Current status and future prospects of KamLAND-Zen

23 October 2018
DBD18 @ Hilton
Waikoloa Village

Kunio Inoue
Research Center for Neutrino Science,
Tohoku University
KamLAND(-Zen) collaboration

**Japan**
Tohoku University, RCNS
University of Tokyo, Kavli IPMU
Osaka University
Tokushima University
Kyoto University  new

**US**
University of California Berkeley
University of Tennessee
Triangle University Nuclear Laboratory
University of Washington
Massachusetts Institute of Technology
Virginia Polytechnic Institute and State University
University of Hawaii
Boston University  new

**Netherland**
Nikhef, University of Amsterdam

※ Second affiliation is not listed.

~50 physicists

Collaboration meeting @MIT
We chose $^{136}\text{Xe}$ as it can be loaded in LS up to ~3 wt%.

**KamLAND - Zen**

90% enriched $^{136}\text{Xe}$
- 320kg for phase-I
- 380kg for phase-II
- 750kg for Zen 800 (to start in months)

**Zero Neutrino double beta decay search**

**136Xe**

Noble gas
Centrifugal enrichment possible
$Q_{\beta\beta}=2459 \text{ keV}$
(below $^{208}\text{TI}$ 3198-5001 keV)

**Advantages of using KamLAND**

① low cost and quick start
   (running detector)
② BG can be identified
   (full active thick shielding)
③ In-situ purification possible
   (liquid media)
④ On/Off measurements possible
   (xenon is removable)
⑤ multi-purpose
   (geo-neutrino)
⑥ easily scalable
   (mini-balloon)
Test fabrication and rehearsal of installation (since 2009)

Xenon handling system

25 µm-T Nylon-6 prototype

10m length when folded

Rehearsal with 8 m depth pool

80 µm-T PE prototype

Xenon mixing, density control

Established stratified replacement

Clean tent in the dome

New cavity, buffer tanks
**Mini-balloon fabrication for Zen 400**

**Work in class-1 super-clean-room**
(class 1: # of 0.5 μm particles in 1 cubic feet < 1

- Less material → 25μm Nylon-6
  - Transparency 99.4% @400nm
  - Strength 19.4 N/cm
  - Xe permeability < 220 g/year
- Low radio impurity → film w/o filler
  - U : 150 → 2×10^{-12}g/g
  - Th : 59 → 3×10^{-12}g/g
  - ^{40}K : 140 → 2×10^{-12}g/g

- all tools and parts are cleaned in this room

**Crafting 24 gores**

**Ultrasonic washer**

**Vectoran strings connected to 12 Nylon belts**

**Corrugated tube (7m)**

**Film part (~6m)**

**Straight part**

**Cone part**

3.08m

24 gores

**newly developed impulse heat welding**
Balloon and tube installation

Go through light insulator

Inflated with dummy LS and replaced with xenon-loaded LS, Retracted the tube after density adjustment.

Good job!
minimum inactive detector material basically 25 µm-t balloon film only

Picture in September 2011, everything has been done in two years!!

低 cost and quick start
KamLAND-Zen 400 phase I
(320kg xenon loading)

(a) DS-1 + DS-2

Before and after filtration

Events/0.05MeV

Visible Energy (MeV)

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

LS balloon
LS
LS

Unexpected BG has found
Thanks to **full active apparatus**, 213.4 days

**208Tl is above ROI**

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**Dominant ①BG identified as 110mAg**

No escape $\beta/\gamma$ makes BG spectrum simple

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**Xenon can be degassed from Xe-LS.**

And $^{136}$Xe ③on/off measurement has been demonstrated.

(useful for signal confirmation)
Phase-1 320kg
before purification

Phase-2 380kg
after purification

110mAg
reduction 1/20

Event distribution:
(a) DS-1 + DS-2
- Data
- Total
- $^{136}$Xe 2νββ
- Total (0νββ U.L.)
- $^{136}$Xe 0νββ
- External BG
- Spallation

(a) Period-2
- Data
- $^{110m}$Ag
- Total
- $^{238}$U + $^{232}$Th + $^{210}$Bi
- Total $^{210}$Po + $^{85}$Kr + $^{40}$K
- $^{136}$Xe 2νββ
- $^{136}$Xe 0νββ
- IB/External
- IB/External
- Spallation

Visible Energy (MeV)

Events/0.05MeV

>1.9x10^{25}y

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

(cf. T_{1/2}(^{110m}Ag)=250 days)

② in-situ purification possible!!
KamLAND-Zen 400 Phase 1+2 combined

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

(sensitivity 5.6×10^{25} \text{ yr})

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

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

Big leap toward IH region!
“Advantages of using KamLAND”

have been all demonstrated;

① low cost and quick start  
   (running detector)

② BG can be identified  
   (full active thick shielding)

③ In-situ purification possible  
   (liquid media)

④ On/Off measurements possible  
   (xenon is removable)

⑤ multi-purpose  
   (ex. geo-neutrino)

⑥ easily scalable  
   (mini-balloon)
4 multi-purpose

Geo-neutrino observation may conclude primordial meteorite of the earth, and dynamics of the mantle!!
And more …
○ Pre-supernova alarm using Silicon-burning neutrinos
○ Simultaneous measurement of supernova temperature and luminosity with coherent scattering on hydrogen
○ Very long baseline (Korean) reactor oscillation (if Japanese ones are suspended)
○ Verification of CPT in comparison with neutrino and anti-neutrino oscillation (when Japanese reactors come up)
○ MSW upturn of solar $^8$B neutrinos above 2 MeV
○ CNO cycle neutrinos (maybe with new electronics)
○ Physics with J-PARC neutrino beam
○ Search for charged dark matter with small mass difference to LSP
○ Sterile neutrino search with cyclotron (IsoDAR)
○ Verification of DAMA/LIBRA with NaI deployment

Yes, KamLAND-Zen has diverse physics targets
2nd mini-balloon fabrication

cleaning, cleaning and cleaning as usual
Example of improvements

before

after

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

cover sheets
after Leak check and repair

New mini-balloon has been deployed and inflated with “dummy” LS in August 2016

spent $1+\alpha$ yrs in total
through characterization of mini-balloon

We confirmed that the mini-balloon is cleaner!!

Measures we took worked!

<table>
<thead>
<tr>
<th></th>
<th>x1E-12 g/g film</th>
<th>232Th</th>
<th>238U</th>
</tr>
</thead>
<tbody>
<tr>
<td>intrinsic</td>
<td></td>
<td>6</td>
<td>2 Target</td>
</tr>
<tr>
<td>This time*</td>
<td></td>
<td>31+-7</td>
<td>5.3+-0.8</td>
</tr>
<tr>
<td>Zen 400 1st</td>
<td></td>
<td>79+-3</td>
<td>14+-1</td>
</tr>
<tr>
<td>Zen 400 2nd</td>
<td></td>
<td>336+-2</td>
<td>46.1+-4</td>
</tr>
</tbody>
</table>

At the same time, we noticed:

Indications of leak;
- camera image
- load cell
- balloon shape reconstruction with 210Po events
- 222Rn decay rate
- mixture of KL-LS and dummy-LS by gas-chromatography

Yes, cleaner!

I might say we demonstrated we can notice...
Inspection of holes with a He leak detector

- **Possible cause**
  - Folded hard part
  - High pressure during deployment

- **Locations**
  - Found in Kamioka
  - Found in Sendai

- **Measurements**
  - 0.5 cm
  - ~2 cm
  - ~1 cm
  - 2-3 mm

- **High pressure when folding**
after 1.5 yrs of effort    Including improvement of welding
mini-balloon installation  May 10, 2018

50cm width for detector access
After 30.5 m³ LS filling, we started DAQ to investigate background status of LS and mini-balloon
Dummy LS filling

Dummy LS = non Xe loaded LS

After 30.5 m³ LS filling, we started DAQ to investigate background status of LS and mini-balloon
Simulation, mini-balloon stays as expected
Characterization of mini-balloon, again

214Bi-Po Delayed coincidence

Basic investigation before xenon.

✅ mini-balloon is clean
✅ no evidence of leakage
✅ 238U is low enough
!

232Th (~10^-15 g/g)

212Bi-Po in 232Th series is a possible BG.

64.06%  
\( \beta + \gamma \)  
2.25 MeV

212Po  
0.299 μs

100%  
\( \alpha \)  
8.95 MeV

208Pb  
22.3 y

Pileup BG is as large as current ¹⁰C BG and tolerable. But ¹⁰C rejection is improving, and we chose purification!
One more way to reduce $^{212}$Bi-Po pileup

KamLAND can tag sequential decay of $^{220}$Rn-$^{216}$Po in $^{232}$Th series.

Both $^{208}$Tl, $^{212}$Bi-$^{212}$Po can be suppressed with 2 days veto after the tag. Useful for $0\nu 2\beta$ search and low threshold $^8$B neutrino observation.
The discovery may be just around the corner.

KamLAND-Zen is closest !!!
And more future plans!

Higher energy resolution for reducing $2\nu$ BG

$\rightarrow$ KamLANDZ2-Zen

- Expansion of entrance

Winston cone  light collection $\times 1.8$

- high q.e. PMT  light collection $\times 1.9$
  $17'' \phi \rightarrow 20'' \phi  \, \varepsilon = 22 \rightarrow 30+\%$

- New LAB LS  light collection $\times 1.4$
  (better transparency)

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

target sensitivity  20 meV

1000+ kg xenon
R&D for KamLAND2-Zen and future

- Winston cone
  - Succeeded with prototype

- HQE-PMT
  - Prototype in hand

- New LAB-LS
  - Purification succeeded with charcoal

- Denser xenon
  - Principle confirmed

- Scintillator film
  - Tag $\alpha$ in the film
  - $^{214}$Po reduction
  - $^{214}$Bi reduction

- Imaging
  - Welding succeeded requires fluor replacement
  - $B/\gamma$ id.

