Experimental review of DBD and KamLAND-Zen experiment

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Double Beta Decay and Underground Science,
Hankyu Sanwa Hall, 8 November 2016
Experimental milestone has been a verification of KK-claim. KL-Zen+EXO-200 refuted it with fairly robust NME assumption. GERDA then clearly rejected it using the same $^{76}\text{Ge}$. What’s next?
full coverage of Quasi Degenerate  → next milestone
full coverage of Inverted Hierarchy  → next gen. exp.
full coverage of $m_{\text{lightest}} \sim 0$ (below 1 meV)  → very difficult

Allowed region from Oscillation and Cosmology

Dell’Oro et al., Advances in High Energy Physics 2016, 2162659

We need to propose a future plan seeking below 10 meV.
comparison of double beta decay nuclei

<table>
<thead>
<tr>
<th>Nucleas</th>
<th>$T_{1/2}^{0\nu}$ (50 meV)</th>
<th>$T_{1/2}^{2\nu}$ measured (year)</th>
<th>Nat. Abundance (%)</th>
<th>Q-value (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca→$^{48}$Ti</td>
<td></td>
<td>$(4.2^{+2.1}_{-1.0}) \times 10^{19}$</td>
<td>0.19</td>
<td>4271</td>
</tr>
<tr>
<td>$^{76}$Ge→$^{76}$Se</td>
<td>0.86×10$^{27}$</td>
<td>$(1.5\pm0.1) \times 10^{21}$</td>
<td>7.8</td>
<td>2039</td>
</tr>
<tr>
<td>$^{82}$Se→$^{82}$Kr</td>
<td>2.44×10$^{26}$</td>
<td>$(0.92\pm0.07) \times 10^{20}$</td>
<td>9.2</td>
<td>2995</td>
</tr>
<tr>
<td>$^{96}$Zr→$^{96}$Mo</td>
<td>0.98×10$^{27}$</td>
<td>$(2.0\pm0.3) \times 10^{19}$</td>
<td>2.8</td>
<td>3351</td>
</tr>
<tr>
<td>$^{100}$Mo→$^{100}$Ru</td>
<td>2.37×10$^{26}$</td>
<td>$(7.1\pm0.4) \times 10^{18}$</td>
<td>9.6</td>
<td>3034</td>
</tr>
<tr>
<td>$^{116}$Cd→$^{116}$Sn</td>
<td>2.86×10$^{26}$</td>
<td>$(3.0\pm0.2) \times 10^{19}$</td>
<td>7.5</td>
<td>2805</td>
</tr>
<tr>
<td>$^{128}$Te→$^{128}$Xe</td>
<td>4.53×10$^{27}$</td>
<td>$(2.5\pm0.3) \times 10^{24}$</td>
<td>31.7</td>
<td>867</td>
</tr>
<tr>
<td>$^{130}$Te→$^{130}$Xe</td>
<td>2.16×10$^{26}$</td>
<td>$(0.9\pm0.1) \times 10^{21}$</td>
<td>34.5</td>
<td>2529</td>
</tr>
<tr>
<td>$^{136}$Xe→$^{136}$Ba</td>
<td>4.55×10$^{26}$</td>
<td>$(2.3\pm0.1) \times 10^{21}$</td>
<td>8.9</td>
<td>2476</td>
</tr>
<tr>
<td>$^{150}$Nd→$^{150}$Sm</td>
<td>$2.23\times10^{25}$</td>
<td>$(7.8\pm0.6) \times 10^{18}$</td>
<td>5.6</td>
<td>3367</td>
</tr>
</tbody>
</table>

Notable nuclei

$^{48}$Ca  highest Q, isotope enrichment is an issue → Iida’s talk
$^{76}$Ge  semiconductor
$^{136}$Xe easy enrichment / purification, various detector technology
$^{130}$Te  high natural abundance
$^{150}$Nd  fast 0ν
So far, leading experiments are using technologies;

Ge semiconductor (GERDA/Majorana)
Tracking (NEMO-3)
bolometer (CUORE)
liquid xenon TPC (EXO-200)
LS with xenon (KamLAND-Zen)

In addition to the above, next generation uses;

doped LS (SNO+)
hybrid bolometer (CUPID, AMoRE, CANDLES)
high pressure gas TPC (NEXT, PandaX-III, AXEL)

