td>
</tr>
</tbody>
</table>
| MAJORANA 10 yr 
(GENIUS) | 500 kg(420)      | 4 keV             | 1.1 \times 10^{-3}   | 4. \times 10^{27}      | 0.02 - 0.07     | 0.75            |
| EXO - 5 yr 
10 yr     | 1 ton            | 120 keV           | 3.5 \times 10^{-4}   | 8. \times 10^{26}      | 0.05 - 0.13     | 0.35            |
| MOON 34 tons 
(3.3 tons) | 34 tons          | 200 keV           | 4.5 \times 10^{-4}   | 0.05                  | ~ 15            |
| NEMO-Next            | 100 kg           | 50 keV            | 1.7 \times 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 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\beta$2ν 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