KamLAND-Zen

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KamLAND(-Zen) collaboration

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

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

Netherland
Nikhef, University of Amsterdam

※ Second affiliation is not listed.

~50 physicists
We chose $^{136}$Xe as it can be loaded in LS up to ~3 wt%.

$^{136}$Xe
Noble gas
Centrifugal enrichment possible
$Q_{\beta \beta} = 2459$ keV
(below $^{208}$Tl 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 easily scalable
  (mini-balloon)

90% enriched $^{136}$Xe
320kg for phase-I
380kg for phase-II
745kg for Zen 800 (started in January)
minimum inactive detector material basically 25μm-t balloon film only

Initial funding in 2009 and picture in September 2011
Everything has been done in two years!!

© low cost and quick start
Thanks to full active apparatus,

(a) DS-1 + DS-2

213.4 days

unpredicted BG found

208TI is above ROI

DS-3: 15.5 days

degassed data

2ν2β reduced

110mAg BG remains

Xenon can be degassed from Xe-LS. And 136Xe 3on/off measurement has been demonstrated.

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

(a) DS-1 + DS-2

Visible Energy (MeV)

Events/0.05MeV

>1.9x10^{25} y

Phase-2 380kg after purification

110mAg reduction 1/20

(a) Period-2

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

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

②in-situ purification possible!!
It also provides upper limit of $m_{\text{lightest}}$ at 180-480 meV.

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

(sensitivity $5.6 \times 10^{25}$ yr)

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

Big leap toward IH region!
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
### “Advantages of using KamLAND” have been almost demonstrated:

1. Low cost and quick start (running detector)
   - Ran in 2 years

2. BG can be identified (full active thick shielding)
   - $^{110}\text{mAg}$ identified

3. In-situ purification possible (liquid media)
   - $^{110}\text{mAg}$ removed

4. On/Off measurements possible (xenon is removable)
   - BG confirmed by degassing

5. Multi-purpose (ex. geo-neutrino)
   - Leading geo-$\nu$

6. Easily scalable (mini-balloon)
⑤ easily scalable
double size 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

laundry twice a day
New mini-balloon has been installed in August 2016 and spent 1+α yrs for fabrication. Characterization confirmed that the mini-balloon is cleaner!!

<table>
<thead>
<tr>
<th>x1E-12 g/g_{film}</th>
<th>^{232}Th</th>
<th>^{238}U</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intrinsic</strong></td>
<td>6</td>
<td>2 \text{ Target}</td>
</tr>
<tr>
<td>This time*</td>
<td>31±7</td>
<td>5.3±0.8</td>
</tr>
<tr>
<td>Zen 400 1st</td>
<td>79±3</td>
<td>14±1</td>
</tr>
<tr>
<td>Zen 400 2nd</td>
<td>336±2</td>
<td>46.1±4</td>
</tr>
</tbody>
</table>

Measures we took worked! preliminary

Yes, cleaner!

At the same time, we noticed:

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

I might say we demonstrated we can notice...
Inspection of holes with a He leak detector
after 1.5 yrs of effort Including improvement of welding mini-balloon installation again  May 10, 2018

50cm width for detector access
Characterization of mini-balloon, again

Basic investigations before xenon.

- mini-balloon is clean
- no evidence of leakage
- $^{238}\text{U}$ is low enough

$^{214}\text{Bi}$-$\text{Po}$ Delayed coincidence

$^{212}\text{Bi}$-$\text{Po}$ in $^{232}\text{Th}$ series is a possible BG.

$^{212}\text{Bi}$

$^{212}\text{Po}$

$^{208}\text{Pb}$

64.06% $\beta + \gamma$
2.25 MeV

$^{212}\text{Bi}$

$^{212}\text{Po}$

60.6 m

0.299 $\mu$s

100% $\alpha$
8.95 MeV

$^{208}\text{Pb}$

22.3 y

$^{232}\text{Th}$($\sim 10^{-15}$g/g)

$\text{U, Th}$ in KL-LS
$\sim 10^{-17}$g/g

Pileup BG is as large as current $^{10}\text{C}$ BG and tolerable.

But $^{10}\text{C}$ rejection is improving, and we chose purification!
One more way to reduce $^{212}\text{Bi}$-$\text{Po}$ pileup

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

Both $^{208}\text{Tl}$, $^{212}\text{Bi}$-$^{212}\text{Po}$ can be suppressed with 2 days veto after the tag. Useful for $0\nu 2\beta$ search and low threshold $^8\text{B}$ neutrino observation.
Xenon loading started in November 2018 after the purification.

