KamLAND-Zen 800 status and future prospects

Masayuki Koga @ RCNS Tohoku University
KAQLI IPMU

2017 ICNFP @AOC
22 August 2017
KamLAND experiment on $\nu_e$

- Detector running over 15 years (from 2002)

- Large volume: 1,200m$^3$ Liquid Scintillator
  Ultra low radioactivity: U: $<3.5\times10^{-18}\text{g/g}$,
  Th: $<5.2\times10^{-17}\text{g/g}$ (from 2007)

- KamLAND Energy Resolution:
  \[ \Delta E = \frac{6.2\%}{\sqrt{E(\text{MeV})}} \]  
  (34% photo coverage)

Depth: 2,700 m.w.e.
$\nu_e$ 2.5m paraffin shield
Acrylic plate for Rn
3.8kL pure-water OD veto
KamLAND reactor $\nu_e$ results

- Stable data-taking
- Low B.G. (ultra pure LS, low reactor $\nu$ flux)
- more precise measurement

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• for Geo neutrino

Livetime: 1259.8 days  2016 Preliminary Result
model prediction: Enomoto et al. EPSL 258, 147 (2007)

We measured clear distribution of geo-neutrino events!

Preliminary

We measured clear distribution of geo-neutrino events!

Preliminary

PRD 88, 03301 (2013)

Livetime: 351 days

Preliminary

Rate+Shape+time analysis (ratio fixed)

| Flux \(\times 10^6 \text{ cm}^2\text{s}^{-1}\) |
|-----------------|-----------------|-----------------|
| [event]         | [TNU]           | 0 signal        |
| U+Th            | 164 +28/-25 (17%) | 34.9 +6.0/-5.4 | 3.9 +0.7/-0.6 | 4.1 | 7.92σ |

We measured clear distribution of geo-neutrino events!
Why neutrino less double beta decay?

$m_\nu \ll m_e, u, d$

- Neutrino
  - 3 generation
  - Oscillation: $m_\nu \neq 0$, so small (why?)
  - Only Left-handed Neutrino (right-handed anti-neutrino).
    where is right-handed?

- Majorana Mass: Neutrino don’t have charge

$$\mathcal{L}_M = m_D (\bar{\psi}_L \psi_R^c + \bar{\psi}_R \psi_L^c) + m_L (\bar{\psi}_L (\psi_L)^c + (\bar{\psi}_L)^c \psi_L) + m_R ((\bar{\psi}_R)^c \psi_R + \bar{\psi}_R (\psi_R)^c)$$

$$\mathcal{L}_{mass} = \mathcal{L}_D + \mathcal{L}_M = \mathcal{L}_D + \mathcal{L}_L + \mathcal{L}_R$$

Violates lepton number!

- Heavy right-handed neutrino? See-saw: (Yanagida, Gell-Mann...)

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Double beta decay isotope and 0νββ

\[ \beta \rightarrow e^- + e^- \]

\[ \beta \rightarrow e^- + e^- \]

\[ 2\nu\beta\beta \]

\[ 0\nu\beta\beta \]

\[ (T_{1/2}^{2\nu})^{-1} = G^{2\nu} |M^{2\nu}|^2 \]

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

G: phase space factor, 
M: nuclear matrix element 
\( \langle m_{\nu}\rangle \): effective neutrino mass

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

Double beta decay
→ very long life >10^{18} yr
→ Large amount isotope
High ΔE

<table>
<thead>
<tr>
<th>isotope</th>
<th>Q-Value(MeV)</th>
<th>abundance(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>48Ca \rightarrow 48Ti</td>
<td>4.271</td>
<td>0.187</td>
</tr>
<tr>
<td>76Ge \rightarrow 76Se</td>
<td>2.040</td>
<td>7.8</td>
</tr>
<tr>
<td>82Se \rightarrow 82Kr</td>
<td>2.995</td>
<td>9.6</td>
</tr>
<tr>
<td>96Zr \rightarrow 96Mo</td>
<td>3.350</td>
<td>2.8</td>
</tr>
<tr>
<td>100Mo \rightarrow 100Ru</td>
<td>3.034</td>
<td>11.8</td>
</tr>
<tr>
<td>116Cd \rightarrow 116Sn</td>
<td>2.802</td>
<td>7.5</td>
</tr>
<tr>
<td>124Sn \rightarrow 124Te</td>
<td>2.228</td>
<td>5.64</td>
</tr>
<tr>
<td>130Te \rightarrow 130Xe</td>
<td>2.533</td>
<td>34.5</td>
</tr>
<tr>
<td>136Xe \rightarrow 136Ba</td>
<td>2.479</td>
<td>8.9</td>
</tr>
<tr>
<td>150Nd \rightarrow 150Sm</td>
<td>3.367</td>
<td>5.6</td>
</tr>
</tbody>
</table>

\* Q>2MeV isotope

Effective Majorana neutrino mass and hierarchy

$$\langle m_\nu \rangle = |\sum U^2_{ei} m_i| = |\cos^2 \theta_{13} (m_1 \cos^2 \theta_{12} + m_2 e^{2i\alpha} \sin^2 \theta_{12}) + m_3 e^{2i\beta} \sin^2 \theta_{13}|$$

$$\langle m_{ee} \rangle^{\text{nor}} = \left| m_1 c_{12}^2 c_{13}^2 + \sqrt{m_1^2 + \Delta m^2_{\odot}} s_{12}^2 c_{13}^2 e^{2i\alpha} + \sqrt{m_1^2 + \Delta m^2_A} s_{13}^2 e^{2i\beta} \right|$$

$$\langle m_{ee} \rangle^{\text{inv}} = \left| \sqrt{m_3^2 + \Delta m^2_A} c_{12}^2 c_{13}^2 + \sqrt{m_3^2 + \Delta m^2_{\odot} + \Delta m^2_A} s_{12}^2 c_{13}^2 e^{2i\alpha} + m_3 s_{13}^2 e^{2i\beta} \right|$$
Motivation of KamLAND-Zen for $\beta\beta$

• **KamLAND**
  
  Large volume: 1,200m$^3$ Liquid Scintillator as a 4pi veto
  Ultra low radioactivity: U:$<3.5\times10^{-18}g/g$, Th:$<5.2\times10^{-17}g/g$
  Distillation technique
  Experience of balloon development
  New electronics MoGRA (available$^{10}C,^{11}C$ tagging)
  Detector is running. => quick start by low cost.

  **mach advantage for $\beta\beta$ experiment!**

• **Disadvantage**
  
  KamLAND Energy Resolution:

  $$\Delta E = \frac{6.2\%}{\sqrt{E(\text{MeV})}}$$
  (34% photo coverage)
Merits of $^{136}\text{Xe}$ on KamLAND

Before EXO-200 and KamLAND-Zen start

<table>
<thead>
<tr>
<th>isotope</th>
<th>$T^{0\nu}_{1/2}$ (50 meV)</th>
<th>$T^{2\nu}_{1/2}$ measured (year)</th>
<th>Nat. Abundance (%)</th>
<th>Q-value (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$</td>
<td>$4.55 \times 10^{26}$</td>
<td>$&gt;10^{22}$</td>
<td>8.9</td>
<td>2476</td>
</tr>
</tbody>
</table>


Merits on KamLAND

• Isotopic enrichment
• Purification established
• Solubility to LS $>3\%$, easy extracted
• Slow $2\nu\beta\beta$ ($T^{2\nu}_{1/2} > 10^{22}$ years)
• Small $T^{0\nu}/T^{2\nu}$ ratio

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KamLAND-Zen project

KamLAND-Zen collaboration
- Tohoku University
- Kavli IPMU Tokyo University
- Osaka University
- Tokushima University
- University of California Berkeley
- LBNL
- Colorado State University
- University of Tennessee
- TUNL
- University of Washington
- MIT
- University of Hawaii
- NIKHEF and University of Amsterdam

1st phase
- $^{136}$Xe $\sim$ 320kg (91% enriched)
- R=1.54m balloon
- V=16.5m$^3$
- LS : C10H22(81.8%) + PC(18%) + PPO + Xe($\sim$ 3wt%)
- $\rho_{LS}$: 0.78kg/$\ell$
- target : $\sim$ 60meV / 2years for 0νββ
KamLAND-Zen MIB (Zen Balloon)

- nylon black corrugate tube
- 12 nylon strings
- 12 Nylon belts
- MIB film (24 gores)

