Results on Neutrinoless Double Beta Decay from GERDA Phase I

Manfred Lindner
(on behalf of the GERDA collaboration)
Outline

- Introduction
- Experimental requirements
- GERDA design and construction
- Phase I run parameters
- Backgrounds
- Pulse shape discrimination
- Results
- Conclusions & Implications
Double Beta Decay Processes

**Standard Model:**

\[ \beta^- \text{ decay} \]

\[ \text{n} \rightarrow \text{p} + \text{e}^- + \text{v}^- + \text{v}^+ \]

\[ \beta^- \text{ decay} \]

\[ \text{n} \rightarrow \text{p} + \text{e}^- + \text{v}^- + \text{v}^+ \]

\[ \text{2 electrons + 2 neutrinos} \]

**Majorana \( \nu \)-masses or other \( \Delta L=2 \) physics:**

\[ \text{2 electrons} \]

Majorana neutrino masses \( \leftrightarrow \) Dirac?

SM + Higgs triplet

SUSY

important connections to LHC and LFV …

sub eV Majorana mass \( \leftrightarrow \) TeV scale physics
Double Beta Decay & Mass Parabolas

Double beta decay: $2n \rightarrow 2p + X$; $Q_x = -2$; energy $Q_{\beta\beta}$ goes $\sim$ into $X$ if $m_X << GeV$

Standard Model: $2$ weak decays $X = 2e^- + 2\nu_e \rightarrow 2\nu$ beta decay

Beyond the SM: $X = 2e^- \rightarrow 0\nu$ (neutrino less) beta decay

Options: a) Majorana neutrino masses *OR* b) other $\Delta L = 2$ operators

M. Lindner, MPIK  
CERN, Oct. 1, 2013
Double Beta Decay Kinematics

$2\nu\beta\beta$ decay seen for diff. isotopes (Kirtsen,...)
$T^{1/2} = O(10^{18}-10^{21} \text{ years}) \Rightarrow \text{up to } 10^{11} \otimes T_{\text{Universe}}$

$0\nu\beta\beta$ decay

$T^{1/2} > O(10^{24}\text{y})$

- $2\nu\beta\beta \rightarrow \text{improvement}$
- search for $0\nu\beta\beta$ signal at $Q_{\beta\beta} = 2039 \text{ keV}$
- …backgrounds!
To best extract a $0\nu\beta\beta$ signal at $Q_{\beta\beta}$ and to avoid any misinterpretations:

- low background index (BI)  
  ➔ careful material selection, screening, shielding, PSD (pulse shape disc.), …
- best possible energy resolution  
  ➔ Germanium: source = detector (diode) ➔ few keV resolution
- if there is a signal  
  ➔ different nuclei to exclude unknown nuclear physics

- extremely rare process  
  ➔ low statistics = few counts/bin
- known (unknown?) nuclear lines
- tail of $2\nu\beta\beta$ signal
- backgrounds
- signal at known $Q_{\beta\beta}$-value ?
\[ (T_{1/2}^0)^{-1} = G_{0\nu}(Q_{\beta\beta}, Z) \left| M_{0\nu} \right|^2 m_{\beta\beta}^2 \]

\[ m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right| \]

**Without background:**

\[ N = \log 2 \cdot \frac{N_A}{W} \cdot \varepsilon \cdot \frac{M \cdot t}{T_{1/2}^{0\nu}} \]

- \( N_A \): Avogadro’s number
- \( W \): atomic weight of isotope
- \( \varepsilon \): signal detection efficiency
- \( M \): isotope mass
- \( t \): data taking time

\[ m_{\beta\beta} = K_1 \sqrt{\frac{N}{\varepsilon M t}} \]

**With background:**

\[ N' = N + N_{\text{background}} \]

\[ m_{\beta\beta} = K_2 \sqrt{\frac{1}{\varepsilon M t}} \left( \frac{c \Delta E}{M t} \right)^{1/4} \]

- \( c \): cts/keV kg yr
- \( \Delta E \): ROI
Which $0\nu\beta\beta$ Isotope?

- mass $\leftrightarrow$ isotopic abundance / enrichment $\leftrightarrow$ cost, feasibility
- cleanliness (radiopurity) of $0\nu\beta\beta$ source and instrumentation
- high $Q_{\beta\beta}$ $\leftrightarrow$ less nuclear backgrounds
- good energy resolution
- uncertainties in nuclear matrix elements (later...)
- ... $\Rightarrow$ Germanium is a very good choice
The GERDA Collaboration

http://www.mpi-hd.mpg.de/gerda/

16 institutions
~100 members
The GERDA Detector (original idea by G. Heusser, MPIK)

- Clean room
- Water tank: 590 m³ high purity water neutron moderator/absorber muon Cherenkov veto
- Lock system
- Cryostat with internal Cu shield
- Very clean liquid Ar
- Naked Ge detectors: 3 strings with 9 coax detectors 1 string with 5 BEGe’s

Background reduction:
- Material selection
- Screening (γ, Rn, …)
- Graded shielding
  - Deep underground
  - Veto systems
  - Water
  - Operation in LiAr
  - Naked Ge
  - …
- Source = detector
- Pulse shape analysis
- …

Model by A. Lindner
GERDA Location: LNGS Hall A
Material $\gamma$-Screening Facilities

- Different screening stations @ MPIK underground lab (1 mBq/kg)
- 4 GEMPIs @ LNGS (10 $\mu$Bq/kg)
- New: GIOVE @ MPIK (50 $\mu$Bq/kg)

$\Rightarrow$ extensive task for GERDA and other experiments (XENON, …)
Rn Screening Facilities

Gas counting systems @ LNGS and @ MPIK

$^{222}$Rn emanation technique:
- sensitivity = few atoms/probe
- large samples $\longleftrightarrow$ absolute sens.
- non-trivial; not commonly available; routine @MPIK
- established numbers:

  - Nylon (Borexino) < 1$\mu$Bq/m$^2$
  - Copper (Gerda): 2$\mu$Bq/m$^2$
  - Stainless steel (Borexino): 5$\mu$Bq/m$^2$
  - Titanium (preliminary): $(100 \pm 30) \mu$Bq/m$^2$
Detector Construction

- 2004: Letter of Intent
- R&D: material selection and screening, tests of bare diodes in LAr
- 2008-2010: construction at LNGS (Gran Sasso, Italy)
  - infrastructure & cryostat
  - water tank & muon veto
  - clean room, lock 6 clean benches
- 2010-2011: commissioning
- Nov. 2011: start of phase I data taking
Single Site Event = SSE

Multi Site Event = MSE

Wanted:
- energy resolution
- fast det. response
- pulse shape discr.
- very high radiopurity
- small capacity
- shape
- crystals
- “naked”
1) re-processed HdM, IGEX and GTF detectors
   p-type semi-coaxial
2) new p-type BEGe (Broad Energy Ge) detectors
   • n\(^+\) conductive Li layer, separated by a grove from the boron implanted p\(^+\) contact
   • operated as `diode`
   • SSE/MSE (single/multi site event) discrimination
BEGe Detector production

To minimize activation by cosmic ray:
- Transportation by truck or ship in shielded containers
- deep underground storage

Accumulated activity and its decay
GERDA Phase I Detectors

Since Nov. 2011:
6 enriched (86% of $^{76}\text{Ge}$)
ANG2, ANG3, ANG4, ANG5, RG1, RG2
→ 14.63 kg

1 natural (7.83% of $^{76}\text{Ge}$)
GTF112
→ 2.96 kg

Since July 2012:
4 BEGe (87% of $^{76}\text{Ge}$)
GD32B-GD32D, GD35B
→ 3.00 kg

In addition: 2 coaxial and 1 BEGe
unused due to high leakage currents
### Detector Parameter Details

<table>
<thead>
<tr>
<th>detector</th>
<th>enrichment factor</th>
<th>mass [g]</th>
<th>active mass [g]</th>
<th>active mass fraction</th>
<th>$d_{dl}$ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>enriched coaxial detectors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANG 1 †)</td>
<td>0.859(29)</td>
<td>958</td>
<td>795(50)</td>
<td>0.830(52)</td>
<td>1.8(5)</td>
</tr>
<tr>
<td>ANG 2</td>
<td>0.866(25)</td>
<td>2833</td>
<td>2468(145)</td>
<td>0.871(51)</td>
<td>2.3(7)</td>
</tr>
<tr>
<td>ANG 3</td>
<td>0.883(26)</td>
<td>2391</td>
<td>2070(136)</td>
<td>0.866(57)</td>
<td>1.9(7)</td>
</tr>
<tr>
<td>ANG 4</td>
<td>0.863(13)</td>
<td>2372</td>
<td>2136(135)</td>
<td>0.901(57)</td>
<td>1.4(7)</td>
</tr>
<tr>
<td>ANG 5</td>
<td>0.856(13)</td>
<td>2746</td>
<td>2281(132)</td>
<td>0.831(48)</td>
<td>2.6(6)</td>
</tr>
<tr>
<td>RG 1</td>
<td>0.855(15)</td>
<td>2110</td>
<td>1908(125)</td>
<td>0.904(59)</td>
<td>1.5(7)</td>
</tr>
<tr>
<td>RG 2</td>
<td>0.855(15)</td>
<td>2166</td>
<td>1800(115)</td>
<td>0.831(53)</td>
<td>2.3(7)</td>
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<tr>
<td>RG 3 †)</td>
<td>0.855(15)</td>
<td>2087</td>
<td>1868(113)</td>
<td>0.895(54)</td>
<td>1.4(7)</td>
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<tr>
<td><strong>enriched BEGe detectors</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GD32B</td>
<td>0.877(13)</td>
<td>717</td>
<td>638(19)</td>
<td>0.890(27)</td>
<td>1.0(2)</td>
</tr>
<tr>
<td>GD32C</td>
<td>0.877(13)</td>
<td>743</td>
<td>677(22)</td>
<td>0.911(30)</td>
<td>0.8(3)</td>
</tr>
<tr>
<td>GD32D</td>
<td>0.877(13)</td>
<td>723</td>
<td>667(19)</td>
<td>0.923(26)</td>
<td>0.7(2)</td>
</tr>
<tr>
<td>GD35B</td>
<td>0.877(13)</td>
<td>812</td>
<td>742(24)</td>
<td>0.914(29)</td>
<td>0.8(3)</td>
</tr>
<tr>
<td>GD35C †)</td>
<td>0.877(13)</td>
<td>635</td>
<td>575(20)</td>
<td>0.906(32)</td>
<td></td>
</tr>
<tr>
<td><strong>natural coaxial detectors</strong></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>GTF 32 †)</td>
<td>0.078(1)</td>
<td>2321</td>
<td>2251(116)</td>
<td>0.97(5)</td>
<td>0.4(8)</td>
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<td>GTF 45 †)</td>
<td>0.078(1)</td>
<td>2312</td>
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<td>GTF 112</td>
<td>0.078(1)</td>
<td>2965</td>
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</tbody>
</table>
Stable data taking during most of the time (556 d, duty cycle 88%) → 20 kg*y in April 2013 ➔ final exposure 21.6 kg * yr
The Blinding Procedure

Data processing details fixed before unblinding:
- quality cuts
- pulse shape discrimination parameters
- analysis method → three data sets
  - golden = 17.9 kg*yr
  - silver = 1.3 kg*yr
  - BEGe = 2.4 kg*yr

After Jan. 2012:
- blinding of $Q_{\beta\beta} \pm 20$ keV
  ↔ avoid biases

In June 2013
- unblinding

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CERN, Oct. 1, 2013
The outer dead layer of the detectors is not active

**Background sources:**
- $\alpha$ decays on the p$^+$ surface
- $\beta$ decay of $^{42}$K on the surface or close to the detector from $^{42}$Ar (10x more than expected)
- $\beta$ decay of $^{60}$Co inside detectors
- $\gamma$ from $^{208}$Tl, $^{214}$Bi and from various setup components

**Generic phase I background reduction**
- use cleanest possible material
- cut detector coincidences
- prevent $^{42}$K ions from drifting to detectors using minishrouds
Energy resolution:
coaxial at $Q_{\beta\beta}$: $(4.8 \pm 0.2)\text{ keV}$
BEGe: $(3.2 \pm 0.2)\text{ keV}$

- stable energy resolution
- no energy drift between consecutive calibrations (<0.05%)
- leakage currents stable (except RG2)
Good Energy Resolution and Gain Stability

FWHM ($\gamma$-peak)

FWHM of long term data at $^{42}$K 1525 keV $\gamma$-peak

FWHM (resolution) of $0\nu\beta\beta$ data at $Q_{\beta\beta}$

<table>
<thead>
<tr>
<th>detector</th>
<th>FWHM [keV]</th>
<th>detector</th>
<th>FWHM [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUM-coax</td>
<td></td>
<td>SUM-bege</td>
<td></td>
</tr>
<tr>
<td>ANG 2</td>
<td>5.8 (3)</td>
<td>GD32B</td>
<td>2.6 (1)</td>
</tr>
<tr>
<td>ANG 3</td>
<td>4.5 (1)</td>
<td>GD32C</td>
<td>2.6 (1)</td>
</tr>
<tr>
<td>ANG 4</td>
<td>4.9 (3)</td>
<td>GD32D</td>
<td>3.7 (5)</td>
</tr>
<tr>
<td>ANG 5</td>
<td>4.2 (1)</td>
<td>GD35B</td>
<td>4.0 (1)</td>
</tr>
<tr>
<td>RG 1</td>
<td>4.5 (3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RG 2</td>
<td>4.9 (3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mean coax</td>
<td>4.8 (2)</td>
<td>mean BEGe</td>
<td>3.2 (2)</td>
</tr>
</tbody>
</table>
The Background Spectrum

2νββ result
arXiv:1212.3210

\[ T_{1/2}^{2\nu} = \left( 1.84^{+0.14}_{-0.08} \right) \times 10^{21} \text{ yr} \]

backgrd. paper
arXiv:1306.5084
to appear in EPJ C

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The Background Model

Background decomposition with all simulated components; fit window 570-7500 keV

Minimum model: minimum set of background components

Gold coax
Larger energy range...

fits data very well

background is FLAT in ROI
For BEGEs...
Larger energy range for BEGE's
### Derived Background Composition

<table>
<thead>
<tr>
<th>source</th>
<th>location</th>
<th>units</th>
<th>\textit{GOLD-coax}</th>
<th>\textit{GOLD-nat}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>minimum</td>
<td>maximum</td>
<td>minimum</td>
</tr>
<tr>
<td>$^{40}\text{K}$</td>
<td>det. assembly</td>
<td>$\mu$Bq/det.</td>
<td>152[136,174]</td>
<td>218[188,259]</td>
</tr>
<tr>
<td>$^{42}\text{K}$</td>
<td>LAr</td>
<td>$\mu$Bq/kg</td>
<td>106[103,111]</td>
<td>98.3[92,108]</td>
</tr>
<tr>
<td>$^{42}\text{K}$</td>
<td>$p^+$ surface</td>
<td>$\mu$Bq</td>
<td>11.6[3.1,18,3]</td>
<td>4.1[1,2,8]</td>
</tr>
<tr>
<td>$^{42}\text{K}$</td>
<td>$n^+$ surface</td>
<td>$\mu$Bq</td>
<td>4.1[1,2,8,5]</td>
<td></td>
</tr>
<tr>
<td>$^{60}\text{Co}$</td>
<td>det. assembly</td>
<td>$\mu$Bq/det.</td>
<td>4.9[3.1,7,3]</td>
<td>2.6[0,6]</td>
</tr>
<tr>
<td>$^{60}\text{Co}$</td>
<td>germanium</td>
<td>$\mu$Bq</td>
<td>&gt;0.4 $^\dagger$</td>
<td>&gt;0.2 $^\dagger$</td>
</tr>
<tr>
<td>$^{214}\text{Bi}$</td>
<td>det. assembly</td>
<td>$\mu$Bq/det.</td>
<td>35[31,39]</td>
<td>34.1[27,3,42.1]</td>
</tr>
<tr>
<td>$^{214}\text{Bi}$</td>
<td>LAr close to $p^+$</td>
<td>$\mu$Bq/kg</td>
<td>&lt;299.5</td>
<td></td>
</tr>
<tr>
<td>$^{214}\text{Bi}$</td>
<td>radon shroud</td>
<td>mBq</td>
<td>&lt;49.9</td>
<td></td>
</tr>
<tr>
<td>$^{214}\text{Bi}$</td>
<td>$p^+$ surface</td>
<td>$\mu$Bq</td>
<td>2.9[2.3,3.9] $^\dagger$</td>
<td>1.6[1.2,2.1] $^\dagger$</td>
</tr>
<tr>
<td>$^{228}\text{Th}$</td>
<td>det. assembly</td>
<td>$\mu$Bq/det.</td>
<td>15.1[12,7,18.3]</td>
<td>15.7[10.0,25.0]</td>
</tr>
<tr>
<td>$^{228}\text{Ac}$</td>
<td>det. assembly</td>
<td>$\mu$Bq/det.</td>
<td>5.5[1.8,8.8]</td>
<td>25.9[16.7,36.7]</td>
</tr>
<tr>
<td>$^{228}\text{Th}$</td>
<td>radon shroud</td>
<td>mBq</td>
<td>&lt;15.7</td>
<td></td>
</tr>
<tr>
<td>$^{228}\text{Ac}$</td>
<td>radon shroud</td>
<td>mBq</td>
<td>&lt;10.1</td>
<td></td>
</tr>
<tr>
<td>$^{228}\text{Th}$</td>
<td>heat exchanger</td>
<td>Bq</td>
<td>&lt;4.1</td>
<td></td>
</tr>
</tbody>
</table>

Good agreement between model and activities of $^{40}\text{K}$, $^{42}\text{K}$, $^{60}\text{Co}$

The position of some components can not be resolved ($^{214}\text{Bi}$, $^{228}\text{Th}$, ...)

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More on Backgrounds…

Intensity of gamma peak outside background analysis energy window

*Gold Coax:*
- Min model: $294 \pm 27$
- Max model: $258 \pm 27$
- Data: $262 \pm 48$

*GTF112:*
- Min model: $70 \pm 11$
- Data: $77 \pm 19$

- Very good agreement between peak intensities vs. background model
- Further cross checks... (BiPo coincidences, PSA)
Background Composition: Minimum Model

minimum set of background components ➔
Background Composition: Maximum Model

total set of known background components leading to distinguishable spectra
Pulse Shape Discrimination

- Single Site Events (SSE)
- Multi Site Events (MSE)

- $0\nu\beta\beta$-decays $\rightarrow$ localized energy deposition $\rightarrow$ SSE
- Compton scattering event $\rightarrow$ background like MSE
- Surface events $\rightarrow$ SSE @ surface
- SSE by γ’s look like events (cannot be rejected)
- β particles enter via n$^+$ surface $\rightarrow$ slow pulses
- α’s @ p$^+$ contact $\rightarrow$ comparatively high signal

Current [a.u.]

gamma\'s

drift paths

Background like multi site event $\rightarrow$ MSE

Signal like single site event $\rightarrow$ SSE

0νββ-decay

α-decay

$E_1 E_2$

e$^-$ e$^-$

$\gamma\gamma'\gamma$

Ge detector

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Pulse Shape Discrimination: Coaxial

3 independent PSD methods:
- likelihood classification
- PSD selection based on pulse asymmetry
- neural network analysis (ANN) ➔ training with calibration data

SSE library: DEP peak of $^{208}$Tl ➔ gamma at 1592 ± 1 keV

MSE library: FAP (Full Absorption Peak) of $^{212}$Bi at 1620 keV
Neural Network Training with Calibration Data

- DEP events in the interval 1592 keV ± 1FWHM serve as proxy for SSE
- Full energy line of $^{212}$Bi in the equivalent interval around 1620 keV are dominantly MSE, taken as background events
Pulse Shape Discrimination: BEGe A/E Cuts

Cutting in A/E → rejects background like MSEs

\[ \varepsilon_{\text{PSD}} = 0.92 \pm 0.02 \] → ca. 85% of background events at \( Q_{\beta\beta} \) rejected.
Application of PSD to Phase I Data

- all events removed by ANN are removed by at least one other method
- events discarded by ANN are in 90% of the cases discarded by all 3 methods
- in a larger energy window about 3% are only rejected by ANN

⇒ About 45% of events are rejected

Efficiency: \( \epsilon_{0\nu\beta\beta} = 0.90^{+0.05}_{-0.09} \)
expected bg from $5.1$ events w/o PSD
interpolation: $2.5$ events with PSD
The Region of Interest

expected bg from interpolation: 5.1 events w/o PSD 2.5 events with PSD

observed  ➔ 7 events w/o PSD  ➔ 3 events with PSD
7 events in $Q_{\beta\beta} \pm 5$ keV
4 events rejected by PSD
⇒ 3 events in $Q_{\beta\beta} \pm 5$ keV after PSD
⇒ 0 events in $Q_{\beta\beta} \pm 1\,\sigma$
profile likelihood (PL) fit:

signal = a*flat background + b*line

→ best fit: $N^{0\nu} = 0$ ; upper limit: $N^{0\nu} < 3.5$ (90\% CL)

→ half life limit $T_{1/2}(0\nu\beta\beta) > 2.1 \times 10^{25}$ yr (90\% C.L.)
Comparison with the KK Claim (2004)

claim:
\[ T_{1/2}(0\nu\beta\beta) = 1.19 \times 10^{25} \text{ yr} \]

Stronger 2006 claim: 100% PSD efficiency assumed
\( \Rightarrow \) incorrect \( \Rightarrow \) realistic efficiency = no improvement

GERDA:
- much lower BI
- no unknown nuclear lines
- remaining flat background in ROI

GERDA upper limit from PL fit:
< 3.5 events (90%CL)

for the KK claim GERDA is expected to see (2\( \sigma \)):
5.9 \( \pm \) 1.4 signal counts
2.0 \( \pm \) 0.3 background counts

\( \Rightarrow \) probability for a fluctuation 1%
Combination of Ge Results

- GERDA phase I
- HdM
- IGEX

- PL fit to combined data
- backgrounds = free parameters
- Best fit for $N^{0\nu} = 0$

- Limit:
  $T_{1/2}^{0\nu}(0\nu\beta\beta) > 3.0 \times 10^{25}$ yr (90% CL)

- claim strongly disfavoured
  Bayes factor $2 \times 10^{-4}$
Comparison with Xenon Results

Assumptions:
- exchange of Majorana neutrinos
- NME ratios better known

→ NME ratio has spread!
→ at best one is right
→ model dependence

Bayes factors:
EXO: 0.23
KamLAND-Zen: 0.40

All with GERDA: 0.0022

→ claim even more disfavoured
NME’s: Relating Lifetimes & Neutrino Masses

\[ 1/\tau = G(Q,Z) |M_{\text{nucl}}|^2 <m_{ee}>^2 \]

---

**nuclear matrix elements:**
- virtual excitations of intermediate states

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**0νββ**

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**in recent years:**
- good progress in TH errors
- reduced uncertainties
- which NME is correct?
- what is a 1σ theory error?

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The $0\nu\beta\beta$-decay NMEs (**Status: 2013**)

**Simkovic Erice 2013**

**Differences:**

i) mean field;

ii) residual int.;

iii) size of the m.s.

iv) many-body appr.

- LSSM (small m.s., negative parity states)
- PHFB (GT force neglected)
- IBM (Hamiltonian truncated)
- (R)QRPA (g.s. correlations not accurate enough)

\[ g_A = 1.25(7), \text{ CCM or UCOM s.r.c., } r_0 = 1.20 \text{ fm}. \]
\[ m_{ee} = |m_{ee}^{(1)}| + |m_{ee}^{(2)}| \cdot e^{i\Phi_2} + |m_{ee}^{(3)}| \cdot e^{i\Phi_3} \]

\[
|m_{ee}^{(1)}| = |U_{e1}|^2 m_1 \\
|m_{ee}^{(2)}| = |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2} \\
|m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2} 
\]

solar \(\Rightarrow |U_{e1}|^2, |U_{e2}|^2, \Delta m_{21}^2\) atmosp. \(\Rightarrow |\Delta m_{31}^2|\) CHOOZ \(\Rightarrow |U_{e3}|^2 < 0.05\)

- free parameters: \(m_1\), \(\text{sign}((\Delta m_{31}^2))\), CP-phases \(\Phi_2, \Phi_3\)
**Comments:**

- **cosmology:** further improvements ↔ systematical errors
- **NMEs** ➔ unavoidable **theory** error in $m_{ee}$
- **assumptions:** no *other* $\Delta L=2$ physics, no sterile neutrinos, ...
Interferences in $0\nu\beta\beta$ Decays

Usually

$$\left( T_{1/2}^{0\nu} \right)^{-1} = \left( \frac{|m_{0\nu\beta\beta}|}{m_e} \right)^2 |M^{0\nu}|^2 G^{0\nu}.$$ 

with interferences

$$\left( T_{1/2}^{0\nu} \right)^{-1} = |m_{0\nu\beta\beta} M^{0\nu} + \epsilon_m M^\epsilon| \frac{2 G^{\text{int}}}{m_e^2}$$

$$= |(m_{0\nu\beta\beta} + \epsilon_m M^\epsilon(M^{0\nu})^{-1}) M^{0\nu}| \frac{2 G^{\text{int}}}{m_e^2}$$

$$= |m_{0\nu\beta\beta}^{\text{int}}| |M^{0\nu}|^2 \frac{G^{\text{int}}}{m_e^2}$$

$G^{\text{int}} = \epsilon_m M^\epsilon$ determined by parameters of new physics

$\equiv m_{0\nu\beta\beta} + m_e$

M. Lindner, MPIK
CERN, Oct. 1, 2013

Dürr, ML, Neuenfeld
growing $m_\epsilon$
fixed $0\nu\beta\beta$ 
shifts:  
- masses
- mixings
- CP phases
- interferences
Transition to phase II:

- drainage, inspection & refilling of WT
- Installation of more new BEGe detectors
  - ~factor 2 in $^{76}$Ge mass
- Installation of light instrumentation
  - fibers and PMTs = anti-Compton veto
  - further reduction of background index
- Continue data taking with more mass, less BI, longer time, …
**Summary**

- GERDA has finished phase I data taking with unprecedented BI in ROI
- The background in the GERDA experiment can be explained well & and is flat around ROI!
- 3 independent pulse shape discrimination techniques efficiently reduces background
- Half life limit for 0νββ-decay of $^{76}$Ge: $2.1 \cdot 10^{25}$ yr (90% C.L.)
- Combined with HdM and IGEX: $3.0 \cdot 10^{25}$ yr (90% C.L.) ➞ HdM claim strongly disfavored!
- Transition to phase II is on-going