Outlook: why, how and when

Nuclear Double Beta Decay
The DBD black box
Neutrino Physics
Nuclear Matrix elements

Experimental Approaches
Sensitivity
Experimental Techniques

Present Situation
Future Experiments

Conclusions
WHY
Rare Nuclear Decay

\((A, Z) \rightarrow (A, Z+2) + 2e^- + [...]\)

occurs in a number of even-even nuclei
in \(A\) even multiplets

\[\beta\beta-2\nu: \text{two neutrino mode}\]

\[(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e\]
- allowed in Standard Model
- second order weak transition

\[\beta\beta-0\nu: \text{neutrinoless mode}\]

\[(A, Z) \rightarrow (A, Z+2) + 2e^-\]
- not allowed in Standard Model \((\Delta L=2)\)
Neutrinoless Double Beta Decay (DBD)

Observables:
- Electron Sum Energy
- Single Electron Energies
- Decay rate
- Angular correlation

Many models beyond SM with lepton number violation can contribute!

Constraints on the model parameters:
- Left-right symmetric models
- R-parity violating ...
- R-parity conserving supersymmetric models
- [...] Light neutrinos
opening the black box: L/R symmetric models

Exchange of a massive neutrino

Non standard contributions when:

\[ m_{W_L} \ll m_{W_R} \]

Constraints on the model parameters:

\[ m_{W_R} \geq 1.4 \left( \frac{m_N}{1 \text{ TeV}} \right)^{-1/4} \text{ TeV} \]
opening the black box: light neutrinos

- exchange of a virtual light neutrino (Racah sequence: Furry 1939)
  - Lepton number violation ($\Delta L = 2$)
  - Helicity mismatch
    - mass mechanism

- neutrino must be:
  - massive
  - a Majorana particle

▲ these conditions hold even if other mechanisms are possible and may dominate
effective neutrino mass

For each vertex:

\[ W_\mu \bar{\nu} \gamma^\mu P_L U_{ek} \nu_k \]

Neutrino propagator

\[ U_{ek}^2 \int \frac{d^4 p}{(2\pi)^4} \frac{m_{\nu_k} + p}{p^2 - m_{\nu_k}^2} \]

in the limit of small neutrino masses, a factor

\[ \langle m_\nu \rangle = \sum_k U_{ek}^2 m_k \]

\[ = c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3 \]

appears (effective neutrino mass)

Seven unknown quantities:
- 3 masses: \( m_k \)
- 2 angles: \( \theta_{12} \) and \( \theta_{13} \)
- 2 CP violating phases: \( \alpha \) and \( \beta \)

Only one experimental constraint

More complementary measurements needed!
The mixing matrix

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix} \quad \begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i \delta} \\
0 & 1 & 0 \\
-s_{13} e^{i \delta} & 0 & c_{13}
\end{pmatrix} \quad \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[c_{ij} \equiv \cos \theta_{ij}\]
\[s_{ij} \equiv \sin \theta_{ij}\]

**Atmospheric Cross-Mixing**

**Solar**

\[\delta m^2 = 7.92 (1 \pm 0.09) \times 10^{-5} \text{ eV}^2\]
\[\Delta m^2 = 2.4 (1^{+0.21}_{-0.26}) \times 10^{-3} \text{ eV}^2\]
\[m_{\beta}, m_{\beta\beta}, \Sigma < O(1) \text{ eV}\]
\[\sin^2 \theta_{12} = 0.314 (1^{+0.18}_{-0.15})\]
\[\sin^2 \theta_{23} = 0.44 (1^{+0.41}_{-0.22})\]
\[\sin^2 \theta_{13} < 3.2 \times 10^{-2}\]
present knowledge

- **neutrino flavour oscillation**
  - neutrinos mix and have masses
  - oscillation experiments measure
    \[ \Delta m_{ik}^2 = |m_i^2 - m_k^2| \text{ and } \sin^2 2\theta_{ik} = f(|U_{ik}|^2) \]

- **direct (kinematic) neutrino mass measurements**
  - \( m_\beta = \sum |U_{ek}|^2 m_k < 2.2 \text{ eV} \)

- **cosmology** (WMAP+2dFGRS+...)
  - \( m_\Sigma = \sum m_\nu < \approx 0.7 \text{ eV} \) (model dependent...)

**still missing:**
- absolute mass scale (i.e. mass of the lightest neutrino)
- neutrino mass hierarchy: \( m_1 \approx m_2 < m_3 \) or \( m_3 < m_1 \approx m_2 \)
- neutrino nature (Dirac/Majorana)
- CPV
- LNV
Neutrino mass hierarchy

Normal

\[ \sin^2 \theta_{13} \]

\[ \Delta m^2_{\text{atm}} \]

\[ \Delta m^2_{\text{sol}} \]

Inverse

\[ \Delta m^2_{\text{atm}} \]

\[ \Delta m^2_{\text{sol}} \]

Quasi-degenerate: \( m_{\text{low}}^2 \gg \Delta m^2_{\text{atm}} \gg \Delta m^2_{\text{sol}} \)
Neutrino mass hierarchy (2)

- **Quasi degenerate** and inverse hierarchy: TESTABLE
- **Normal** hierarchy: UNTESTABLE

\[ \langle m_\nu \rangle = f(m_{\text{low}}, U_{\text{ek}}) \]

\( \langle m_\nu \rangle \) threshold: \(~10\) meV

\( \Delta m^2_{\text{atm}} < 0 \)

\( \Delta m^2_{\text{atm}} > 0 \)

disfavoured by \( \beta\beta-0\nu \)

Next generation \( \beta\beta-0\nu \) exp

\( m_1 \approx m_2 \approx m_3 \)

inverse hierarchy: \( m_3 < m_1 \approx m_2 \)

normal hierarchy: \( m_1 \approx m_2 < m_3 \)
Decay rate: where the Nuclear Physics comes in

\[ \tau^{-1} = G_{0\nu} \cdot |M_{0\nu}|^2 \cdot \langle m_\nu \rangle^2 = F_N \cdot \frac{\langle m_\nu \rangle^2}{m_e^2} \]

Particle Physics

Nuclear Physics

Phase space factor

Nuclear Matrix Element

Effective Neutrino Mass

Nuclear Factor of Merit

uncertainties
Nuclear Matrix Elements (NME)

- Phase space $G^{0\nu}(Q_{\beta\beta},Z)$ can be precisely evaluated.
- Large uncertainties in NME calculation $M^{0\nu}$ also affect $\langle m_\nu \rangle$:
  - About factor of \textbf{100} in $F_N$.
  - Of the order of \textbf{2-3} in $|\langle m_\nu \rangle|$.