30L prototype
PolyEthylene Naphthalate (PEN)

- $n = 10,500 \text{ph/MeV}$
- $\lambda_{\text{PEN}} = 425 \text{nm}$
- U, Th < 3 ppt

Welding easier & strong enough

Requires Bis-MSB in LS

$\tau \approx 27 \text{ nsec}$, much slower than Kam-LS 4 nsec

PSD possible

Test PEN balloon in UV light
Possible BG from natural radioactivity

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

- LS: 99.975% rejection (double pulse)
- Nylon6: ~50% rejection \( \rightarrow \) Obstacle to enlarge FV
- PEN: 99.95% rejection (double pulse)

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

- 95% rejection (double pulse)
- 95% rejection (\(^{220}\text{Rn}-^{216}\text{Po} \) tagging)
- LS: 99.75% rejection in total \( \rightarrow \) Requires only \( 10^{-15}\text{g/g} \)
- Nylon6: 97.5% rejection (no \( \alpha \) or double pulse)
- PEN: ~99.95% rejection (double pulse, \(^{220}\text{Rn}-^{216}\text{Po}, \text{PSD} \))

Any one of three \( \alpha \)

PEN enables thicker (easier to handle) film and/or larger FV.
Further $^{10}$C reduction, analysis & electronics

1. Triple fold coincidence

μ

$\tau = 208 \, \mu s$

2. Energy loss along $\mu$ track

$\tau = 27.8 \, s$

Two channel prototype (real is 16ch)

Wide range, low noise, fast FADC, ethernet data transfer

Baseline restoration with digital feedback or feedforward

Overshoot is the problem
# Conceptual design

## Rough extrapolation of BG estimation & sensitivity

<table>
<thead>
<tr>
<th></th>
<th>KamLAND-Zen 400</th>
<th>KamLAND-Zen 800</th>
<th>KamLAND2-Zen 2.38-2.58 MeV</th>
<th>KamLAND2-Zen High P</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2\nu 2\beta$ [100kgXe/y]</td>
<td>7.4</td>
<td>7.4</td>
<td>&lt;0.15</td>
<td>&lt;0.15</td>
</tr>
<tr>
<td>$^{10}\text{C}$ [100kgXe/y]</td>
<td>1.3 analysis</td>
<td>0.18</td>
<td>0.09 1.8 atm 0.05</td>
<td></td>
</tr>
<tr>
<td>$^{8}\text{B}$ [100kgXe/y]</td>
<td>0.33</td>
<td>0.33</td>
<td>0.16 1.8 atm 0.09</td>
<td></td>
</tr>
<tr>
<td>FV (loading) [kgXe]</td>
<td>100 (380)</td>
<td>300 (750)</td>
<td>1000 (1000)</td>
<td>1000 (1000)</td>
</tr>
<tr>
<td>(Expected) reach</td>
<td>61-165 meV 1.07$\times 10^{26}$yr</td>
<td>40 meV 5$\times 10^{26}$yr</td>
<td>20 meV 2$\times 10^{27}$yr</td>
<td>&lt;20meV &gt;2$\times 10^{27}$yr</td>
</tr>
</tbody>
</table>
Schedule

2019  KamLAND-Zen 800

2020  Environmental and peripheral preparation

2021  KamLAND upgrade

2022  No observation

2023  KamLAND2 start

2024  Geo-neutrino observation

2025  KamLAND2-Zen start

2026  Investigation of Majorana nature

2027  

2028  

- Purchase enriched Xenon (200kg)
- Installation of MoGURA2
- Clean room fabrication
- Clean air system installation
- Purification system upgrade
- Light concentrator production
- Large balloon production

- Purchase HQE-PMT
- LS drain
- Expansion of entrance
- PMT replacement/mirror attachment
- Large balloon installation
- Refurbishment of N2 system
- New LS production
- LS filling
- Development of calibration system

- Mini-balloon installation
- Xenon installation
Summary

• KamLAND-Zen 400 has the current world best record on effective Majorana mass of neutrinos.

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

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

• It also validated “advantages of using KamLAND”, and the last item of scalability is on-going.

• KamLAND-Zen 800 will start in a few month with a target sensitivity of 40 meV.

• KamLAND2-Zen aims at sensitivity below 20 meV, adopting HQE-PMT, Winston Cone, LAB-LS, new electronics with BLR, PEN-MIB, and maybe high pressure xenon loading.

• R&D for KL2-Zen to launch around 2027 is going well.
Thank you!