Results and Future plans for the KamLAND-Zen

Junpei Shirai
(Tohoku University)
for the
KamLAND-Zen Collaboration

XXVII International Conference on Neutrino Physics and Astrophysics, Jul.8, 2016, London
$$M_\nu \neq 0$$

$$\nu = \bar{\nu} ?$$

2 mass eigenstates

GUT

$${\cal N}$$

Seesaw

Big Bang

Matter dominance

$$0\nu\beta\beta$$ Key process to test $\nu = \bar{\nu}$

$\Delta L = 2$ (beyond the SM)

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}(Q,Z) |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

$>10^{26}\text{yr}$

Very challenging!

$\lesssim 0.1\text{eV}$

Absolute $\nu$ mass scale

$\nu$ mass hierarchy

Oscillation parameters, CP-phase
0νββ: Large Mass + Low B.G. + Technique

$^{136}$Xe is excellent!

<table>
<thead>
<tr>
<th></th>
<th>$^{48}$Ca</th>
<th>$^{76}$Ge</th>
<th>$^{82}$Se</th>
<th>$^{96}$Zr</th>
<th>$^{100}$Mo</th>
<th>$^{116}$Cd</th>
<th>$^{130}$Te</th>
<th>$^{136}$Xe</th>
<th>$^{150}$Nd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q-val. (MeV)</td>
<td>4.271</td>
<td>2.04</td>
<td>2.995</td>
<td>3.35</td>
<td>3.03</td>
<td>2.80</td>
<td>2.53</td>
<td>2.458</td>
<td>3.367</td>
</tr>
<tr>
<td>Nat. Ab. (%)</td>
<td>0.189</td>
<td>7.44</td>
<td>8.73</td>
<td>2.80</td>
<td>9.67</td>
<td>7.49</td>
<td>34.1</td>
<td>8.9%</td>
<td>5.6</td>
</tr>
</tbody>
</table>

$B(F_4F;S,P)E_{5F}$

Xe: Noble gas
Isotope Enrichment Purification
High chemical stability
Safety handling
Repeated purification

Excellent scalability!

Xe + Large volume LS
Unique strategy for the search!
Location: 2,700 m.w.e. underground in Kamioka mine in Gifu prefecture

Cosmic ray flux: 1/100,000 of the above ground

KamLAND

- Huge & ultra-clean facility for $0\nu\beta\beta$ search!
- Successfully operated since 2002.
- Detector performance is well understood!

Stainless steel tank (18 mφ)
Buffer oil
13 mφ balloon
1000 ton ultra-pure LS (Dodecane+PC+PPO)

1879 PMT (17”+20”)
34% of 4π
3200 ton water
Cherenkov detector (225 20” PMTs)

Reactor $\bar{\nu}_e$ oscillation
2 cycles of oscillation

Geo $\bar{\nu}_e$ detection
Precise determination of oscillation parameters!
Radiogenic heat measurement and constrain earth models.

Kamioka Liquid scintillator Anti-Neutrino Detector
Mini-balloon

- Nylon film: 25μ-thick
- U, Th ~ $10^{-12}$, $^{40}$K ~ $10^{-11}$ g/g
- Xe tightness
- >95% transparent @400nm

KamLAND-Zen

Zero neutrino double beta decay experiment

- Quick start with relatively low cost!
- Flexible operation: blank run, repeated Xe-LS purification
- Easy to scale up!
- Other physics (geo-ν, SN, etc.) in parallel!

Mini-balloon

Xe-LS:
Xe 383kg
(91% $^{136}$Xe)
+ Decane-based LS

Xe distillation/control/storage
+ LS purification plant
KamLAND-Zen Collaboration

48 physicists from 11 institutes


Tokyo Univ. IPMU: A.Kozlov, Y.Takemoto, B.E.Berger, D.Chernyak

Oska Univ: S.Yoshida

Tokushima Univ: K.Fushimi

Berkeley National Lab: T.I.Banks, B.K.Fujikawa, T.O'Donnell

Massachusetts Institute of Technology: L.A.Winslow, J.Ouellet, E.Krupczak

Univ. of Tennessee: Y.Efremenko

North Carolina Univ: H.J.Karwowski, D.M.Markoff

Duke Univ: W.Tornow

Univ. of Washington: J. Detwiler, S.Enomoto

Univ. of Amsterdam: M.P.Decowski
KamLAND-Zen history

May-Aug. 2011
Mini-balloon construction, installed into the detector.

Phase1 (320kg enriched Xe)
89.5kg yr $^{136}$Xe
$T_{1/2}^{0} > 1.9 \times 10^{25}$ yr (90% C.L.)
$ > 3.4 \times 10^{25}$ yr (90% C.L.) (KLZ+EXO-200)
KK claim on $^{76}$Ge was refuted (97.5% C.L.).

Xe-LS Purification

Nov.2013 ~ Oct.2015
Phase2 (383kg enriched Xe)
504kg yr $^{136}$Xe
Calibration

Oct.2015~
Preparation for a new phase

Limits from Phase1+Early Phase2(115d)
$T_{1/2}^{0} > 2.6 \times 10^{25}$ yr (90% C.L.)
$\langle m_{\beta\beta} \rangle < 140 \sim 280$meV (QRPA)

*KamLAND-Zen (v2014)
Phase 1 (before purification)

PRL 110 062502 (2013)

0ν region (2.3-2.7MeV) is dominated by $^{110m}$Ag ($Q=3.01\text{MeV}, T_{1/2}=260\text{d}$)

**Spectrum shape**

**Time variation**

Fallout from the Fukushima reactor accident in Mar.2011 when mini-balloon was constructed in Tohoku Univ.

2ν region (1.2~2.0MeV): $^{134}$Cs ($\tau=2.06\text{yr}, 2.06\text{MeV}$)

---

**Xe-LS Purification**

- Stop Phase 1 Jun.2012
- Extract Xe and purify
- Dissolve Xe
- Start Phase 2 Nov.2013
- LS vac. distillation (+Water extraction, N$_2$ purge)
- Xe distillation + filtration (charcoal, sintered metal, 3nm PTFE)+ getter

---

10 C (spallation)
2νββ
214 Bi (mini-balloon)
134 Cs

Q(0ν): $2.45\text{MeV}$

Visible Energy (MeV)

Events/0.05MeV

(a) DS-1 + DS-2
- Data
- Total
- $^{136}$Xe 2νββ
- $^{208}$Bi
- $^{88}$Y
- $^{110m}$Ag
- $^{238}$U + $^{232}$Th
- $^{210}$Bi + $^{85}$Kr
- (0νβ U.L.)
- (90% C.L. U.L.)
- IB/External
- Spallation

110mAg

---

$^{110m}$Ag remained

3 x (full volumes)

Purified Xe (383kg)+LS

---

8/20
$^{110m}$Ag was removed by ~10!

Purification method was found effective.

$^{214}$Bi studies

MC study of $^{214}$Bi→$^{214}$Po decay vertex
distribution by using Geant4 full detector
simulation tuned for KamLAND.

$^{214}$Bi β− decays with multi-γs

Vertex distribution is well reproduced!
$^{10}$C rejection by neutron tagging

Triple coincidence: $\mu$-on + neutrons + $^{10}$C

Cut conditions
$\Delta T<180s$
$\Delta R<1.6m$

New dead-time free electronics
“Mogura” for n-detection

$^{10}$C detection efficiency: 64±4 %
Signal inefficiency: 7%

* $^{137}$Xe ($\beta^-$, $\tau=5.5$min, $Q=4.17$MeV) production is dominated by n+$^{136}$Xe.
  (Estimated by spallation neutron rate & capture cross section)
Post-purification data (Phase2)

Exposure of 504 kg yr $^{136}$Xe

Dots: Selected events in 0v window
Color: MC-reproduced $^{214}$Bi b.g. events

(a) $2.3 < E < 2.7$ MeV

Event selection
i) $R<2m$.  
ii) Cut $\mu$-ons +2ms events after $\mu$-ons. 
iii) Delayed Coincidence cut for  
   - $^{214}$Bi-$^{214}$Po($\tau=237\mu$s) with  
     $\Delta T<1.9$ms, $\Delta R<1.7$m 
   - $^{212}$Bi-$^{212}$Po($\tau=0.4\mu$s) + Pulse shape  
   - Reactor $\nu_e$ cut ($e^+$, n capture $\gamma$)  
iv) Vertex quality cut (PMT time-charge)

$^{214}$Bi on the film: Dominant external B.G.!

