Double Beta Decays

Manfred Lindner
(on behalf of the GERDA collaboration)
Double Beta Decay & Mass Parabolas

Special nuclei:
- single $\beta$-decay energetically forbidden
- double beta decay allowed

$\text{even-even nuclei: } ^{76}\text{Ge, ...}$

$Q_{\beta\beta} = 2039 \text{ keV}$

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

Standard Model:

\[ \nu_\beta \rightarrow 2 \text{ electrons} + 2 \nu \]

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

\[ \nu_\beta \rightarrow 2 \text{ electrons} \]

- Majorana neutrino masses \(\leftrightarrow\) Dirac?
- SM + Higgs triplet
- SUSY

important connections to LHC and LFV …
sub eV Majorana mass \(\leftrightarrow\) TeV scale physics
$m_{ee}: The \text{ Effective Neutrino Mass}$

$$m_{ee} = |m_{ee}^{(1)}| + |m_{ee}^{(2)}| \cdot e^{i\Phi_2} + |m_{ee}^{(3)}| \cdot e^{i\Phi_3}$$

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

**Comments:**

- cosmology: further improvements?
- systematic errors
- NMEs: unavoidable theory errors
- assumption: no *other* $\Delta L=2$ physics, no sterile neutrinos, ...
Interference of $\Delta L=2$ Operators

Usually

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

with interferences

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

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

$m_{0\nu\beta\beta}^\text{int} \equiv m_{0\nu\beta\beta} + \epsilon m_e M^\epsilon (\mathcal{M}^{0\nu})^{-1} \equiv m_{0\nu\beta\beta} + m_\epsilon$

$m_\epsilon \sim (\Lambda_{\text{new}})^{-5}$

$m_{0\nu\beta\beta} = 1 \text{ eV} \iff \Lambda_{\text{new}} \sim \text{TeV}$
interferences

Growing $m_\epsilon$ for fixed $0\nu\beta\beta$

$\rightarrow$ shifts of masses, mixings and CP phases

$\rightarrow$ destroys ability to extract Majorana phases

$\rightarrow$ sensitivity to TeV
Double Beta Decay Kinematics

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

- $T^{1/2} > O(10^{24} \text{y})$
- $2\nu\beta\beta \rightarrow$ improvement
- search for $0\nu\beta\beta$ signal at $Q_{\beta\beta} = 2039 \text{ keV}$
- ...backgrounds!

M. Lindner, MPIK  
NNN13, Nov. 11-13, 2013
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) $\Rightarrow$ few keV resolution
- if there is a signal
  - different nuclei to exclude unknown nuclear physics
Sensitivity & Background (for a Majorana Mass)

\[
(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z) \left| M_{0\nu} \right|^2 m_{\beta\beta}^2
\]

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

Without background:

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

\[N_A = \text{Avogadro's number}\]
\[W = \text{atomic weight of isotope}\]
\[\epsilon = \text{signal detection efficiency}\]
\[M = \text{isotope mass}\]
\[t = \text{data taking time}\]

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

With background:

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

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

\[c = \text{cts/keV kg yr} \ ; \ \Delta E = \text{ROI}\]
Which $0\nu\beta\beta$ Isotope?

- active 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 $\leftrightarrow$ background rejection
- uncertainties in nuclear matrix elements
- ...

→ various promising options
### List of Recent $0\nu\beta\beta$ Experiments / Projects

<table>
<thead>
<tr>
<th>isotope</th>
<th>$G^{0\nu}$ [$10^{-14}$ yr$^{-1}$]</th>
<th>$Q_{\beta\beta}$ [keV]</th>
<th>nat. ab. [%]</th>
<th>$T_{1/2}^{2\nu}$ [$10^{20}$ y]</th>
<th>experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>6.3</td>
<td>4273.7</td>
<td>0.187</td>
<td>0.44</td>
<td>CANDLES</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>0.63</td>
<td>2039.1</td>
<td>7.8</td>
<td>15</td>
<td>GERDA, Majorana Demonstr.</td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>2.7</td>
<td>2995.5</td>
<td>9.2</td>
<td>0.92</td>
<td>SuperNEMO, Lucifer</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>4.4</td>
<td>3035.0</td>
<td>9.6</td>
<td>0.07</td>
<td>MOON, AMoRe</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>4.6</td>
<td>2809.1</td>
<td>7.6</td>
<td>0.29</td>
<td>Cobra</td>
</tr>
<tr>
<td>$^{130}\text{Te}$</td>
<td>4.1</td>
<td>2530.3</td>
<td>34.5</td>
<td>9.1</td>
<td>CUORE</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>4.3</td>
<td>2457.8</td>
<td>8.9</td>
<td>21</td>
<td>EXO, Next, Kamland-Zen</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$</td>
<td>19.2</td>
<td>3367.3</td>
<td>5.6</td>
<td>0.08</td>
<td>SNO+, DCBA/MTD</td>
</tr>
</tbody>
</table>