Let me explain my view of their pros and cons, briefly.
GERDA  (→Salamida’s next talk)

pros  
- high resolution (no 2ν BG)
- active shielding
- PSD
- easier cooling (in comparison with bolometers)

cons  
- costly enrichment
- external gamma/neutron-surface BG

\[ T_{1/2} > 5.2 \times 10^{25} \text{yr (90\%CL)} \]  

neutrino 2016
NEMO-3 (→Vilela’s talk)

Pros:
- Tracking various nuclei

Cons:
- Relatively poor energy resolution
- Limited scalability

Super NEMO is aiming at 50~100meV sensitivity (with 500kg · yr)
CUORE (→ O’Donnell’s talk)

pros
- high resolution ideally with various nuclei
- scintillation / phonon hybrid detection possible

cons
- costly low T cavity (makes active shielding expensive or difficult)

(Vignati’s talk)
CUORE/CUPID are aiming at 50~130, O(10) meV sensitivity
(CUORE Upgrade with Particle IDentification ← scintillation hybrid)

AMoRE, CANDLES are also pursuing Hybrid concept.
(Park’s talk) (lid’s talk)
**EXO-200** (→ Sinclair’s talk)

**pros**
- compact monolithic detector (scalability)
- 3D reconstruction (BG rejection)
- sufficient energy resolution
- purification possible

**cons**
- Radon emanation
- massive structure

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**nEXO (5 ton Xe)**

nEXO target sensitivity below 10 meV widely covers NH.
KamLAND-Zen

**pros**
- scalability (380kg→750kg planned)
- all active detector (\(^{208}\)Tl is above ROI)
- large active shielding
- minimum detector material (all \(\beta\) & \(\gamma\) detectable)
- on/off measurement
- in-situ purification

**cons**
- low resolution (2 \(\nu\) BG)
- low concentration
- high muon rate (spallation BG)

So far providing the world best limit

\[ T_{1/2} > 1.07 \times 10^{26} \text{yr (90\%CL)} \]
\[ m_{ee} < 61-165 \text{ meV} \]

future target: KL-Zen 800 → KL2-Zen → SuperKL-Zen? 50meV → 20meV → 8meV?
SNO+ (→Singh’s talk) SNO+ Phase I 0.5wt% Te → 1333kg $^{130}$Te (260kg FV) expected to start in early 2018

5 yr expected sensitivity $1.96 \times 10^{26}$yr

(similar to KL-Zen 800)

Phase II aiming at $10^{27}$yr sensitivity

pros

negligible spallation BG
huge target mass
all active

cons

low concentration (tough after-purification)
moderated energy resolution

Ichikawa/Han’s talks)

(AXEL/PandaX-III are developing with a similar concept.)

NEXT (→JJ’s talk)

NEXT-100

target

80~160meV

• Size and active shielding are the issues for higher sensitivities.
There are only a few proposals those offer NH sensitivity, but they seem to be very expensive.

Integration of complementary technologies and multiple collaborations may be necessary. Let’s think big!!

More to concern

factor 3 uncertainty of NME ---\(\rightarrow\) requires \(10^{(BG \text{ free})}\)~100 times more exposure

Experimental / theoretical efforts to reduce NME uncertainty are very important.
Ultra-low BG underground (& huge) experiment is necessary

It is KamLAND !!

2 cycles of oscillations

Precision measurement

Radiogenic heat measured, Model discrimination started

7Be solar $\nu$ measured, BG well-understood

Advantages of using KamLAND

- **running detector**
  → relatively low cost and quick start

- **huge and clean** (1200m$^3$, U: $3.5 \times 10^{-18}$ g/g, Th: $5.2 \times 10^{-17}$)
  → negligible external gamma
  (Xe and mini-balloon need to be clean)

- **Xe-LS can be purified, mini-balloon replaceable** if necessary, with relatively low cost
  → highly scalable (up to several tons of Xe)

- **No escape or invisible energy from $\beta, \gamma$**
  → BG identification relatively easy

- **anti-neutrino observation continues**
  → geo-neutrino w/o Japanese reactors

320kg 90% enriched $^{136}$Xe installed for phase-I and 380kg for phase-II

Zero Neutrino
double beta decay search
minimum inactive detector material basically 25 \( \mu \text{m-t} \) balloon film only
KamLAND-Zen started in 2011
only 2 years from initial funding (very quick!)