$^{76}\text{Ge}$ from nucl-ex/0311013

$^{130}\text{Te}$ for $\tau_{1/2}^{0\nu}=10^{25}$ y
Nuclear Matrix Elements (2)

Different approaches:
- Quasi Random Phase Approximation (most used; many versions)
- Shell Model
- Operator Expansion Model
- [...]

Large spread of values even within the same method

“Democratic approach:”

- Difficult to quantify with absolute confidence the range of uncertainties in nuclear matrix elements calculated with different theoretical models or approximations
- It is assumed that the published range of calculated matrix elements defines a plausible approximation to the uncertainty in our knowledge of the matrix elements:


Criticized in V.A.Rodin et al, nucl-th/0503063 which calibrate their model parameters on the available experimental results for 2ν-DBD, obtaining a lower spread in the final predictions as a function of different model ingredients
The uncertainty in the calculated NME for neutrinoless DBD could constitute *the principal obstacle to answering some basic questions about neutrinos.* Comparable *efforts* and *resource investments* are therefore needed both on the experimental and theoretical frameworks.

**Ongoing activities:**
- International working groups on NME calculation (UE Design Study)
- Information sharing
- Dedicated resources
- Cross checks (comparison with indirect measurements):
  - Two neutrino DBD rates
  - $\beta^+/EC$ decays
  - $\mu$ induced reactions
HOW
Experimental approach: inhomogeneous

Source ≠ detector
- source in thin foils
- electron analyzed by TPC, scintillators, drift chambers, semiconductor detectors

▲ topology (background rejection)
▲ angular correlation and single electron energies
▲ any isotopes with solid form possible

▼ relatively small amount of material
▼ poor efficiency
▼ (generally) poor energy resolution
Experimental approach: homogeneous

Source ⊆ detector (calorimetry)
- detector measures sum energy $E = E_{\beta_1} + E_{\beta_2}$
  - $\beta\beta-0\nu$ signature: a peak at $Q_{\beta\beta}$
- scintillators, bolometers, semiconductor diodes, gas chambers
  - large masses
  - high efficiency
  - many isotopes possible
- no blanks

depending on technique
- high energy resolution (bolometers, semiconductors)
- moderate topology recognition (Xe TPC, semiconductors)

Other approaches (geochemical, milking)
- do not separate $\beta\beta-0\nu$ and $\beta\beta-2\nu$ (inclusive measurements)
**Experimental $\beta\beta$-$0\nu$ rate**

- with $N_{\beta\beta}$ $\beta\beta$-$0\nu$ decays observed

$$\tau_{1/2}^{0\nu} = \ln(2) \frac{\epsilon N_{\text{nuclei}} t_{\text{meas}}}{N_{\beta\beta}}$$

**Experimental sensitivity to $\tau_{1/2}^{0\nu}$**

- with no $\beta\beta$-$0\nu$ decay observed

$$N_{\beta\beta} \leq (bkg \cdot \Delta E \cdot M \cdot t_{\text{meas}})^{1/2} \text{ at } 1\sigma$$

$$\sum (\tau_{1/2}^{0\nu}) \propto \epsilon \cdot \frac{i.a.}{A} \sqrt{\frac{M t_{\text{meas}}}{\Delta E \cdot bkg}}$$

- for $bkg = 0$, at $1\sigma$

$$\sum (\tau_{1/2}^{0\nu}) \propto \frac{\epsilon i.a.}{A} M t_{\text{meas}}$$

**Crucial parameters:**
- Isotopical abundance
- Mass
- Background level
their relevance depends on technique all experiments are somehow affected by them

- internal to source (and detector for calorimeters)
  - primordials ($^{238}$U, $^{232}$Th, $^{40}$K)
  - cosmogenic activation

- external
  - primordials in surrounding materials
  - neutrons
  - cosmic rays

- specific
  - quenched $\alpha$'s for scintillators
  - primordials on surface for bolometers

$\beta\beta$-2$\nu$ tail is an unavoidable background

- importance of energy resolution
Background control

- **solutions also depend on technique**
  - short exposure to cosmic rays
  - material selection and purification
  - heavily shielded underground experiments
  - PSD, tracking, segmentation, signatures ...
  - choose isotope with $Q_{\beta\beta}$ as high as possible

- **effective diagnosis techniques**
  - are crucial to identify selective and effective reduction procedures

- **material screening with the required sensitivity (ppt) is becoming quite difficult**
  - an intermediate mass experiment is often required
WHEN
## Present/past experimental situation

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Experiment</th>
<th>Latest Result</th>
<th>i.a. [%]</th>
<th>$Q_{\beta\beta}$ [eV]</th>
<th>enrich [%]</th>
<th>exp [kg×y]</th>
<th>tech</th>
<th>Material</th>
<th>$\tau_{1/2}^{0\nu}$ [10$^{23}$ y] min</th>
<th>$\langle m_\nu \rangle$ [eV] max</th>
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<td>s</td>
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<td>2039</td>
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<td>2005</td>
<td>33.8</td>
<td>2529</td>
<td>-</td>
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<td>69</td>
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<td>Irvine TPC</td>
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<td>t</td>
<td>Nd$_2$O$_3$</td>
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</tbody>
</table>

- s: scintillation
- i: ionization
- t: tracking
- b: bolometric

Range of uncertainties in NME
5 HP-Ge crystals, enriched to 87% in $^{76}$Ge
- total active mass of 10.96 kg ⇒ 125.5 moles of $^{76}$Ge
- run from 1990 to 2003 in Gran Sasso Underground Laboratory
- total statistics 71.7 kg×y
  - 820 moles×y
- main background from U/Th in the set-up
  - $b \approx 0.11$ c/keV/kg/y at $Q_{\beta\beta}$

1990 – 2001 data
exposure = 35.5 kg×y SSD
$\tau_{1/2}^{0\nu} > 1.9 \times 10^{25}$ years
$\langle m_\nu \rangle < 0.35$ eV (0.3 – 1.24 eV)

Heidelberg/Moscow: $^{76}$Ge 0\textnu-DBD evidence

- First claim in January 2002 (Klapdor-Kleingrothaus HV et al. hep-ph/0201231) with a statistics of 55 kg\,y and a 2.2-3.1 statistical significance
- Claim confirmed in 2004 with the addition of a significant (~1/4) new statistics