➡️ GERDA
➡️ EXO, KamLAND-Zen
➡️ future
The GERDA Collaboration

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

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

M. Lindner, MPIK

NNN13, Nov. 11-13, 2013

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background reduction:
• material selection
• screening (γ, Rn, …)
• graded shielding
  - deep underground
  - veto systems
  - water
  - operation in LiAr
  - naked Ge
  - …
• source = detector
• pulse shape analysis
• …

clean room

lock system

water tank:
590 m³ high purity water
neutron moderator/absorber
muon Cherenkov veto

cryostat with
internal Cu shield

very clean liquid Ar

naked Ge detectors:
3 strings with 9 coax detectors
1 string with 5 BEGe’s

plastic scintillator veto
γ and Rn Screening Facilities

- γ-screening stations (1mBq/kg) @MPIK underground lab
- 4 GEMPIs (10µBq/kg) @LNGS
- New: GIOVE (50µBq/kg) @MPIK

→ extensive task for GERDA and other experiments (XENON, …)

**Rn Screening Facilities:**

Gas counting systems (LNGS, MPIK)

$^{222}$Rn emanation technique

sensitivity = few atoms/probe

→ typ. sensitivity: few µBq/m²

ICPMS: …
Detector Construction @LNGS Hall A

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

1 natural (7,83% of $^{76}$Ge)
GTF112
$\rightarrow$ 2.96 kg

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

In addition: 2 coaxial and 1 BEGe unused due to high leakage currents
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
Data processing details fixed before unblinding:
- quality cuts
- pulse shape discrimination parameters
- analysis method \( \rightarrow \) three data sets

- golden = 17.9 kg\(\times\)yr
- silver = 1.3 kg\(\times\)yr
- BEGe = 2.4 kg\(\times\)yr

After Jan. 2012:
- blinding of \(Q_{\beta\beta}\pm20\text{keV}\)
- avoid biases

Unblinding in June 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 set-up components

**Generic phase I background reduction**
- use cleanest possible materials
- cut detector coincidences
- prevent $^{42}$K ions from drifting to detectors using mini-shrouds
Detector Performance

Energy resolution:

coaxial at $Q_{\beta\beta}$: $(4.8 \pm 0.2)$ keV

BEGe: $(3.2 \pm 0.2)$ keV

- stable energy resolution
- no energy drift between consecutive calibrations (<0.05%)
- leakage currents stable (except RG2)
The Background Spectrum

$2\nu\beta\beta$ result
arXiv:1212.3210

$T^{2\nu}_{1/2} = (1.84^{+0.14}_{-0.08}) \times 10^{21}$ yr

backgrd. paper
arXiv:1306.5084
to appear in EPJ C
Background decomposition with all simulated components; fit window 570-7500 keV

Minimum model: minimum set of background components

Gold coax
Background Composition: Maximum Model

total set of known background components leading to distinguishable spectra

![Graph depicting various background components and their respective spectra.](image-url)
Pulse Shape Discrimination

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

- $0\nu\beta\beta$-decays $\rightarrow$ localized energy deposition $\rightarrow$ SSE
- Compton scattering evt. $\rightarrow$ background like MSE
- surface events $\rightarrow$ SSE @ surface
- SSE by $\gamma$’s look like events (cannot be rejected)
- $\beta$ particles enter via n$^+$ surface $\rightarrow$ slow pulses
- $\alpha$’s @ p$^+$ contact $\rightarrow$ comparatively high signal
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 $1592\text{ keV} \pm 1\text{FWHM}$ serve as proxy for SSE
- Full energy line of $^{212}\text{Bi}$ in the equivalent interval around $1620\text{ keV}$ are dominantly MSE, taken as background events
Cutting in A/E rejects background like MSEs

$$\epsilon_{\text{PSD}} = 0.92 \pm 0.02 \Rightarrow \text{ca. 85% of background events at } Q_{\beta\beta} \text{ rejected}$$
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: \( \epsilon_{0\nu\beta\beta} = 0.90^{+0.05}_{-0.09} \)
The Region of Interest

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
observed: 7 events w/o PSD

2.5 events with PSD
observed: 3 events with PSD
Profile Likelihood Fit to PSD Spectrum

profile likelihood (PL) fit:

\[
\text{signal} = a\text{*flat background} + b\text{*line}
\]

\(\Rightarrow\) best fit: \(N_{0\nu} = 0\) ; upper limit: \(N_{0\nu} < 3.5\) (90\%CL)

\(\Rightarrow\) half life limit \(T_{1/2}(0\nu\beta\beta) > 2.1 \times 10^{25}\) yr (90\% C.L.)
Combine: GERDA phase I + HdM + IGEX
⇒ PL fit to combined data
⇒ backgrounds = free parameters
⇒ Best fit for $N^{0\nu} = 0$
⇒ $T_{1/2}(0\nu\beta\beta) > 3.0 \times 10^{25}$ yr (90% CL)

KK-claim: $T_{1/2}(0\nu\beta\beta) = 1.19 \times 10^{25}$ yr

Stronger 2006 claim has known error:
100% PSD efficiency assumed
⇒ realistic efficiency = no improvement

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

GERDA upper limit from PL fit:
$< 3.5$ events (90% CL)
KK claim strongly disfavoured
(Bayes factor $2 \times 10^{-4}$)

KK claim ⇒ GERDA should see (2σ):
$5.9 \pm 1.4$ signal counts
$2.0 \pm 0.3$ background counts
⇒ probability for a fluctuation 1%
Transition to phase II:

- drainage, inspection & refilling of WT
- Installation of more new BEGe detectors
  - \( \sim \) factor 2 in \( ^{76}\text{Ge} \) 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, ...

\[ \rightarrow \]
University of Alabama, Tuscaloosa AL, USA - D. Auty, T. Didberidze, M. Hughes, A. Piepke
University of Bern, Switzerland - M. Auger, S. Delaquis, D. Franco, G. Giroux, R. Gornea, T. Tolba, J-L. Vuilleumier
California Institute of Technology, Pasadena CA, USA - P. Vogel
Colorado State University, Fort Collins CO, USA - C. Benitez-Medina, C. Chambers, A. Craycraft, W. Fairbank, Jr., T. Walton
Drexel University, Philadelphia PA, USA - M.J. Dolinski, M.J. Jewell, Y.H. Lin, E. Smith
Duke University, Durham NC, USA – P.S. Barbeau
IHEP Beijing, People’s Republic of China - G. Cao, X. Jiang, Y. Zhao
University of Illinois, Urbana-Champaign IL, USA - D. Beck, M. Coon, J. Liu, M. Tarka, J. Walton, L. Yang
Indiana University, Bloomington IN, USA - J. Albert, S. Daugherty, T. Johnson, L.J. Kaufman
University of California, Irvine, Irvine CA, USA - M. Moe
Laurentian University, Sudbury ON, Canada - B. Cleveland, J. Farine, B. Mong, U. Wichoski
University of Maryland, College Park MD, USA - C. Davis, A. Dobi, C. Hall, S. Slutsky, Y-R. Yen
University of Massachusetts, Amherst MA, USA - T. Daniels, S. Johnston, K. Kumar, A. Pocar, D. Shy, J.D. Wright
University of Seoul, South Korea - D.S. Leonard
Technical University of Munich, Garching, Germany - W. Feldmeier, P. Fierlinger, M. Marino
TRIUMF, Vancouver BC, Canada - P.A. Amaudrux, D. Bishop, J. Dilling, P. Gumplinger, R. Krucken, C. Lim, F. Retière, V. Strickland
No peak observed at $Q_{\beta\beta}$.

MC background model: $1.5 \cdot 10^{-3}$ cnts/(keV·yr·kg)

Measured background: $153 \pm 69$ cnts/(±2·σ·ton·yr)
$31 \pm 31$ cnts/(±σ·ton·yr)

$T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25}$ yr (90% CL)

$\langle m \rangle_{\beta\beta} < 140 - 380$ meV
KamLAND-Zen collaboration
Tohoku University
Kavli IPMU Tokyo University
Osaka University
University of California Berkeley
LBNL
Colorado State University
University of Tennessee
TUNL
University of Washington
NIKHEF and University of Amsterdam

1st phase
$^{136}\text{Xe} \sim 320\text{kg (91\% enriched)}$
R=1.58m balloon
V=16.5m$^3$
LS : C10H22(81.8\%) + PC(18\%) + PPO + Xe(\sim 3wt\%)
$\rho_{LS} : 0.78\text{kg}\/\ell$
target : \sim 60\text{meV} / 2\text{years for 0v\beta\beta}$

courtesy M. Koga
KamLAND-Zen Phase I Results

2.2 MeV < E < 3.0 MeV

\[ T_{1/2}^{0v} > 2.1 \times 10^{-25} \text{ yr @} 90\% \text{CL} \]


M. Lindner, MPIK

NNN13, Nov. 11-13, 2013
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

→ KK claim even more disfavoured
Future Plans of KamLAND-Zen

re-start (from Nov. 2013?)

KamLAND-Zen2
- we will purchase 700~800kg enrich $^{136}$Xe to the end of 2013
- make bigger balloon
- same component XeLS ($\sim$3wt%)
- main tank inspection & OD repair (beginning of 2015?)

tank opening (201?)

KamLAND2-Zen $^{136}$Xe 800~1000kg
- R=2.3m balloon, V=51.3m$^3$, S=66.7m$^2$
- Detector upgrade improvement of energy resolution (brighter LS, higher light concentrator)
  \[\sim 25\text{meV with 5 years}\]
Future Plans of EXO: ➔ nEXO

- EXO has 3.6 times more data ➔ should be published soon…
- EXO started to study the case for a 5 ton (~4.5 ton fiducial) Xe experiment, initially without Ba-tagging. Tagging should remain an option, you could consider it a (backgd.) risk mitigation tool:
  - 4.5 tons of active \(^{enr}\)Xe (80% or higher)
  - 1.5\% (\(\sigma\)) energy resolution
  - Background from Monte Carlo using normalizations derived from EXO-200 data and materials assay
  - 3 times finer wire pitch than EXO-200, lower energy threshold ➔ 2 times better e-\(\gamma\) discrimination than EXO-200

Goals: probe and possibly fully cover the inverted hierarchy neutrino mass range. In case Ba detection is added test part of the normal hierarchy
Future of Ge-Experiments

GERDA: on-going modifications for phase II → data taking

MAJORANA demonstrator:
under construction → data taking

- ~ 30 kg $^{enr}$Ge + ~ 10 kg $^{nat}$Ge detectors, in two cryostats
- Ultrapure materials; copper that has been electroformed and machined underground
- Compact passive and active shields
- At the 4850-foot level of SURF, Lead, SD
- Construction scheduled for completion in 2015

GERDA + MAJORANA cooperation agreement:
- open exchange of knowledge & technologies (e.g. MaGe, R&D)
- intention to merge for ton-scale experiment
→ best techniques developed & tested in GERDA and MAJORANA
Conclusions

- GERDA phase I finished data taking with unprecedented BI
- The background is understood very well: flat in ROI
- 3 independent pulse shape discrimination techniques efficiently reduces background
- Half life limit for $0
\nu\beta\beta$-decay of $^{76}$Ge: $2.1 \cdot 10^{25}$ yr (90% C.L.)
  GERDA+HdM+ IGEX: $3.0 \cdot 10^{25}$ yr (90% C.L.)
- Similar limits from EXO and KamLAND-Zen
  Xe$\rightarrow$Ge translation depends on matrix element ratios...
- Ge+Xe combined: HdM claim very strongly disfavored!

- New result from EXO expected soon
- Very promising upgrades / plans for the future!