(a) DS-1 + DS-2

Events/0.05MeV

Visible Energy (MeV)

Data
Total
$^{136}\text{Xe}$ $2\nu\beta\beta$
Total
($0\nu\beta\beta$ U.L.)
$^{136}\text{Xe}$ $0\nu\beta\beta$
(90% C.L. U.L.)

$^{238}\text{U}$ Series
$^{232}\text{Th}$ Series
$^{210}\text{Bi}$
$^{85}\text{Kr}$
$^{208}\text{Bi}$
$^{88}\text{Y}$
$^{110m}\text{Ag}$

External BG
Spallation

110m Ag
Balloon

$^{10}$C

$2\nu2\beta$

Unexpected BG has found
KamLAND-Zen Phase I (320kg xenon loading)

Thanks to full active apparatus,

- **DS-1 + DS-2**
  - 213.4 days

Dominant BG identified as $^{110m}$Ag

- No escape $\beta/\gamma$ makes BG spectrum simple
- $^{208}$TI is above ROI

Xenon can be degassed from Xe-LS.
And $^{136}$Xe on/off measurement has been demonstrated.
(useful for signal confirmation)
What can we do?

purification !!

fine binning of volume

triple fold coincidence

triple fold coincidence for $^{10}\text{C}$ rejection

$\frac{1}{2}^\mu_1$  
$\frac{1}{2}^\tau = 208 \mu s$

$\frac{1}{2}^n_2$

$\frac{1}{2}^\tau = 27.8 s$

$\frac{1}{2}^{12}\text{C}$

$\frac{1}{2}^{10}\text{C}$

magnetic field

90% C.L.

90% C.L.

imaging

$^{10}\text{C}$

$^{110m}\text{Ag}$

$^{214}\text{Bi}$

$^{2\nu2\beta}$

dead time free electronics MoGURA

Yet only 64% efficiency

KL-LS

Xe-LS
Purification Campaign

June 2012 ~ November 2013

1. cold oil trap → charcoal filter → sintered metal filter → getter \( N_2 \)
2. 3nm particle filter (PTFE) → distillation XMASS proto. → particle filter
3. new \( ^{136}\text{Xe} \) ↓

Xe-LS + \( ^{110}\text{mAg} \)

- Vacuum extraction of \( ^{136}\text{Xe} \)
- Replace with new Xe-LS
- Add purified PC for density adjustment
- Confirm \( ^{110}\text{mAg} \) remains in LS

new LS

- New LS
- Confirm whole \( ^{110}\text{mAg} \) drained
- Replace with new purified Xe-LS

~380kg Xe installed aim: 1/100 reduction
Phase-1 320kg
before purification

Events/0.05MeV

Visible Energy (MeV)

(a) DS-1 + DS-2

10^5

10^4

10^3

10^2

10

1

0.1

0.01

0.001

0.0001

Data
Total
$^{136}$Xe 2$\nu$β
Total (0$\nu$β U.L.)
$^{136}$Xe 0$\nu$β
(90% C.L. U.L.)
External BG
Spallation

>1.9x10^{25} y

110mAg
214Bi
10C

Phase-2 380kg
after purification

110mAg reduction <1/10

Events/0.05MeV

Visible Energy (MeV)

(a) Period-2

10^5

10^4

10^3

10^2

10

1

0.1

0.01

0.001

0.0001

2013/12/11 - 2014/10/27
534.5 days (504 kg-yr)

R < 1m

(90% C.L. U.L.)

External BG
Spallation

in-situ purification possible!!

(f) $^{110}$m Ag
110mAg Balloon
We have acquired phase-2 data (after purification) from December 11 2013 to October 27, 2015; total livetime of 534.5 days (cf. $T_{1/2}(^{110}\text{mAg})=250$ days) and exposure of 504 kg-yr.

Balloon surface has higher BG rate but still provides some sensitivity.