1990 – 2003 data, all 5 detectors
exposure = 71.7 kg\,\times\,y
$\tau_{\nu_e}^{0\nu} = 1.2\times10^{25}$ years
$\langle m_\nu \rangle = 0.44$ eV


The claim has drawn criticism and has been refuted by other members of the HM coll.
- Signal is still faint ($4\sigma$) to be blindly accepted as unquestionable evidence
- Still some weak points in the published analysis:
  - Presence of not understood peaks around the signal (comparable significance)
  - Impossibility to check an energy window larger than the published one
  - Disagreement on the evaluated significance level

All future experiment will certainly have to cope with this result
IGEX: $^{76}\text{Ge}$

- 6 HP-Ge crystals, enriched to 86% in $^{76}\text{Ge}$
  - total active mass of 8.4 kg
- operated in Homestake, Canfranc and Baksan (1991-2000)
- total statistics 8.87 kg×y
  - 116.75 moles×y
- PSD applied only to a subset (∼45%)
- main background from cosmogenics in Ge
  - $b \approx 0.17$ c/keV/kg/y at $Q_{\beta\beta}$

Low Temperature Detectors (LTD)

**Detection Principle**

- $\Delta T = E/C$
- $C$: thermal capacity
  - $\Rightarrow$ low C
  - $\Rightarrow$ low $T$ (i.e. $T \ll 1K$)
  - $\Rightarrow$ dielectrics, superconductors
- ultimate limit to E resolution: statistical fluctuation of internal energy $U$
  $$\langle \Delta U^2 \rangle = k_B T^2 C$$

**Thermal Detectors Properties**

- good energy resolution
- wide choice of absorber materials
- true calorimeters
- slow $\tau = C/G \sim 1 \div 10^3$ ms
Cuoricino tower: 62 TeO$_2$ crystals

TeO$_2$ thermal calorimeters
- **Active isotope** $^{130}$Te
  - natural abundance: a.i. = 33.9%
  - transition energy: $Q_{\beta\beta} = 2529$ keV
  - encouraging predicted half life
    - $\langle m_\nu \rangle \approx 0.3$ eV $\Rightarrow \tau_{1/2}^{0\nu} \approx 10^{25}$ years
- **Absorber material** TeO$_2$
  - low heat capacity
  - large crystals available
  - radiopure

- **intermediate size $\beta\beta$ experiment**
- **important test for**
  - radioactivity
  - performance of large LTD arrays
CUORICINO tower (2)

- **11 modules with 4 big detectors**
  - 44 TeO$_2$ crystals
  - $5 \times 5 \times 5$ cm$^3 \Rightarrow 790$ g
  - TeO$_2$ mass $\Rightarrow 34.76$ kg

- **2 modules with 9 small detectors**
  - 18 TeO$_2$ crystals
  - $3 \times 3 \times 6$ cm$^3 \Rightarrow 330$ g
  - TeO$_2$ mass $\Rightarrow 5.94$ kg

- **4 crystals are enriched**
  - $2 \times ^{130}$TeO$_2 + 2 \times ^{128}$TeO$_2$

Total number of detectors: 62

Central crystal has a $4\pi$ active shielding like in CUORE configuration
⇒ anti-coincidence for background reduction

**total active mass**
- TeO$_2$ $\Rightarrow 40.7$ kg
- $^{130}$Te $\Rightarrow 11.2$ kg
- $^{128}$Te $\Rightarrow 10.3$ kg
CUORICINO results

- total statistics 5 kg×y (duty cycle 64%)
- energy resolution FWHM $\Delta E = 7.5$ keV at $Q_{\beta\beta}$ ($\sigma_E = 1.3\%$)
- anticoincidence applied to reduce surface U/Th background and external $\gamma$'s
- background mainly from U/Th on Cu and TeO$_2$ surfaces ($\alpha$ and $\beta$)
  \[ b \approx 0.18 \pm 0.02 \text{ c/keV/kg/y at } Q_{\beta\beta} \]

\[ \tau_{1/2} \geq 1.8 \times 10^{24} \text{ years at 90\% C.L.} \]
\[ \langle m_{\nu} \rangle \leq 0.2 \div 1.1 \text{ eV} \]

- experiment still running
- 3 y sensitivity
  \[ \tau_{1/2} \geq 6.1 \times 10^{24} \text{ y} \]
  \[ \langle m_{\nu} \rangle \leq 0.1 \div 0.6 \text{ eV} \]

C. Arnaboldi et al., hep-ex/0501034
NEMO3: $^{100}\text{Mo}$ and $^{82}\text{Se}$

- Tracking detector for $\beta\beta$-2$\nu$ and $\beta\beta$-0$\nu$ at Frejus (4800 m.w.e.)
  - 10 kg of enriched material in foils
  - 6180 geiger cells $\Rightarrow$ drift wire chamber
  - 1940 plastic scintillators + PMTs
  - iron ($\gamma$) + water with B ($n$) shielding + anti-Rn box
  - $e^-$, $e^+$, $\gamma$ and $\alpha$ identification

![Diagram of NEMO3 detector](image)

- $^{100}\text{Mo}$ (6.9 kg)
- $^{82}\text{Se}$ (0.9 kg)
- $^{130}\text{Te}$ (0.45 kg)
- $^{116}\text{Cd}$ (0.4 kg)
- $^{150}\text{Nd}$ (37g)
- $^{96}\text{Zr}$ (9.4 g)
- $^{48}\text{Ca}$ (7.0g)
- nat $\text{Te}$ (0.5 kg)
- Cu (0.6 kg)
**NEMO3: $^{100}$Mo and $^{82}$Se results (1.08 y)**

**$^{100}$Mo**
- 6914 g

**$^{82}$Se**
- 932 g

**main background sources ($^{100}$Mo)** [2.8-3.2 $E_1$+$E_2$ window]
- Radon (1 c/kg/y), $\beta\beta$-$2\nu$ (0.3 c/kg/y), $^{208}$Tl in the foils (0.1 c/kg/y)

**$^{100}$Mo**
- $\tau_{1/2}^{0\nu}>4.6 \times 10^{23}$ years (90% CL)
- $\langle m_\nu \rangle < 0.66 \div 2.81$ eV
- Efficiency: 8%
- Signal/Bkg: 7 / (8.1 ± 1.3)

**$^{82}$Se**
- $\tau_{1/2}^{0\nu}>1 \times 10^{23}$ years (90% CL)
- $\langle m_\nu \rangle < 1.75 \div 4.86$ eV
- Efficiency: 13%
- Signal/Bkg: 5 / (3.1 ± 0.6)
Next generation $0\nu$-DBD experiment goals

- sensitivities of few 0.01 eV on $\langle m_\nu \rangle$
  - hierarchy problem solution
  - good chances to observe $\beta\beta-0\nu$ (LNV, Majorana $\nu$'s)
- confirmation/rejection of the $^{76}$Ge result
  - confirmation: sensitivities of few 100 meV on $\langle m_\nu \rangle$ are enough to check different isotopes
  - rejection: much better sensitivities on $\langle m_\nu \rangle$ must be achieved

How?