$^{238}$U: 160ppt $\leftrightarrow$ 2ppt (ICP-MS)
Not uniform (Upper$<$Lower)

Dusts during mini-balloon construction and diaphragm pump trouble

Radial distribution of the candidate events in 0νββ region.

$^{214}$Bi is dominant at the mini-balloon but rapidly decreases in the central part where $^{110m}$Ag is remained.

Position dependent energy bias < 1%

Energy resolution
$$\frac{\sigma}{E} = (7.3 \pm 0.4)\% / \sqrt{E_{[MeV]}}$$

Position dependent vertex bias
< 1.0cm for $|z| < 1.0$ m

* Energy response at off-axis region (studied by spallation neutron capture on protons) < 1%
Energy spectrum of the central region (R<1m)

Considering the time dependence of the $^{110m}\text{Ag}$ rate, data is divided into equal periods: Period-1 (270.7d) & Period-2 (263.8d). Fits are performed in $0.8<E<4.8\text{MeV}$ independently for the two periods.

No excess is found over the B.G. 90% C.L. upper limits on $^{136}\text{Xe}$ 0νββ rate [1/(kton-day)]: < 5.5 (period-1), < 3.4 (period-2) Combined < 2.4 $\Rightarrow T^{0\nu}_{1/2}>9.2\times10^{25}$ yr

Variance of events/day (2.3-2.7MeV, R<1m)
Summary of the B.G.  (2.3<E<2.7MeV, R<1m)

<table>
<thead>
<tr>
<th></th>
<th>Period-1 (270.7 days)</th>
<th>Period-2 (263.8 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>22</td>
<td>11</td>
</tr>
<tr>
<td>Background</td>
<td></td>
<td></td>
</tr>
<tr>
<td>136 Xe 2νββ</td>
<td>-</td>
<td>5.48</td>
</tr>
<tr>
<td>Residual radioactivity in Xe-LS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>214 Bi (238 U series)</td>
<td>0.23 ± 0.04</td>
<td>0.25</td>
</tr>
<tr>
<td>208 Tl (232 Th series)</td>
<td>-</td>
<td>0.001</td>
</tr>
<tr>
<td>110m Ag</td>
<td>-</td>
<td>8.5</td>
</tr>
<tr>
<td>External (Radioactivity in IB)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>214 Bi (238 U series)</td>
<td>-</td>
<td>2.56</td>
</tr>
<tr>
<td>208 Tl (232 Th series)</td>
<td>-</td>
<td>0.02</td>
</tr>
<tr>
<td>110m Ag</td>
<td>-</td>
<td>0.003</td>
</tr>
<tr>
<td>Spallation products</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 C</td>
<td>2.7 ± 0.7</td>
<td>3.3</td>
</tr>
<tr>
<td>6 He</td>
<td>0.07 ± 0.18</td>
<td>0.08</td>
</tr>
<tr>
<td>12 B</td>
<td>0.15 ± 0.04</td>
<td>0.16</td>
</tr>
<tr>
<td>137 Xe</td>
<td>0.5 ± 0.2</td>
<td>0.5</td>
</tr>
</tbody>
</table>

* 137Xe production rate was overestimated in the e-print (arXiv:1605.02889v1[hep-ex]10 May 2016). The correct numbers and figures are slightly changed and presented here, and is appeared in arXiv:1605.02889v2. today.

Improve $\sigma_E$ (future plan)

Improve neutron detection

Replace the mini-balloon with a clean one (Next phase), now in preparation.
* $^{137}$Xe production rate was overestimated by ~2 in the e-print (arXiv:1605.02889v1[hep-ex]10 May 2016). $^{137}$Xe production is almost from neutron captures, but we misunderstood part of the calculations in FLUKA. Corrected numbers and figures are presented which are slightly changed as follows.*