Physics run started on January 22, 2019 with ~745kg xenon loading.

$^{222}$Rn is still decaying.
Picture taken on 29 January 2019

mini balloon with 745 kg of enriched xenon
2ν region $Z$ vs $\rho^2$

Zen 400 phase 2

contaminated with $^{134}$Cs,
dust sank

0ν region (2.3-2.7 MeV) $r^3$

$1.76 \text{ m}^3$

$2.87 \text{ m}^3$

Zen 800

$1.0 \text{ MeV} < E_{vis} < 2.3 \text{ MeV}$

$2\nu 2\beta$ dominates in all volume

R~1.6m

~10 times less BG

before $^{10}$C tagging
After $^{214}$Bi-Po cut

- $r < 220$ cm ($r_{balloon} = 1.92$ m)
- $r < 150$ cm

No strange BG is seen in $2\nu2\beta$ region even in all volume.

$^{208}$Tl and probably $^{214}$Bi are seen in higher energies.

$^{214}$Bi rejection efficiency on the mini-balloons is ~50%.

Radius cut reduces $^{208}$Tl and $^{214}$Bi (potential BG) very well. FV can be 3~4 times larger and equivalent with all volume of Zen 400.
Finally,

“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)
The discovery may be just around the corner. KamLAND-Zen is closest!!!
And more future plans!

Higher energy resolution for reducing $2\nu$ BG

$\Rightarrow$ KamLAND2-Zen

- **Winston cone** light collection $\times 1.8$
- **high q.e. PMT** light collection $\times 1.9$
  - $17'' \phi \rightarrow 20'' \phi$ $\epsilon = 22 \rightarrow 30+\%$
- **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
  - welding succeeded, requires fluor replacement
- **imaging**: $\beta/\gamma$ id.

Xe solubility (wt\%) vs. Xe partial pressure (MPa) at 3→12% @30m depth

30L prototype
Polyethylene Naphthalate (PEN)

welding easier & strong enough

requires Bis-MSB in LS

$\tau \sim 27$ nsec, much slower than Kam-LS 4 nsec

PSD possible
Possible BG from natural radioactivity

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

- LS 99.975% rejection (double pulse)
- Nylon6 ~50% rejection ← 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 ← Requires only \(10^{-15}\)g/g

- Nylon6 97.5% rejection (no \(\alpha\) or double pulse)
- PEN ~99.95% rejection (double pulse, \(^{220}\text{Rn}-^{216}\text{Po}\), PSD)

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

1. Triple fold coincidence

\[ \mu \]

\[ \tau = 208 \mu s \]

2. Energy loss along $\mu$ track

\[ \tau = 27.8 s \]

3. Wider timing distribution for spread vertices

~50\% reduction possible

New electronics will improve $^{10}$C reduction from 64\% to ~99\%.

Zen 800 is going to introduce them.

Wide range, low noise, fast FADC, ethernet data transfer (real adds digital BLR)
# 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>$2\nu 2\beta$ &amp; /100kgXe/y</td>
<td>7.4</td>
<td>7.4</td>
<td>&lt;0.15</td>
<td>&lt;0.15</td>
</tr>
<tr>
<td>$^{10}$C &amp; /100kgXe/y</td>
<td>1.3 analysis 0.18</td>
<td></td>
<td>0.09 1.8 atm 0.05</td>
<td></td>
</tr>
<tr>
<td>$^{8}$B $\nu$ &amp; /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) &amp; [kgXe]</td>
<td>100 (380)</td>
<td>300+ (745)</td>
<td>1000 (1000)</td>
<td>1000 (1000)</td>
</tr>
<tr>
<td>(Expected) reach</td>
<td>61-165 meV 1.07$\times10^{26}$yr</td>
<td>40 meV 5$\times10^{26}$yr</td>
<td>20 meV 2$\times10^{27}$yr</td>
<td>&lt;20meV &gt;2$\times10^{27}$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  

installation of new electronics planned during Zen 800

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.
  \[ T^{0\nu}_{1/2} > 1.07 \times 10^{26} \text{ yr} \]
  \[ \langle m_{\beta\beta} \rangle < (61 - 165) \text{ meV} \]
  \[ \text{PRL117, 082503} \]
- It also validated “advantages of using KamLAND.”
- KamLAND-Zen 800 successfully launched in January 2019 with a target sensitivity of 40 meV.
- KamLAND2-Zen aims at sensitivity below 20 meV, adopting HQE-PMT, Winston Cone, LAB-LS, new electronics, PEN-MIB, and maybe high pressure xenon loading.
- R&D for KL2-Zen to launch around 2027 is going well.

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Thank you!