- promote as many as possible experiments on different isotopes
- reduce uncertainties in nuclear matrix $F_N$
- increase sensitivity

\[ \sum (\tau_{1/2}^{0\nu}) \propto \epsilon \cdot \frac{a.i.}{A} \sqrt{\frac{M_{\text{meas}}}{\Delta E \cdot bkg}} \]

- increase isotopic abundance by enrichment
- reduce background by:
  - material selection and proper handling
  - choosing proper technique
  - using signatures
  - improving energy resolution
- increase experimental mass
### Next generation $0\nu$-DBD experiment sensitivities

<table>
<thead>
<tr>
<th>Element</th>
<th>$\tau_{1/2}^{0\nu}$</th>
<th>$F_N$</th>
<th>$\langle m_\nu \rangle_{\text{exp}}$</th>
<th>$\tau_{1/2}^{0\nu}$</th>
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<tr>
<td></td>
<td>[10$^{25}$ y]</td>
<td>[10$^{-13}$ y$^{-1}$]</td>
<td>[eV]</td>
<td>[10$^{28}$ y]</td>
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### Next generation proposed projects

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<tr>
<th>Project</th>
<th>Isotope</th>
<th>$Q_{\beta\beta}$</th>
<th>$T_M$</th>
<th>$\sigma_E$</th>
<th>$b$</th>
<th>$\tau_{1/2}^{0\nu}$</th>
<th>Technique</th>
<th>$\langle m_\nu \rangle$</th>
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**Projected experimental parameters**

**Projected background levels**
- Large spread
- Too large gap with respect to present

**Nuclear matrix elements $F_N$ selected by Elliott & Vogel**

$\langle m_\nu \rangle$ evaluated according to Staudt et al. Europhys. Lett. 13 (1990) 31
Calorimetric experiments: ionization detectors

- **Germanium diode experiments**
  - well known technique
  - high energy resolution
  - large masses
  - segmentation and PSD to reduce background
  - cost of enrichment
  - standard cooling in ultra low background cryostats
    - **Majorana** experiment
    - naked crystals in cryogenic liquids (scintillating)
    - **GERDA** or **Genius/GEM**

- **CdTe or CdZnTe diode experiments**
  - many isotopes at once (including $\beta^+\beta^+$)
  - segmentation (tracking) to reduce background
  - new technique, still *poor* energy resolution and small masses
**Majorana**

White paper nucl-ex/0311013

- **concept:** *cosmogenics* main background source (IGEX)
  - 500 kg Ge crystals in ultra low background cryostats
  - segmentation and PSD to reduce bkg
- 2 experimental phases: 180 kg → 500 kg

**Phase I:**
- 180 kg 86% $^{76}$Ge (centrifugation)
- Modules with 57 crystals each (40 cm x 40 cm Cryostat)
  - Three modules for 180 kg
  - Eight modules for 500 kg (phase II)

Maximal use of copper electroformed underground

Background rejection methods
- Granularity
- Pulse Shape Discrimination
- Single Site Time Correlation
- Detector Segmentation

**Underground Lab**
- 6000 mwe
- Class 1000

**FULL EXPERIMENT**
(9 years from start in 2006)
- expected bkg 1.21 c/ton/y in ROI
- mainly Th from Cu structure

- $\tau_{1/2} \geq 4 \times 10^{26}$ y in 3 years
- $\langle m \rangle \leq 0.07 \div 0.21$ eV
**57 crystal module**

- Cap
- Tube (0.007” wall thickness)
- Ge (62mm x 70 mm)
- Tray (Plastic, Si, etc)

**40 cm x 40 cm Cryostat**
- Vacuum jacket
- Cold Plate
- Cold Finger
- 1.1 kg Crystal
- Thermal Shroud
- Bottom Closure
- 1 of 19 Towers

**Veto Detector**

**Sliding Monolith**

**LN Dewar**

**Inner Shield**

**57 Detector Module**

**Shield design**

**segmentation concept**

\[\gamma \ ("High\" \ Energy)\]

\[\gamma \ ("Low\" \ Energy)\]
- **Goal**: Analyse HM evidence in a short time using existing $^{76}$Ge enriched detectors (HM, Igex)
- Approach similar to GENIUS but less LN2
  - Naked Ge crystals in LN2 or LAr
- More compact than GENIUS
  - 1.5 m LN2 (LAr) + 10 cm Pb + 2 m water
  - 2-3 orders of magnitude better bkg than present Status-of-the-Art
  - Active shielding with LAr scintillation
- 3 phases experiment
- Phase I:
  - Radioactivity tests
  - $\approx 20$ kg $^{76}$Ge from HM and Igex
  - Expected bkg $\leq 0.01$ c/keV/kg/y (intrinsic)
  - Check at $5\sigma$ HM evidence
  - $15$ kg $\times y \Rightarrow 6 \pm 1 \beta\beta$ events on 0.5 bkg events
- Phase II:
  - Add **new enriched segmented detectors** with special care for activation
  - Expected background $\approx 0.001$ c/keV/kg/y
  - $\tau_{1/2} \geq 2 \times 10^{26}$ y with 100 kg $\times y$
  - $\langle m_{\nu} \rangle \leq 0.09 \div 0.29$ eV
- Phase III: $\langle m_{\nu} \rangle \leq 0.01$ eV with 1 ton Ge
  - Worldwide collaboration

- Approved by LNGS S.C.
  - **Site**: Hall A northern wing
- Funded 40 kg enriched $^{76}$Ge for phase II
- Aggressive time schedule

---

**GERDA**

Proposal: hep-ex/0404039
Calorimetric experiments: bolometers

▲ true calorimeters
▲ wide isotopes choice $^{48}$Ca, $^{76}$Ge, $^{100}$Mo, $^{116}$Cd, $^{130}$Te, $^{150}$Nd
▲ high energy resolution
▲ large masses
▲ segmentation to reduce background

▼ fully sensitive to surface radioactivity
▼ difficult to reduce the amount of close materials (holders, wires, cryostats,...)