In order to improve the sensitivity, we have performed all volume and time-binned analysis.
Source calibration
(Oct. 2015)

vertex deviation within 2 cm

position dependence of energy within 1%

also in-situ calibration with n-capture on $^1$H/$^12$C and $^{214}$Bi

Energy resolution in phase-2: $\sim 7.3\%/\sqrt{E}$
investigation of energy resolution tail with tagged $^{214}$Bi

![Graph showing energy resolution tail with tagged $^{214}$Bi.]

investigation of vertex resolution tail with $^{60}$Co source and tagged $^{214}$Bi-Po

![Graph showing vertex resolution tail with $^{60}$Co source and tagged $^{214}$Bi-Po.]

distance from source position [cm]

Data

MC
40 equal-volume bins

Energy and radial distributions are well-reproduced by known BGs.
Phase 1 (first 112.3 days)
2.2 < E < 3.0 MeV, R < 1 m

Phase 2 534.5 days
2.3 < E < 2.7 MeV, R < 1 m

A hypothesis: “Dust” sank !?
Yet only \( \sim 2 \sigma \) discrepancy from the simple decay

22 events
11 events

Kown BG other than \(^{110}\text{mAg}\) are \( \sim 11 \) events in each periods
### Event summary

$2.3 < E < 2.7 \text{ MeV, } R < 1 \text{ m}$

<table>
<thead>
<tr>
<th></th>
<th>Period-1</th>
<th></th>
<th>Period-2</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(270.7 days)</td>
<td></td>
<td>(263.8 days)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Observed events</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Background</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{136}\text{Xe } 2\nu\beta\beta$</td>
<td>Estimated</td>
<td>$\ldots$</td>
<td>Best-fit</td>
<td>$5.48$</td>
<td>Estimated</td>
</tr>
<tr>
<td><strong>Residual radioactivity in Xe-LS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{214}\text{Bi (}{^{238}\text{U series}}$</td>
<td>$0.23 \pm 0.04$</td>
<td>$0.25$</td>
<td>$0.028 \pm 0.005$</td>
<td>$0.03$</td>
<td>$0.001$</td>
</tr>
<tr>
<td>$^{208}\text{Tl (}{^{232}\text{Th series}}$</td>
<td>$\ldots$</td>
<td>$0.001$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$^{110m}\text{Ag}$</td>
<td>$\ldots$</td>
<td>$8.5$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td><strong>External (Radioactivity in IB)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{214}\text{Bi (}{^{238}\text{U series}}$</td>
<td>$\ldots$</td>
<td>$2.56$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$^{208}\text{Tl (}{^{232}\text{Th series}}$</td>
<td>$\ldots$</td>
<td>$0.02$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$^{110m}\text{Ag}$</td>
<td>$\ldots$</td>
<td>$0.003$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td><strong>Spallation products</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$^{10}\text{C}$</td>
<td>$2.7 \pm 0.7$</td>
<td>$3.3$</td>
<td>$2.6 \pm 0.7$</td>
<td>$2.8$</td>
<td>$2.8$</td>
</tr>
<tr>
<td>$^{6}\text{He}$</td>
<td>$0.07 \pm 0.18$</td>
<td>$0.08$</td>
<td>$0.07 \pm 0.18$</td>
<td>$0.08$</td>
<td>$0.08$</td>
</tr>
<tr>
<td>$^{12}\text{B}$</td>
<td>$0.15 \pm 0.04$</td>
<td>$0.16$</td>
<td>$0.14 \pm 0.04$</td>
<td>$0.15$</td>
<td>$0.15$</td>
</tr>
<tr>
<td>$^{137}\text{Xe}$</td>
<td>$0.5 \pm 0.2$</td>
<td>$0.5$</td>
<td>$0.5 \pm 0.2$</td>
<td>$0.4$</td>
<td>$0.4$</td>
</tr>
</tbody>
</table>
**Results on $0\nu 2\beta$**

<table>
<thead>
<tr>
<th></th>
<th>period-1</th>
<th>period-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>livetime</td>
<td>270.7 days</td>
<td>263.8 days</td>
</tr>
</tbody>
</table>

$^{136}\text{Xe} \, 0\nu 2\beta$

- decay rate: $< 5.5 /\text{kton/day}$
- $< 3.4 /\text{kton/day}$
- combined: $< 2.4 /\text{kton/day}$ (90% C.L.)

$^{136}\text{Xe} \, 0\nu 2\beta$

- half-life: $> 9.2 \times 10^{25} \text{ yr}$ (90% C.L.)
- sensitivity: $> 4.9 \times 10^{25} \text{ yr}$
  (11% probability)

Lucky (11%) comes from R > 1m region

use FV for period-2 data
- upper hemisphere: R < 1.26 m (5 bins)
- lower hemisphere: R < 1.06 m (3 bins)

provides better limit of $< 3.25 /\text{day/kton}$
Phase-1 & 2 combined limit

\[ T_{1/2}^{0\nu} > 1.07 \times 10^{26} \text{ yr} \]

\[ \langle m_{\beta\beta} \rangle < (61 - 165) \text{ meV} \]
\[ \langle m_{\beta\beta} \rangle < (61 - 165) \text{ meV} \]

It also provides upper limit of \( m_{\text{lightest}} \) at 180-480 meV.

Big leap toward IH !!
Our challenge continues!

Three dominant BGs; $2 \nu$, "$^{214}$Bi on the film" and $^{10}$C.

We have purchased 800 kg of enriched xenon in total.

We have fabricated a larger mini-balloon with better measures against dusts.

We will resume the search with 750 kg of xenon. To be called as “KamLAND-Zen 800”.

(Expected sensitivity is below 50 meV hoping to cover Yanagida’s prediction.)
Mini-balloon has been extracted. (Dec. 2015) for tank investigation required by law

Xenon has been recovered during recirculation and deflation of the mini-balloon.
2nd mini-balloon fabrication

cleaning, cleaning and cleaning as usual
Example of improvements

before

keep staying away
goggle  
welding machine
cover sheet .
glove on glove
laundry twice a day .
clean underwear .
changing room in a clean room .
dust visualization
more neutralizer

...
after Leak check and repair

New mini-balloon has been deployed and inflated with “dummy” LS in last August
through characterization of mini-balloon

We confirmed that the mini-balloon is cleaner!!

Measures we took worked! → see Hachiya’s poster

At the same time, we noticed; → further information Obara’s poster

9/1 11:35

10/11 8:45

Indications of leak;
- camera image
- load cell
- balloon shape reconstruction with $^{210}$Po events
- $^{222}$Rn decay rate
- mixture of KL-LS and dummy-LS by gas-chromatography
And more future plans!

Higher energy resolution for reducing $2\nu$ BG

$\Rightarrow$ KamLAND2-Zen

Winston cone
light collection $\times 1.8$

high q.e. PMT
$17''\phi \to 20''\phi$ $\varepsilon = 22\rightarrow 30+$%

New LAB LS
(better transparency)
light collection $\times 1.9$

expected $\sigma (2.6\text{MeV}) = 4\%$ $\rightarrow$ $\sim 2\%$

target sensitivity 20 meV

And more?

Super-KamLAND-Zen
in connection with Hyper-Kamiokande

target sensitivity 8 meV
R&D for KamLAND2-Zen and future

- winston cone
  - succeeded with prototype
  - prototype in hand

- HQE-PMT
  - succeeded with Molecular sieve (13x)

- New LAB-LS
  - prototype in hand

- denser xenon

- scintillator film
  - tag $\alpha$ in film

- imaging
  - welding succeeded requires fluor replacement

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Xe solubility (wt%)

- Xe partial pressure (MPa)
  - $3 \rightarrow 12\%$
  - @30m depth

- principle confirmed

30L prototype
Summary

• $0\nu 2\beta$ experiments very briefly reviewed
• Results from KL-Zen Phase-2 (534.5 days, 380 kg) presented

$^{110m}$Ag has been successfully reduced.

improved analysis: 40 equal bins for volume, 2 time bins

• Phase-1 & 2 combined result for $0\nu 2\beta$ of $^{136}$Xe

\[
T_{1/2}^{0\nu} > 1.07 \times 10^{26} \text{ yr}
\]

\[
\langle m_{\beta\beta} \rangle < (61 - 165) \text{ meV}
\]

• KamLAND-Zen 800 is planned

Mini-balloon for 750kg once installed, but there was a leak. (→ Obara’s poster)
Balloon film was cleaner than previous installation. (→ Hachiya’s poster)
Target sensitivity is below 50 meV, and next deployment will be in autumn 2017.

• R&D for KamLAND2-Zen is going well.

Target sensitivity is below 20 meV.
Thank you!