**Table: KamLAND-Zen MIB Specifications**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere diameter</td>
<td>3.16m</td>
</tr>
<tr>
<td>Volume</td>
<td>17m³</td>
</tr>
<tr>
<td>Film thickness</td>
<td>25μm</td>
</tr>
<tr>
<td>Film strength</td>
<td>3kg/cm</td>
</tr>
<tr>
<td>Connection part strength</td>
<td>2kg/cm</td>
</tr>
<tr>
<td>Xe leakage</td>
<td>&lt;1.3kg/5years</td>
</tr>
<tr>
<td>Transparency (@400nm)</td>
<td>99%</td>
</tr>
<tr>
<td>U contamination</td>
<td>2x10⁻¹²g/g</td>
</tr>
<tr>
<td>Th contamination</td>
<td>3x10⁻¹²g/g</td>
</tr>
<tr>
<td>⁴⁰K contamination</td>
<td>2x10⁻¹²g/g</td>
</tr>
</tbody>
</table>

- filling test by water
- Real balloon construction in the ultra clean room (class 1)
- Ultra-sonic cleaning using pure water
- Heat welding
- He leak test & Repair work
- Before shipping

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Installation of KamLAND-Zen mini balloon
Making Xe loaded LS

New 25kL LS storage tank x 2

Temporary storage

Distilled and N2 purged LS

Purified materials By Water Extraction

LS distillation system

LS water extraction system

Xe storage and handing area (degas and Xe Load / Extract)

Xe Loaded LS

Delivery

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Normal data taking has been started on 24 September 2011

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Background study around Q-value

Simultaneous fit and 90% CL upper limit for 0νββ

<table>
<thead>
<tr>
<th>Reaction</th>
<th>χ²</th>
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</thead>
<tbody>
<tr>
<td>110mAg + 0nu</td>
<td>13.1</td>
</tr>
<tr>
<td>208Bi + 0nu</td>
<td>22.7</td>
</tr>
<tr>
<td>88Y + 0nu</td>
<td>22.2</td>
</tr>
<tr>
<td>60Co + 0nu</td>
<td>82.9</td>
</tr>
<tr>
<td>0nu only</td>
<td>85.0</td>
</tr>
</tbody>
</table>

Time distribution of events

BG is likely to be 110mAg.
KamLAND-Zen phase-1 result

\[ T^{0\nu}_{1/2} > 1.9 \times 10^{-25} \text{ yr} @90\%\text{CL} \]

How to reduce the BG?

136Xe purification

- Distillator (XMASS proto type)
- Getter
- PTFE filters

Xe Distillator Zr alloy getter

3.0wt% solubility (136Xe 383kg)
More brighter LS

Xe-LS + 110mAg → LS + 110mAg → new LS → new Xe-LS

Confirm 110mAg remains in LS.
Confirm whole 110mAg drained.
Reduction of BG.

May 2012 → Aug 2012 → Nov 2013

3.0wt% solubility (136Xe 383kg)

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

Phase 1 (first 112.3 days)
2.2 $< E < 3.0$ MeV, $R < 1$ m

Phase 2 (first 114.8 days)
2.2 $< E < 3.0$ MeV, $R < 1$ m

$^{110m}\text{Ag BG reduction to < 1/10}$

Visible Energy (MeV)

Events

$^{137}\text{Cs}$
$^{134}\text{Cs}$
$^{214}\text{Bi}$ (U)
$^{208}\text{Th}$

$^{110m}\text{Ag (balloon film)}$

$^{110m}\text{Ag (Xe-LS)}$

Preliminary
KamLAND-Zen 400 phase-2 calibration

Z-axis calibration with composite source ($^{137}\text{Cs}$ $^{68}\text{Ge}$ $^{60}\text{Co}$)

- bias <1% (IB)
- bias <2cm (IB)
- <1cm ($|z|<1m$)

energy
vertex

miniCAL
Deploy in MIB

$^{137}\text{Cs}$ 0.662MeV
$^{137}\text{Cs}$ 1.17+1.33MeV
$^{137}\text{Cs}$ 0.511MeV×2
$^{68}\text{Ge}$
$^{60}\text{Co}$
KamLAND-Zen 400 phase-2 BG

- delayed coincidence
  \( \text{\(^{214}\text{Bi-}^{214}\text{Po}\)} \)
- pileup event search

\( \text{\(^{214}\text{Bi-}^{212}\text{Po}\)} \)

\( \text{\(^{10}\text{C tagging}\)} \)

1. muon
2. neutron capture
3. \( \text{\(^{10}\text{C decay}\)} \)

\( \text{\(^{214}\text{Bi on IB surface}\)} \)

\( \text{\(^{214}\text{Bi on IB surface}\)} \)

LS purification cycle did not remove Bi on surface
(Some Po signal extinction by film)

Reconstruction of non-uniform \( \text{\(^{214}\text{Bi distribution}\)} \)

\( \text{\(^{10}\text{C detection efficiency: 64 \pm 4 %}\)} \)

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KamLAND-Zen 400 phase-2

**0νββ analysis**
- Systematic uncertainty 3.1%
- Data: 110mAg, 238U + 232Th + 210Bi + 210Po + 85Kr + 40K
- (0νββ U.L.)
- 136Xe 2νββ
- 136Xe 0νββ (90% C.L. U.L.)

**2νββ analysis**
- Small Film BG area
- Internal BG
- Spallation (11C)
- Film BG (134Cs, 40K)

**2νββ analysis**
- Estimated - - 0.23 ± 0.04 - - 3.4 ± 0.8
- Best-fit 0 5.48 0.25 8.5 2.56 4.04 20.8

**0νββ analysis**
- Estimated - - 0.03 ± 0.01 - - 3.3 ± 0.8
- Best-fit 0 5.29 0.03 0.0 2.45 3.43 11.3

**T1/22ν = 2.21 ± 0.02 (stat) ± 0.07 (syst) × 10^{21} year (90% C.L.)**

**T1/20ν > 9.2 × 10^{25} year (90% C.L.)**
Upper limit of $^{136}\text{Xe}$ 0νββ half life (90%C.L.)

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

Effective Majorana mass

$\langle m_{\beta\beta} \rangle < 61 \sim 165$ meV
$m_{\text{lightest}} < 180 \sim 480$ meV
Recent $0\nu\beta\beta$ Summary (form TAUP2017)

- EXO: $^{136}\text{Xe}$
  - New EXO-200 data results show no statistically significant $0\nu\beta\beta$ excess
  - $T_{1/2} > 1.8\times10^{25}$ yr (90% CL), $\langle m_{\beta\beta} \rangle < 147 - 398$ meV
  - On-going EXO-200 Phase-II running will continue to improve sensitivity

- GERDA: $^{76}\text{Ge}$ Preliminary 11:30 24th Aug GUSEV, Konstantin
  - Unblinding of 12.4 kg•yr of best-quality data
  - $T_{1/2} > 8.0 \times 10^{25}$ yr @ 90% CL, $m_{\beta\beta} < 0.12-0.27$ eV
  - For full 100 kg•yr exposure: sensitivity to a signal up to $T_{1/2} > 8.0 \times 10^{25}$ yr (or limit $T_{1/2} > 1.3 \times 10^{26}$ yr at 90%CL)
Recent $0\nu\beta\beta$ Summary (form TAUP2017)

- **CUORE**: $^{130}\text{Te}$ Bolometers
  - Combined result with 19.75 kg·yr of Cuoricino and 9.8 kg·yr of CUORE-0
  - The combined 90% C.L. limit is $T_{0\nu} > 6.6 \times 10^{24}$ yr, $m_{\beta\beta} < 210$–590 meV

- **SNO+**: $^{130}\text{Te}$ Loaded LS
  - LAB+PPO+Te-ButaneDiol Cocktail: 0.5% Te (~1300 kg $^{130}\text{Te}$)
  - Commissioning Ongoing, Filling with Scintillator later this year
  - Sensitivity: $T_{1/2} > 2 \times 10^{26}$ y, 90% CL, $m_{\beta\beta} \approx 40$–90 meV (after 5 yrs, 0.5% loading)

- **Others**: Se (SuperNEMO, CUPID-0), Mo (CUPID-Mo, AMoRE) Ge (MJD, LEGEND), gas-Xe (NEXT, PandaX-III), Ca (CANDLES), ....
KamLAND-Zen 400 removal

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>10</td>
<td>12</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

1. Xe extraction from LS
2. LS draining from inner balloon
3. Inner balloon removal
4. Close top flange

Smooth work!!
KamLAND-Zen 800

Motivation:

KamLAND need spherical tank inspection under the flammable liquid law. (≈May 2016, every 16 years) So, we need to drain OD water.

- Good chance to improve Zen mini-balloon and OD!
- We kept extra $^{136}$Xe in the mine. (>2 years)

<table>
<thead>
<tr>
<th>KL-zen 400</th>
<th>KL-zen 800</th>
</tr>
</thead>
<tbody>
<tr>
<td>balloon size : 3.16mφ =&gt; ~4mφ</td>
<td></td>
</tr>
<tr>
<td>$^{136}$Xe amount : 383kg =&gt; 756kg</td>
<td></td>
</tr>
</tbody>
</table>

=> establish more cleaner production technique
   (particle and electro static Ctrl., screening, etc....)
Original Schedule for KamLAND-Zen 800

<table>
<thead>
<tr>
<th></th>
<th>2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>

- **New MIB production @Sendai**
- **Calibration source deployment**
- **Xe collection, current MIB removal**
- **OD refurbishment**
- **Clean room preparation**
- **Install New MIB**
- **LS filling / Xe loading**

**Deployed MIB with LS from September 2016**

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new mini-balloon production (June 2015〜2016) in class-1 ultra clean room, Sendai
KamLAND-Zen 800 status

- New MIB was installed in August, and LS was filled.
- lower Th/U concentration
  
  But,....

- We found a leakage from MIB

\[ ^{210}\text{Po events} \]

\[ \text{MIB looks shrink on upper hemisphere} \]

\[ \text{Detected Buffer oil component N12} \]
KamLAND-Zen 800 status

• Removed 800 MIB was checked carefully.
• Five small holes were found.
• Film didn’t break but welding line broke.
• Welding from top as done for the first 400 MIB which didn’t break.
  - 400 MIB: handy tool, from bottom
  - 800 MIB: machine, from top
• Welding parameter was scanned again.
• Review to JP and US balloon experts. (April 2017)
• Customize welding machine and method.
• New MIB production will be finished in September.
• Retrial for new MIB installation will be in October.
KamLAND-Zen & KamLAND-Zen 800 sensitivity

KamLAND-Zen Phase 1

- 2011
- MIB: ~Φ3.12m
- Livetime 270.7 days.
- $^{136}$Xe ~320kg (91%)
- FV: $^{136}$Xe 125 kg.

KamLAND-Zen Phase 2

- 2014
- LS & $^{136}$Xe Purification
- More $^{136}$Xe
- 2015
- Livetime 263.8 days.
- $^{136}$Xe ~383kg (91%)

KamLAND-Zen 800

- 2016
- Livetime 263.8 days.
- $^{136}$Xe ~383kg (91%)
- 2017
- 2018
- 2019
- 2020

KamLAND2-Zen?

- 202?
- MIB: ~Φ4m
- $^{136}$Xe ~756kg (91%)
- 5 years

・KL-Zen800 50meV?
・KL2-Zen~20meV (5years)
Future prospects on KamLAND

KamLAND2-Zen
1000kg $^{136}$Xe phase

Energy resolution at 2.6MeV

- $4\% \rightarrow 2\%$
- light correction by WC $\times 1.8$
- High light emission LS $\times 1.4$
- High Q.E. 20”PMT or HPD (QE $\sim 22\% \rightarrow 30\%, \ 17” \rightarrow 20”$) $\times 1.9$

Dead layer free scintillation film balloon

New electronics and trigger

Target sensitivity $\sim 20$meV by 5 years
Cover inverted hierarchy region!

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Other future option on KamLAND

- Sterile neutrino
  IsoDAR + KamLAND
  - Low energy, high-powered cyclotron
  - 16.5m
  - 95% C.L (5 years of running)
  - PRL 109, 141802 (2012)

- Dark matter
  PICO-LON + KamLAND
  - 1ton NaI
  - KamLAND: Ultra low BG
  - 4pi active shield

- other $\beta\beta$ source?
- super-KamLAND?
summary

• KamLAND-Zen 400 phase-2 was ended.

• Recent 0νββ decay result

  KamLAND-Zen combined (phase-1 + phase-2)

  \[ T_{1/2}^{0\nu} > 1.07 \times 10^{26} \text{ yr (90\%C.L.)} \]

  corresponding to \( \langle m_{\beta\beta} \rangle < 61-165 \text{ meV} \).

• KamLAND-Zen 800 MIB was installed in August 2016 after inspection of KamLAND main tank. But, it was removed for leakage problem.

• New 800 MIB will be produced and deployed in end of this year.

• KamLAND2/KamLAND2-Zen will be future project. Some of other possibility.