■ hybrid detectors can do particle identification (i.e. e/γ-α)
  • heat + scintillation detection
  • heat + ionization detection (with PSD + segmentation)

▶ CUORE ($^{130}$Te)
▶ Edelweiss ($^{76}$Ge) G.Chardin NIM A 520 (2004) 145
▶ MOON ($^{100}$Mo)?
**CUORE**

**Cryogenic Underground Observatory for Rare Events**
- array of 988 TeO$_2$ crystals 5×5×5 cm$^3$ (750 g)
  - 741 kg TeO$_2$ granular calorimeter
  - 600 kg Te = 203 kg $^{130}$Te
- $\beta\beta(0\nu)$, Cold Dark Matter, Axions searches

**SINGLE HIGH GRANULARITY DETECTOR**

- Single tower: thirteen (4 crystal) modules
  - Crystals grouped in a “cylindrical” matrix of 19 towers

- Single dilution refrigerator (~ 10 mK)

Proposal: hep-ex/0501010
CUORE (2)

- **enrichment** still open option: full detector / only core (2\textsuperscript{nd} phase)
- **compact and granular** ⇒ self shielding detector
- work in progress to reduce surface radioactivity
  - advanced cleaning techniques
  - new **surface sensitive detectors** for active bkg rejection under test

**Present status**
- approved LNGS S.C. **Site: Hall A southern wing**
- approved and funded by INFN for the Italian part
- proposal to DOE and NuSAG meeting for the American part

- dilution refrigerator funded: **tender in progress**
- underground building design and construction
- material selection and cleaning procedure settling

**Full experiment**
- CUORE experiment due to start data taking in 01/01/2010 @ LNGS

| B (c/keV/ton/y) | D (keV) | $T_{1/2}$ ($10^{26}$ y) | $|\langle m_\nu \rangle|$ (eV) |
|----------------|---------|-------------------------|-----------------------------|
| 10             | 10      | 1.5                     | 23-118                      |
| 10             | 5       | 2.1                     | 19-100                      |
| 1              | 10      | 4.6                     | 13-67                       |
| 1              | 5       | 6.5                     | 11-57                       |

- **5 y sensitivities**
Calorimetric experiments: scintillators

▲ large masses (solid or liquid)
▲ well known simple techniques
▲ wide isotopes choice $^{48}\text{Ca}$, $^{116}\text{Cd}$, $^{136}\text{Xe}$, $^{160}\text{Gd}$
▲ *immersion* in clean liquids to reduce background (Borexino, SNO...)
▲ PSD to reduce background
▼ poor energy resolution
▼ in some cases difficult to have radiopure crystals
▼ background from PMTs

▶ CAMEO ($^{116}\text{Cd}$)
▶ CANDLES ($^{48}\text{Ca}$)
▶ XMASS ($^{136}\text{Xe}$)
▶ *Xenon in Borex* (or SNO) ($^{136}\text{Xe}$) B.Caccianiga Astropart. Phys. 14 (2000) 15
▶ *nanocrystals* in SNOlab ($^{48}\text{Ca}$, $^{82}\text{Se}$, $^{96}\text{Zr}$, $^{116}\text{Cd}$, $^{130}\text{Te}$, $^{150}\text{Nd}$)
▶ Corea project: $\text{CaMoO}_4$, $\text{PbMoO}_4$, $\text{SrMoO}_4$
Xe scintillators

XMASS (Xenon MASSive detector) @ KAMIOKA

- **concept**: a **self shielding detector** for DM, $\nu_\odot$ & $\beta\beta$
- presenty running 100 kg prototype (with light guide)
- 10 t natural LXe
  - considering only $\beta\beta$-2$\nu$ bkg
    - $\langle m_\nu \rangle \leq 0.01 \div 0.02$ eV in 5 years
  - but self shielding at 3 MeV is not effective
  - PMT bkg limits $\beta\beta$-0$\nu$ sensitivity
- ongoing:
  - Background reduction
    - 3ppt in $^{85}$Kr, $10^{-14}$ g/g in U/Th
  - R&D for a 800 kg detector
  - design and development of new PMT
- **Primary goal**: still WIMP detection

Proposals for inclusion of large $^{136}$Xe samples in radioclean environments such as SNO or BOREX have also been submitted
Tracking experiments

▲ background reduction by vertex and track reconstruction
▲ mass mechanism demonstration by electron angular correlation
▼ poor energy resolution
▼ small masses ⇒ enrichment necessary

▶ MOON ($^{100}\text{Mo}$)
▶ DCBA ($^{82}\text{Se}$, $^{150}\text{Nd}$)
▶ SuperNEMO ($^{82}\text{Se}$)
▶ EXO, calorimeter + “tracking” ($^{136}\text{Xe}$)
**SuperNemo**

- **concept**: scale NEMO setup
- tracking calorimeter
- already tested technology (NEMO)
  - event topology (Detection of the 2 electrons)
  - single and sum energy + angular correlation
  - particle identification
  - Background control
    - source purification
    - background level measurement
    - external background reduction (Rn)

No strong theoretical criteria for isotope selection: $^{82}\text{Se}$
- transition energy: 2 995 keV
- natural i.a.: 8.7%

3 years R&D aiming at a 50 meV $<m_{\nu}>$

**sensitivity**: accepted by IN2P3 s.c.

- 5 kg of $^{82}\text{Se}$ funded by ILIAS (Europe)
- Enrichment:
  - 1 kg of $^{82}\text{Se}$ in 2005
  - 2 kg of $^{82}\text{Se}$ in 2006
  - 5 kg of $^{82}\text{Se}$ in 2007
- Enrichment of 100 kg of $^{82}\text{Se}$ is possible in 3 years at ECP (Zelenogorsk)

- **Planar geometry**
  - source (40 mg/cm$^2$): 12m$^2$
  - tracking volume: ~3000 channels
  - calorimeter: ~1000 PMT

- **Modular**
  - ~5 kg of enriched isotope/module
  - 100 kg: 20 modules

- ~ 60 000 channels for drift chamber
- ~ 20 000 PMT
- energy resolution $\sigma_E = 2.6\%$ @ 3 MeV
- efficiency: 40%

2006-2008: R&D
2009: first module
2011: all modules
2016: final results

- **LNGS/LSM**
**EXO**

- **concept**: scale Gotthard experiment adding Ba tagging to suppress background ($^{136}$Xe$\rightarrow^{136}$Ba$^{++}$+2e)
- single Ba$^+$ detected by optical spectroscopy
- two options with 63% enriched Xe
  - High pressure Xe TPC
  - LXe TPC + scintillation
- calorimetry + tracking
- expected bkg only by $\beta\beta$-$2\nu$
  - energy resolution $\sigma_E = 2\%$

**Present R&D**

- Ba$^+$ spectroscopy in HP Xe / Ba$^+$ extraction
- energy resolution in LXe (ion.+scint.): OK
- Prototype scale:
  - 200 kg enriched $^{136}$Xe without tagging
  - all EXO functionality except Ba id
  - operate in WIPP for ~two years
- Prototype goals:
  - Test all technical aspects of EXO (except Ba id)
  - Measure $2\nu$ mode
  - Set decent limit for $0\nu$ mode (probe Heidelberg- Moscow)

**LXe TPC**

**Full scale experiment at WIPP or SNOLAB**

- 10 t (for LXe $\Rightarrow$ 3 m$^3$)
  - $b = 4 \times 10^{-3}$ c/keV/ton/y
  - $\tau_{1/2} \geq 1.3 \times 10^{28}$ y in 5 years
  - $\langle m_\nu \rangle \leq 0.013 \div 0.037$ eV
- Concept: Mo foils inside a tracking detector for solar $\nu$ and $\beta\beta-0\nu$
- $^{100}\text{Mo}$ 85% enriched
- Prove mass mechanism by $\beta$ angular correlation
- Bkg from source and detector
  - Signal Selection by Spatial Correlation
  - Signal Selection by Time Selection
- Position by XY scintillating fibers
- Energy by $1.8\times1.8\times6\text{mm}$ plastic scintillators
  - Energy resolution $\Delta E_{\text{FWHM}} = 2\%$ (4.5% with Mo)
  - Main background from $\beta\beta-2\nu$

**MOON I (2004 – 2005) prototype**
- 500 g $^{100}\text{Mo}$ in Elegant V active shield
  - $\tau_{1/2} \geq 1\times10^{24}$ y $\Rightarrow \langle m_{\nu} \rangle \leq 1\text{ eV}$

**MOON II (2007)**
- 100 kg one module ($1.8\times1.8\text{m}$) with 180 layers
  - $\tau_{1/2} \geq 4.4\times10^{26}$ y $\Rightarrow \langle m_{\nu} \rangle \leq 0.03\text{ eV}$

**MOON III (?)**
- 1 ton in 10 modules
  - $\tau_{1/2} \geq 1.6\times10^{27}$ y in 10 y $\Rightarrow \langle m_{\nu} \rangle \leq 0.015\text{ eV}
### A (more) likely (next) future

<table>
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<th>isotope</th>
<th>i.a.</th>
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#### $^{76}$Ge claim

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<td>85</td>
<td>t</td>
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**expected half-lifetime according to $^{76}$Ge evidence claim**
Conclusions

- **Neutrinoless Double Beta Decay** is a unique tool to study neutrino properties:
  - Absolute Mass Scale
  - Nature (Majorana/Dirac)
  - Lepton Number Violation
  - CP Violation
- Parameter constraints for GUTs and SUSY models can be obtained
- Still large uncertainties due to spread in NME calculations

**Experimental situation:**
- **one claimed evidence** for $\beta\beta^0\nu$ of $^{76}\text{Ge}$
  - 2 medium size (1-10kg) ongoing experiments (NEMO & CUORICINO)
  - 1 improved sensitivity $^{76}\text{Ge}$ experiment in preparation (GERDA)
- **intermediate future goal:** $\langle m_\nu \rangle < 100$ meV
  - 2-3 intermediate size (200 kg) approved experiments
- **ultimate future goal:** $\langle m_\nu \rangle \sim 10$ meV
  - many proposals with different techniques and isotopes
  - promote as many as possible experiments on different isotopes
  - reduce uncertainties in nuclear matrix $F_N$
We recommend, as a high priority, that a phased program of increasingly sensitive searches for neutrinoless nuclear double beta decay (0νββ) be initiated as soon as possible.

### APS neutrino study

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<td>1 ton</td>
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<td>2 – 5</td>
<td>Any</td>
<td>100 tons</td>
<td>future technology</td>
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</table>

In the first two stages, more than one experiment is desirable, worldwide, both to permit confirmation and to explore the underlying physics.
a few possible diagrams

Exchange of a **light** neutrino, only left-handed currents

\[
\begin{array}{c}
d \quad W_L \\ e^- \\ e^- \\ W_L \\ d \\
\end{array}
\]

Exchange of a light or heavy neutrino and one **right-handed** \(W_R\)

\[
\begin{array}{c}
d \quad W_R \\ e^- \\ e^- \\ W_L \\ d \\
\end{array}
\]

Exchange of a **heavy** neutrino, short range hadron physics at play

\[
\begin{array}{c}
d \quad W_R \\ \nu_{\text{heavy}} \\ e^- \\ W_R \\ d \\
\end{array}
\]

Exchange of **supersymmetric** particles, R-symmetry violated

\[
\begin{array}{c}
d \quad \bar{e} \quad (\text{selectron}) \\ e^- \\ \chi \quad (\text{neutralino}) \\ e^- \\ \bar{e} \quad (\text{selectron}) \\ d \\
\end{array}
\]
most general superpotential allowed by SU(3)xSU(2)xU(1)

\[ W = W_{\text{RPC}} + W_{\text{RPV}} (\lambda, \lambda', \varepsilon) \]

\( \lambda, \lambda', \varepsilon \) LNV terms.

Many possible diagrams

Just an example

\[ \lambda'_{111} \leq 3 \cdot 10^{-4} \left( \frac{m_{\tilde{q}}}{100 \text{ GeV}} \right)^2 \left( \frac{m_{\chi, \tilde{g}}}{100 \text{ GeV}} \right)^{1/2} \]

M.Hirsch – ENTAPP 2005
Neutrino mass hierarchy (3)

**goal of next generation experiments**

\[ \langle m_{\nu} \rangle \approx 10 \text{ meV} \]

- discovery with \( \langle m_{\nu} \rangle \geq 10 \text{ meV} \)
  - Lepton number is not conserved (LNV)
  - the neutrino is a Majorana particle
  - inverse hierarchy or degeneration
  - absolute \( \nu \) mass scale fixed (quasi-degeneration)
- upper limit with \( \langle m_{\nu} \rangle < 10 \text{ meV} \)
  - normal hierarchy

Debate on the quantitative interpretation of discovery potential (when considering the possible outcome of measurements of \( \langle m_{\nu} \rangle \), \( m_{\beta} \) and \( m_{\Sigma} \)) [Bachall, Murayama and Pena-Garay Phys. Rev. D 70 (2004) 033012]

<table>
<thead>
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<th>Assumptions</th>
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<th>( N_{\text{exp}} ) at 99.73 % C.L.</th>
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<td>Dirac ?</td>
<td>230 (( \infty ))</td>
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<tr>
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<td>Dirac ?</td>
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<td>16 (( \infty ))</td>
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<td>Neutrinoless double ( \beta ) decay:</td>
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</tr>
<tr>
<td>( T_{1/2} (^{76}\text{Ge})=(3.2\pm0.2) \times 10^{25} \text{ yr} )</td>
<td>Total mass ?</td>
<td>[0.46,9.56] ([0.48,9.58])</td>
</tr>
<tr>
<td>Neutrinoless double ( \beta ) decay:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_{1/2} (^{76}\text{Ge})=(1.\pm0.1) \times 10^{26} \text{ yr} )</td>
<td>Total mass ?</td>
<td>[0.24,8.34] ([0.28,8.40])</td>
</tr>
<tr>
<td>Neutrinoless double ( \beta ) decay:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_{1/2} (^{76}\text{Ge})=(3.2\pm0.5) \times 10^{26} \text{ yr} )</td>
<td>Total mass ?</td>
<td>[0.08,5.68] ([0.16,6.06])</td>
</tr>
<tr>
<td>Detected neutrinoless double ( \beta ) decay</td>
<td>Hierarchy ?</td>
<td>No</td>
</tr>
<tr>
<td>Detected neutrinoless double ( \beta ) decay,</td>
<td>Hierarchy ?</td>
<td>Yes</td>
</tr>
<tr>
<td>private communication: ( m=0 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
- PSD since end 1995 for 4 detectors (51.4 kg×y, i.e. 72% of full data set)
  - $\beta\beta$ decays and double escape $\gamma$ peaks are **Single Site Events**
  - $\gamma$ interactions are usually **Multiple Site Events**
  - also internal $\beta$s are SSE

H.V. Klapdor-Kleingrothaus et al., NIM A 522 (2004) 371
Taking data since Feb 2003. 389 days analysed.

2νββ event every 2.5 minutes!

- Total statistics: 7.37 kg.y

- Single electron energy distributions also measured

\[ T_{1/2} = 7.11 \pm 0.02 \text{ (stat)} \pm 0.54 \text{ (syst)} \pm 10^{18} \text{ y} \]
NEMO3: others two neutrino DBD

- $^{82}\text{Se}$: $T_{1/2} = 0.98 \pm 0.2 \text{ (stat)} \pm 0.1 \text{ (syst)} \times 10^{20} \text{ y}$
- $^{116}\text{Cd}$: $T_{1/2} = 2.8 \pm 0.1 \text{ (stat)} \pm 0.3 \text{ (syst)} \times 10^{19} \text{ y}$
- $^{150}\text{Nd}$: $T_{1/2} = 9.7 \pm 0.7 \text{ (stat)} \pm 1.0 \text{ (syst)} \times 10^{18} \text{ y}$
- $^{96}\text{Zr}$: $T_{1/2} = 2.0 \pm 0.3 \text{ (stat)} \pm 0.2 \text{ (syst)} \times 10^{19} \text{ y}$

Data

$^{82}\text{Se}$ $^{116}\text{Cd}$ $^{150}\text{Nd}$ $^{96}\text{Zr}$

Number of events/0.05 MeV

$E_{2e}$ (MeV)

$E_{1}+E_{2}$ (MeV)

$E_{1}+E_{2}$ (MeV)

$E_{1}+E_{2}$ (MeV)
Gotthard and DAMA experiments: $^{136}$Xe

**GOTTHARD experiment**
- high pressure Xe TPC (5 atm) in Gotthard tunnel
  - calorimetric experiment with tracking
- $^{136}$Xe enriched at 62.5%
  - $^{136}$Xe total mass 3.3 kg (24.2 moles)
- total $^{136}$Xe statistics 4.9 kg×y (36 moles×y)
- energy resolution FWHM $\Delta E = 165$ keV
- background $b \approx 0.015$ c/keV/kg/y, largely from $\beta\beta$-2ν
  - $\tau_{1/2} \geq 4.4 \times 10^{23}$ y at 90%
  - $\langle m_\nu \rangle \leq 1.8 \div 5.2$ eV

**DAMA experiment**
- LXe scintillator in the DAMA set-up at LNGS
  - calorimetric experiment
- $^{136}$Xe enriched at 68.8%
  - $^{136}$Xe total mass 4.5 kg (32.9 moles)
- total statistics 4.5 kg×y (23 moles($^{136}$Xe)×y)
- energy resolution FWHM $\Delta E \approx 500$ keV
- background $b \approx 0.08$ c/keV/kg/y
  - by subtracting the background
    - $\tau_{1/2} \geq 4.9 \times 10^{24}$ y at 90%
    - $\langle m_\nu \rangle \leq 1.1 \div 2.9$ eV
GENIUS and GEM

- **idea**: main background sources in HM exp are in **close materials**
  - 1 ton **naked** Ge crystals in LN2
- enriched $^{76}$Ge
- 12 m tank to reduce external bkg
- LN2 purity: $10^{-15}$ g/g U/Th
- expected bkg 0.2 c/keV/t/y
  - $\tau_{1/2} \gg 10^{28}$ y in 10 years
  - $\langle m_\nu \rangle \leq 0.015 \div 0.05$ eV
- could be used also for solar neutrinos and DM
- authors think may no longer be worth to proceed

- very similar to GENIUS, but with less LN2:
  - 1 ton **naked** Ge crystals in LN2 + water
- expects same bkg as GENIUS: 0.2 c/keV/t/y
  - $\tau_{1/2} \gg 10^{28}$ y in 10 years
  - $\langle m_\nu \rangle \leq 0.015 \div 0.05$ eV
CdWO$_4$ and CaF$_2$ scintillators

CAMEO nucl-ex/0007012, INFN/BE-00/03 (project frozen because of environmental problems at LNGS)

- **idea**: CdWO$_4$ in CTF or Borex (LNGS), using the Liquid Scintillator as light guide and anticoincidence
- PSD and $\Delta E = 110$ keV (FWHM)

**CAMEO II**
- $24 \times 2.7$ kg crystals $\Rightarrow 20$ kg of $^{116}$Cd
- $\beta\beta-2\nu$, internal and cosmogenic bkg $\Rightarrow 0.6$ c/y
  - $\tau_{1/2} \gg 1 \times 10^{26}$ y in $5 \div 8$ y

**CAMEO III**
- $370 \times 2.7$ kg crystals enriched to 83% in Borex
  - lower bkg $\Rightarrow T_{1/2} \gg 1 \times 10^{27}$ y

**CANDLES**

- **idea**: CaF$_2$ crystals in Liquid Scintillator at Oto Cosm. Obs.
- PSD to reject internal $\alpha$ and
- LS used as active shielding (LS is faster)
- **CANDLES III** (presently under construction)
  - 200 kg crystals $\Rightarrow \langle m_v \rangle \leq 0.5$ eV in 3 years

**CANDLES IV**
- 3.2 tons in 1000 natural crystals $\Rightarrow 77$ mol of $^{48}$Ca
- $\Delta E = 4\%$ (FWHM) and internal bkg reduced by 1/10
  - $\langle m_v \rangle \leq 0.15$ eV in 5 years
  - 2.3% enrichment (940 mol) $\Rightarrow \langle m_v \rangle \leq 0.03$ eV in 10 years
Drift Chamber Beta ray Analyzer N. Ishihara et al. NIM A 443 (2000) 101

e⁺/e⁻/α identification, insensitive to γ

use angular correlation between 2 electrons to determine ββ-0ν decay mechanism

82Se, 100Mo, 150Nd enriched foil sources with 60% efficiency

600 kg in 40 module 15 kg each (not yet settled)

expected bkg only by ββ-2ν

▶ resolution on sum energy (FWHM) ΔE = 200 keV
▶ ββ-2ν bkg reduced by cuts on electron distributions *

Present R&D

DCBA-T 21×24×60 cm³ with 0.015 mol 150Nd

Towards the Final Experiment

DCBA-I one module with 25 m² sources

DCBA-II 40 (100) modules

▶ 2.7 kmol 150Nd (80% enriched)

▶ τ½ > 10²⁶ y in 10 years

▶ ⟨m⟩ < 0.02 eV

DCBA-C calorimeter to study decay to excited states

* A.S. Barabash, V.A. Vasilyev, NIM A 473 (2001) 283
Majorana and $^{76}$Ge claim


Used five $^{76}$Ge crystals, with a total of 10.96 kg of mass, and 71 kg-years of data.

\[ \tau_{1/2} = 1.2 \times 10^{25} \text{ y} \]

\[ 0.24 < m_\nu < 0.58 \text{ eV} \ (3\sigma) \]

Background level depends on intensity fit to other peaks.

- Expected signal in Majorana (for 0.456 t-y) **135 counts**
- With a background
  
  **Goal: < 1 cnt in the ROI**
CUORICINO and NME

\[ m_{ee} = 50 \text{ meV} \] – half life for different nuclei and models \([10^{26} \text{ y}]\)

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Ref.: (20)</th>
<th>(80)</th>
<th>(81)</th>
<th>(82)</th>
<th>(24, 83)</th>
<th>(84)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{48}\text{Ca})</td>
<td>12.7</td>
<td>35.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>10.0</td>
</tr>
<tr>
<td>(^{76}\text{Ge})</td>
<td>6.8</td>
<td>70.8</td>
<td>56.0</td>
<td>9.3</td>
<td>12.8</td>
<td>14.4</td>
</tr>
<tr>
<td>(^{82}\text{Se})</td>
<td>2.3</td>
<td>9.6</td>
<td>22.4</td>
<td>2.4</td>
<td>3.2</td>
<td>6.0</td>
</tr>
<tr>
<td>(^{100}\text{Mo})</td>
<td>-</td>
<td>-</td>
<td>4.0</td>
<td>5.1</td>
<td>1.2</td>
<td>15.6</td>
</tr>
<tr>
<td>(^{116}\text{Cd})</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.9</td>
<td>3.1</td>
<td>18.8</td>
</tr>
<tr>
<td>(^{130}\text{Te})</td>
<td>0.6</td>
<td>23.2</td>
<td>2.8</td>
<td>2.0</td>
<td>3.6</td>
<td>3.4</td>
</tr>
</tbody>
</table>

| \(T_{1/2}(^{76}\text{Ge})/T_{1/2}(^{130}\text{Te})\) | 11.3 | 3.0 | 20.0 | 4.6 | 3.5 | 4.2 |
| expected \(T_{1/2}(^{130}\text{Te})\) (units: \(10^{24} \text{ y}\)) | 1.06 | 4.0 | 0.6 | 2.6 | 3.4 | 2.8 |

Half-lifetime extrapolation of the HM result \((1.2 \times 10^{25} \text{ y})\) to Tellurium assuming a given NME calculation

Elliot Vogel 2002

Staudt et al.
### Expected event number in 3 y in a 16 keV energy window (2 FWHM)

<table>
<thead>
<tr>
<th>Ref.:</th>
<th>(20)</th>
<th>(80)</th>
<th>(81)</th>
<th>(82)</th>
<th>(24, 83)</th>
<th>(84)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>141</td>
<td>37</td>
<td>251</td>
<td>57</td>
<td>44</td>
<td>53</td>
</tr>
</tbody>
</table>

1 σ BKG fluctuation = \((0.18 \times 16 \times 40.7 \times 3)^{0.5} = 19\)

<table>
<thead>
<tr>
<th>S/N ratio ((\sigma))</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.4</td>
</tr>
</tbody>
</table>

- **CUORICINO discovery potential**
- Good chance to have a positive indication
- No definite conclusion if no signal is seen
a few possible diagrams

Exchange of a **light** neutrino, only left-handed currents

\[
\begin{array}{c}
\text{Exchange of a light or heavy neutrino} \\
\text{and one right-handed } W_R
\end{array}
\]

Exchange of a **heavy** neutrino, short range hadron physics at play

Exchange of **supersymmetric** particles, R-symmetry violated

\[
\begin{array}{c}
\bar{e} \text{ (selectron)} \\
\chi \text{ (neutralino)} \\
\bar{e} \text{ (selectron)}
\end{array}
\]