KamLAND: Status and Prospects

Neutrino Geoscience 2010
Oct. 7, 2010
I. Shimizu (Tohoku Univ.)
KamLAND Collaboration


1Research Center for Neutrino Science, Tohoku University, Sendai 980-8578, Japan
2Institute for the Physics and Mathematics of the Universe, Tokyo University, Kashiwa 277-8568, Japan
3Physics Department, University of California, Berkeley, and Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
4Department of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama 35487, USA
5W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA
6Department of Physics, Colorado State University, Fort Collins, Colorado 80523, USA
7Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822, USA
8Department of Physics, Kansas State University, Manhattan, Kansas 66506, USA
9Physics Department, Stanford University, Stanford, California 94305, USA
10Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA
11Department of Physics, Duke University, Durham, North Carolina 27708, USA and Physics Departments at Duke University, North Carolina Central University, and the University of North Carolina at Chapel Hill
12Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA
13Nikhef, Science Park 105, 1098 XG Amsterdam, the Netherlands
KamLAND Experiment

2 flavor neutrino oscillation

\[ P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 [eV^2] l [m]}{E [MeV]} \right) \]

most sensitive region

\[ \Delta m^2 = \left( \frac{1}{1.27} \right) \cdot \left( \frac{E [MeV]}{L [m]} \right) \cdot \left( \frac{\pi}{2} \right) \sim 3 \times 10^{-5} eV^2 \]

reactor neutrino: sensitive to LMA solution

geo neutrino: U and Th decays inside the Earth
KamLAND
Kamioka Liquid Scintillator Anti-Neutrino Detector

1,000 ton Liquid Scintillator
Pseudocumene (20%)
PPO (1.5 g/l)

Dodecane (80%)

1,325 17 inch + 554 20 inch PMTs
commissioned in February, 2003
photocathode coverage : 22% → 34%

Water Cherenkov Outer Detector
Physics Target in KamLAND

- **0.4** solar neutrino
- **1.0** geo neutrino
- **2.6** reactor neutrino
- **8.5** supernova neutrino

- