A combined limit for neutrinoless double-beta decay

Pawel Guzowski
Outline

• Combined limit from 6 experimental inputs:
  • CUORICINO and CUORE-0
  • EXO-200
  • GERDA
  • KAMLAND-Zen
  • NEMO-3

• Cross-check of these individual results

• The combination
  – Nuclear Matrix Element model dependence

• Limits on sterile Majorana neutrinos
Introduction

• Limits on $0\nu\beta\beta$ have only so far been set for single experiments, or for a single isotope
• Combining results for multiple isotope is important, for improving sensitivity, and also for disentangling mechanisms if an observation is made
• We introduce a method for combining results of different experiments, and apply it to 6 recent experimental results
  – COURICINO/CUORE-0, EXO-200, GERDA, KamLAND-Zen & NEMO-3
THE EXPERIMENTS
NEMO-3

- Tracker-calorimeter
  - $^{100}$Mo isotope

$T_{1/2} > 1.1 \times 10^{24}$ years

See S Blot’s talk
CUORICINO

- $^{130}$Te Bolometer

Astropart.Phys. 34, 822 (2011)

$T_{1/2} > 2.8 \times 10^{24}$ years
CUORE-0

• Next phase of CUORICINO technique

\[ T_{1/2} > 2.7 \times 10^{24} \text{ years} \]

\[ \text{arXiv:1504.02454} \]

C Bucci’s talk
GERDA

- Germanium crystal
  - \( ^{76}\text{Ge} \) isotope

\[ T_{1/2} > 2.1 \times 10^{25} \text{ years} \]

Talk by K Gusev
KamLAND-Zen

- Xenon-loaded liquid scintillator
  - $^{136}$Xe isotope

$T_{1/2} > 1.9 \times 10^{25}$ years

PRL 110 062502 (2013)
EXO-200

- Liquid xenon TPC
  - $^{136}$Xe isotope

$T_{1/2} > 1.1 \times 10^{25}$ years

Talk by I Ostrovskiy

Nature 510, 229 (2014)
### Summary of experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Isotope</th>
<th>Method</th>
<th>Exposure (kg y)</th>
<th>$T_{1/2}$ 90% CL limit (years)</th>
<th>$m_{\beta\beta}$ limit (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUORICINO</td>
<td>$^{130}\text{Te}$</td>
<td>Bolometer</td>
<td>19.75</td>
<td>$2.8 \times 10^{24}$</td>
<td>300 - 710</td>
</tr>
<tr>
<td>CUORE-0</td>
<td>$^{130}\text{Te}$</td>
<td>Bolometer</td>
<td>9.8</td>
<td>$2.7 \times 10^{24}$</td>
<td>330 - 790</td>
</tr>
<tr>
<td>EXO-200</td>
<td>$^{136}\text{Xe}$</td>
<td>TPC</td>
<td>100</td>
<td>$1.1 \times 10^{25}$</td>
<td>190 - 450</td>
</tr>
<tr>
<td>GERDA</td>
<td>$^{76}\text{Ge}$</td>
<td>Calorimeter</td>
<td>21.6</td>
<td>$2.1 \times 10^{25}$</td>
<td>240 - 480</td>
</tr>
<tr>
<td>KamLAND-Zen</td>
<td>$^{136}\text{Xe}$</td>
<td>Loaded scintillator</td>
<td>89.5</td>
<td>$1.9 \times 10^{25}$</td>
<td>160 - 330</td>
</tr>
<tr>
<td>NEMO-3</td>
<td>$^{100}\text{Mo}$</td>
<td>Foil-Tracker-Calorimeter</td>
<td>34.7</td>
<td>$1.1 \times 10^{24}$</td>
<td>300 - 900</td>
</tr>
</tbody>
</table>
THE COMBINATION
The experimental data distributions

CUORICINO

CUORE-0

GERDA

EXO

KamLAND-Zen

NEMO-3
Aside: $CL_s$ limit setting method

- For each experimental data distribution there are two models
  - Background only (B)
  - Signal + background (S+B)
  - Signal normalisation can be scaled
- Calculate the Log Likelihood Ratio (LLR) for the data in both hypotheses
- Adjust signal normalisation until $CL_s = 0.1$ (for 90% CL)

$CL_s = CL_{s+b} / CL_b$

$CL_H$ is the p-value of the data LLR in the H hypothesis
## Cross checks of experimental inputs

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Published limit ((10^{24} \text{ y}))</th>
<th>Our limit ((10^{24} \text{ y}))</th>
<th>Sensitivity ((10^{24} \text{ y}))</th>
<th>1σ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUORE(INO+o)</td>
<td>4.0</td>
<td>4.4</td>
<td>4.3</td>
<td>2.9 – 6.2</td>
</tr>
<tr>
<td>EXO</td>
<td>11</td>
<td>13</td>
<td>21</td>
<td>14 – 30</td>
</tr>
<tr>
<td>GERDA</td>
<td>21</td>
<td>20</td>
<td>21</td>
<td>14 – 29</td>
</tr>
<tr>
<td>KamLAND-Zen</td>
<td>19</td>
<td>17</td>
<td>11</td>
<td>7 – 15</td>
</tr>
<tr>
<td>NEMO-3 ((^{100}\text{Mo}))</td>
<td>1.1</td>
<td>1.1</td>
<td>0.9</td>
<td>0.6 – 1.4</td>
</tr>
</tbody>
</table>

For the experiments based on \(^{76}\text{Ge}\) and \(^{100}\text{Mo}\), our limits are in excellent agreement with those published by the experiment collaborations.

Up to 15% difference in the \(^{130}\text{Te}\) and \(^{136}\text{Xe}\) experiments.
Calculating half life

Decay rate:
- signal
- normalisation

\[
\left[ T_{1/2}^{0\nu} \right]^{-1} = G^{0\nu} \left| M^{0\nu} \right|^2 \frac{m_{\beta\beta}^2}{m_e^2}
\]

Phase space factor (isotope-dependent)

Effective neutrino mass

Nuclear matrix element (isotope-dependent)
Nuclear Matrix Elements

- Use phase space factors and NMEs to give you the relative normalisation of signals between experiments.
NME effects on signal rates

For the GCM or QRPA NMEs with $m_{\beta\beta} = 400$ meV
NME effects on signal rates

• For a constant $m_{\beta\beta}$, between two models:
  – For some isotopes ($^{76}\text{Ge}$, $^{100}\text{Mo}$) the signal normalisation has increased
  – For other isotopes ($^{130}\text{Te}$, $^{136}\text{Xe}$) the signal normalisation has decreased
  – Some isotopes have large change, some very similar

• We produce limits on $m_{\beta\beta}$ that depend on the NME

• The combined limit is made through summing the LLRs of the individual experiments in the $CL_s$ method
  – signal normalisation depending on $m_{\beta\beta}$ as per the half-life formula
## Results

(improvement wrt best individual experiment)

<table>
<thead>
<tr>
<th>NME</th>
<th>limit (meV)</th>
<th>Improvement limit</th>
<th>Improvement sensitivity</th>
<th>HM p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCM [1]</td>
<td>130</td>
<td>12%</td>
<td>10%</td>
<td>0.0001</td>
</tr>
<tr>
<td>IBM [2]</td>
<td>190</td>
<td>16%</td>
<td>13%</td>
<td>0.021</td>
</tr>
<tr>
<td>NSM [3]</td>
<td>310</td>
<td>14%</td>
<td>10%</td>
<td>0.003</td>
</tr>
<tr>
<td>QRPA [4]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Argonne</td>
<td>new</td>
<td>200</td>
<td>23%</td>
<td>0.095</td>
</tr>
<tr>
<td></td>
<td>old</td>
<td>180</td>
<td>26%</td>
<td>0.100</td>
</tr>
<tr>
<td>Bonn</td>
<td>new</td>
<td>180</td>
<td>28%</td>
<td>0.073</td>
</tr>
<tr>
<td></td>
<td>old</td>
<td>170</td>
<td>28%</td>
<td>0.077</td>
</tr>
<tr>
<td>pnQRPA [5]</td>
<td>170</td>
<td>19%</td>
<td>16%</td>
<td>0.029</td>
</tr>
<tr>
<td>(R)QRPA [6]</td>
<td>290</td>
<td>23%</td>
<td>21%</td>
<td>0.311</td>
</tr>
</tbody>
</table>

Results Graphically

![Graph showing beta decay measurements and predictions](image)

- **NEMO-3**
- **CUORE**
- **GERDA**
- **KamLAND-Zen**
- **EXO-200**
- **Combination**

- **GCM**
- **IBM-2**
- **NSM**
- **QRPA**
- **pnQRPA**
- **(R)QRPA**

- **obs.**
- **exp.**

*7 September TAUP 2015 Pawel Guzowski*
QRPA uncertainty & correlation

Isotope

<table>
<thead>
<tr>
<th>Rel. Unc.</th>
<th>76 Ge</th>
<th>100 Mo</th>
<th>130 Te</th>
<th>136 Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>76 Ge</td>
<td>0.191</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 Mo</td>
<td>0.254</td>
<td>0.973</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>130 Te</td>
<td>0.247</td>
<td>0.899</td>
<td>0.862</td>
<td>1</td>
</tr>
<tr>
<td>136 Xe</td>
<td>0.293</td>
<td>0.805</td>
<td>0.747</td>
<td>0.916</td>
</tr>
</tbody>
</table>

- NME uncertainties lead to ~40-60% normalisation uncertainty on signal
- Effect of correlations can increase mass limit by up to 50 meV

**PRD 79, 053001 (2009)**

Pawel Guzowski

7 September

TAUP 2015
The bigger picture

Excluded at 90% confidence level

Combination (CUORE, EXO-200, GERDA, KamLAND-Zen, NEMO-3)

310 – 130 meV

Σm_ν < 0.49 eV

Planck 95% limit

Mass of lightest neutrino (eV)

Inverted Hierarchy

Normal Hierarchy

Σm_ν < 0.49 eV

Mass of lightest neutrino (eV)

Planck 95% limit
IMPLICATION FOR A STERILE MAJORANA NEUTRINO
How effective mass is calculated

\[ m_{\beta\beta} = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha} + 
+ m_3 |U_{e3}|^2 e^{i\beta} + m_4 \sin^2 \theta_{14} e^{i\gamma} \right| \]

Effective mass can be thought of as the length of the sum of vectors in the complex plane.

- Neutrino masses
- PMNS matrix elements
- Majorana phases
- 3+1 sterile neutrino model
How effective mass is calculated

\[
\begin{align*}
\nonumber m_{\beta\beta} &= \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha} + \\
\nonumber &+ m_3 |U_{e3}|^2 e^{i\beta} + m_4 \sin^2 \theta_{14} e^{i\gamma} \right|
\end{align*}
\]

Complex plane
How effective mass is calculated

\[ m_{\beta\beta} = |m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha} + \\
+ m_3 |U_{e3}|^2 e^{i\beta} + m_4 \sin^2 \theta_{14} e^{i\gamma} \]
How effective mass is calculated

\[ m_{\beta\beta} = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha} + m_3 |U_{e3}|^2 e^{i\beta} + m_4 \sin^2 \theta_{14} e^{i\gamma} \right| \]
How effective mass is calculated

\[ m_{\beta\beta} = |m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha} + \\
+ m_3 |U_{e3}|^2 e^{i\beta} + m_4 \sin^2 \theta_{14} e^{i\gamma} | \]
How effective mass is calculated

\[ m_{\beta\beta} = |m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha} + \\
+ m_3 |U_{e3}|^2 e^{i\beta} + m_4 \sin^2 \theta_{14} e^{i\gamma} | \]

The effective mass is the length of this vector
If we want to set limits on the sterile neutrino, we have two extreme cases:

- ‘Best’ upper limit on $m_4$ for a fixed $m_{\beta\beta}$ – all Majorana phases aligned
- ‘Worst’ upper limit on $m_4$ – ‘sterile’ Majorana phase antiparallel to active phases
Sterile Majorana neutrino limits

Global fit from oscillation experiments

\textit{JHEP 05, 050 (2013)}

(\textit{approx} limit from unitarity constraints in oscillation experiments)

Regions in the top right of the phase space are excluded at 90\% CL

\begin{itemize}
  \item \textbf{‘Worst’ limits}
  \item \textbf{‘Best’ limits}
\end{itemize}

\begin{itemize}
  \item NSM; \(\alpha = \beta = 0; \gamma = \pi\)
  \item GCM; \(\alpha = \beta = \gamma = 0\)
  \item \(m_1 = 0\, \text{meV}\)
  \item \(m_1 = 50\, \text{meV}\)
  \item \(m_1 = 100\, \text{meV}\)
  \item \(m_1 = 150\, \text{meV}\)
  \item \(\Delta m_{41}^2 = 1.78\, \text{eV}^2\)
  \item \(\sin^2 2\theta_{14} = 0.09\)
\end{itemize}
Summary

• A first combination of $0\nu\beta\beta$ limits with multiple isotopes has been performed
  \[ m_{\beta\beta} < 130 - 310 \text{ meV} \] (depending on NME)
• The combination can offer a sensitivity improvement equivalent to \(~2x\) increase of exposure of the most sensitive individual experiment
• Limits can be set for a sterile Majorana neutrino, with the global best-fit candidate excluded in some favourable scenarios

• For more detailed information, please read
  \textbf{Phys Rev D 92, 012002}