## Old version


<table>
<thead>
<tr>
<th></th>
<th>Period-1</th>
<th>Period-2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(270.7 days)</td>
<td>(263.8 days)</td>
</tr>
<tr>
<td>Observed events</td>
<td>22</td>
<td>11</td>
</tr>
<tr>
<td>Background $^{136}$Xe $2\nu\beta\beta$</td>
<td>Estimated: -, Best-fit: 5.48</td>
<td>Estimated: -, Best-fit: 5.29</td>
</tr>
<tr>
<td>Residual radioactivity in Xe-LS $^{214}$Bi ($^{238}$U series)</td>
<td>$0.23 \pm 0.04$, $0.25$, $0.028 \pm 0.0005$, $0.03$</td>
<td>$0.001$, $0.0001$, $0.00002$</td>
</tr>
<tr>
<td>$^{208}$Tl ($^{232}$Th series)</td>
<td>$-0.001$, $-0.0001$, $-0.000002$</td>
<td>$-0.001$, $-0.0001$, $-0.000002$</td>
</tr>
<tr>
<td>$^{110}$mAg</td>
<td>-8.0, -0.002, -0.00002</td>
<td>-8.0, -0.002, -0.00002</td>
</tr>
<tr>
<td>External (Radioactivity in IB) $^{214}$Bi ($^{238}$U series)</td>
<td>Estimated: -2.55, Best-fit: 2.45</td>
<td>Estimated: -2.55, Best-fit: 2.45</td>
</tr>
<tr>
<td>$^{208}$Tl ($^{232}$Th series)</td>
<td>-0.02, -0.003, -0.00003</td>
<td>-0.02, -0.003, -0.00003</td>
</tr>
<tr>
<td>$^{110}$mAg</td>
<td>-0.002, -0.001, -0.00001</td>
<td>-0.002, -0.001, -0.00001</td>
</tr>
<tr>
<td>Spallation products $^{10}$C</td>
<td>2.7, 3.2, 2.6, 2.7</td>
<td>2.7, 3.2, 2.6, 2.7</td>
</tr>
<tr>
<td>$^{6}$He</td>
<td>0.07, 0.08, 0.07, 0.08</td>
<td>0.07, 0.08, 0.07, 0.08</td>
</tr>
<tr>
<td>$^{12}$B</td>
<td>0.15, 0.16, 0.14, 0.15</td>
<td>0.15, 0.16, 0.14, 0.15</td>
</tr>
<tr>
<td>$^{137}$Xe</td>
<td>0.9, 1.1, 0.9, 0.8</td>
<td>0.9, 1.1, 0.9, 0.8</td>
</tr>
</tbody>
</table>

Limits (90%C.L.)

$T_{1/2}^{0\nu} > 1.1 \times 10^{26}$ yr

$\langle m_{\beta\beta} \rangle < (60 - 161)$ meV

$m_{\text{lightest}} < (180 - 470)$ meV

## Corrected version


<table>
<thead>
<tr>
<th></th>
<th>Period-1</th>
<th>Period-2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(270.7 days)</td>
<td>(263.8 days)</td>
</tr>
<tr>
<td>Observed events</td>
<td>22</td>
<td>11</td>
</tr>
<tr>
<td>Background $^{136}$Xe $2\nu\beta\beta$</td>
<td>Estimated: -, Best-fit: 5.48</td>
<td>Estimated: -, Best-fit: 5.29</td>
</tr>
<tr>
<td>Residual radioactivity in Xe-LS $^{214}$Bi ($^{238}$U series)</td>
<td>$0.23 \pm 0.04$, $0.25$, $0.028 \pm 0.0005$, $0.03$</td>
<td>$0.001$, $0.0001$, $0.00002$</td>
</tr>
<tr>
<td>$^{208}$Tl ($^{232}$Th series)</td>
<td>$-0.001$, $-0.0001$, $-0.000002$</td>
<td>$-0.001$, $-0.0001$, $-0.000002$</td>
</tr>
<tr>
<td>$^{110}$mAg</td>
<td>-8.0, -0.002, -0.00002</td>
<td>-8.0, -0.002, -0.00002</td>
</tr>
<tr>
<td>External (Radioactivity in IB) $^{214}$Bi ($^{238}$U series)</td>
<td>Estimated: -2.56, Best-fit: 2.45</td>
<td>Estimated: -2.56, Best-fit: 2.45</td>
</tr>
<tr>
<td>$^{208}$Tl ($^{232}$Th series)</td>
<td>-0.02, -0.003, -0.00003</td>
<td>-0.02, -0.003, -0.00003</td>
</tr>
<tr>
<td>$^{110}$mAg</td>
<td>-0.002, -0.001, -0.00001</td>
<td>-0.002, -0.001, -0.00001</td>
</tr>
<tr>
<td>Spallation products $^{10}$C</td>
<td>2.7, 3.2, 2.6, 2.7</td>
<td>2.7, 3.2, 2.6, 2.7</td>
</tr>
<tr>
<td>$^{6}$He</td>
<td>0.07, 0.08, 0.07, 0.08</td>
<td>0.07, 0.08, 0.07, 0.08</td>
</tr>
<tr>
<td>$^{12}$B</td>
<td>0.15, 0.16, 0.14, 0.15</td>
<td>0.15, 0.16, 0.14, 0.15</td>
</tr>
<tr>
<td>$^{137}$Xe</td>
<td>0.5, 0.9, 0.9, 0.8</td>
<td>0.5, 0.9, 0.9, 0.8</td>
</tr>
</tbody>
</table>

Limits (90%C.L.)

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

$\langle m_{\beta\beta} \rangle < (61 - 165)$ meV

$m_{\text{lightest}} < (180 - 480)$ meV
$^{136}\text{Xe}$ $0\nu\beta\beta$ Decay Half-life

KamLAND-Zen

Half-life limit (@90% C.L.)

Phase 1: $T_{1/2}^{0\nu} > 1.9 \times 10^{25}$ yr
Phase 2: $T_{1/2}^{0\nu} > 9.2 \times 10^{25}$ yr
Combined: $T_{1/2}^{0\nu} > 1.07 \times 10^{26}$ yr

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

Commonly used NME with $g_A \sim 1.27$, improved phase space calculations.

$m_{\text{lightest}} < (180-480) \text{ meV}$

$\langle m_{\beta\beta} \rangle$ limit reaches below 100 meV and getting close to the IH region!
2νββ decay rate

Fiducial vol.  R<1m (126 kg-yr $^{136}$Xe exposure)
Likelihood fit to 0.5<E<4.8 MeV

Results on $T^{2ν_{1/2}}$ =

- $2.21\pm0.02\text{(stat)}\pm0.07\text{(sys)} \times 10^{21}\text{yr (Phase2)}$
- $2.30\pm0.02\text{(stat)}\pm0.12\text{(sys)} \times 10^{21}\text{yr (Phase1)}$
- $2.165\pm0.016\text{(stat)}\pm0.059\text{(sys)} \times 10^{21}\text{yr (EXO-200)}$

$2νββ$ decay rate

Fiducial vol.                    3.0*
Xe-mass                        0.8
Detector energy scale          0.3
Efficiency                     0.2
$^{136}$Xe enrichment          0.09
⇒ Total 3.1%                   

Systematic uncertainty (%)

Recent activity & schedule

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Activity</th>
<th>Phase1&amp;2: KamLAND-Zen 400</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>Oct</td>
<td>Source calibration, Phase 2 terminated</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dec</td>
<td>Mini-balloon extraction</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>Jan~Mar</td>
<td>Outer detector refurbishment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>May~</td>
<td>Xe-distillation, LS-distillation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Apr~Jul</td>
<td>New Mini-balloon construction finalized (<em>⇒next slide</em>)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aug</td>
<td>New mini-Balloon installation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sep~Oct</td>
<td>Xe dissolving and Xe-LS filling</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Start new phase : KamLAND-Zen 800.</td>
<td></td>
</tr>
</tbody>
</table>

Taking out the mini-balloon (Dec.2015)

Last drip of the LS in the mini-balloon

OD refurbishment (225 PMTs were replaced with new 140 PMTs)

*from initial radon-rich data of uniform $^{214}$Bi in Xe-LS
⇒ consistent with radial vtx. resolution=1cm.
Towards higher sensitivity (1)

“KamLAND-Zen 800” (now in preparation !)
(P1.064 S.Hayashida)

A new, clean & double-volume mini-balloon construction
(750kg enriched Xe)

Construction of the main body was finished (2015) in a class1 super-clean room in Tohoku Univ. with much better cleanliness and improved dust control.

The new mini-balloon is deployed in KamLAND in the next month!

The new mini-balloon is deployed in KamLAND in the next month!

Gore welding

Two-stage clean wears including shoes and gloves. Wear changing in one of the clean rooms.

Clean wears and goggles are washed every after the shift.

A new large welding machine
Protection films on the balloon film.
A new storage bag for the mini-balloon
A new particle counter.
More electrostatic eliminators

Washing nylon films (Ultra-pure water + ultrasonic machine)

Leak hunting with helium detector

2016

Miniballoon assembly for deployment is underway. It is sent to Kamioka very soon.

2015

Repair

Air-tight bag

Washing parts

Container

\[ ^{214}\text{Bi removal} \langle m_{\beta\beta} \rangle \sim 40 \text{meV} \]
Towards higher sensitivity (2)

“KamLAND2-Zen”
with 1000kg enriched Xe

Many R&Ds are ongoing!

More photons for better $\sigma_E$
- New LAB-based LS (L.Y.×1.4),
- New High Q.E. PMT (×1.9),
- Light collector of PMT (×1.8)

Better $\sigma_E/E$~2% to remove 2ν b.g.
$\Rightarrow \langle m_{\beta\beta} \rangle \sim 20$meV

Full coverage of IH!

New-type high Q.E. PMT

Background rejection
- Scintillating balloon ($^{214}$Bi tagging)
- New method for LS purification:
  Molecular sieve, Metal scavenger
- Imaging sensor
- Pressurized Xe-LS

Light collector of PMT

Metal scavenger

Imaging sensor

Molecular sieve 13X

Results clearer than no-purified LAB at 388 nm

Molecular Sieve 13X is highly effective

Activated Alumina

Molecular Sieves

$[\text{Al}_2\text{O}_3 (99.7\%) ]$

$\phi \times 10cm$ column

Water Extraction

No scavengers

Water Extraction

Scavenger

Events / 3min

Time [hr]

Full coverage of IH!
KamLAND-Zen sensitivity

Achieved
KL-Zen 400
Next
KL-Zen 800
Future
KL2-Zen (1000kg)

Our goal!

Branch point of the IH and NH
Cosmological observation
Accelerator, reactor, atmospheric, solar $\nu$ experiments
Theoretical research

Covering most of the IH region!
Summary

- KamLAND-Zen phase2 (post purification phase) data corresponding to 504kg-yr $^{136}$Xe exposure showed successful reduction of $^{110m}$Ag and higher sensitivity to the $0\nu\beta\beta$ search.
- Combined 90\%C.L. limits on $0\nu\beta\beta$ of phase1+phase 2 (KamLAND-Zen 400) are
  \[ T^{0\nu}_{1/2} > 1.07 \times 10^{26} \text{yr} \ (90\%\text{CL}) : \sim 6 \text{ times improvement of phase1} \]
  \[ \langle m_{\beta\beta} \rangle < 61-165\text{meV} : \text{approaching to the IH region}. \]
- Preparation is ongoing for the next phase of KamLAND-Zen 800; a new mini-balloon is installed next month and data taking will be started in the autumn aiming to $\langle m_{\beta\beta} \rangle \sim 40\text{meV}$ entering the IH region.
- Various R&Ds are ongoing for the future KamLAND2-Zen aiming to $\langle m_{\beta\beta} \rangle \sim 20\text{meV}$ fully covering the IH region.
Announcement!

International Workshop on Double Beta Decay and Underground Science
Nov. 8-10, 2016, Osaka, Japan
http://www.rcnp.osaka-u.ac.jp/dbd16/index.html

Please join!
Thank you!
Backup slides
The obtained limit is better than the sensitivity
Optimized volume sensitive to 0nbb search:
R<1.063m in z<0, R>1.260m in z>0
(3 volume bins in z<0 and 5 volume bins in z>0)

We find 9 events in 2.35-2.65 MeV region over the expected background of 12.9 providing 90% C.L. upper limit on 0nbb to <3.3 events.
If we had found 13 events, the same as the B.G. expectation, the limit would increase to <7.2 events, indicating the above limit (< 3.3) is ~2 times stronger than the sensitivity.
Cs and U show similar z-dependence indicating they are both from dust contamination.
$^{214}$Bi events tagged with delayed coincidence in high $^{220}$Rn data are well reproduced.
Pull histogram of 2.8-4.8MeV region.
No data points are outside of 2 sigma.
Upper limits from Toy MC

Limit at 90% C.L. (events/day/kton-LS)

$T_{1/2}^{0\nu} > 9.2 \times 10^{25}$ yr

50% sensitivity $5.6 \times 10^{25}$ yr

Sensitivity is checked by MC assuming best-fit BG rate.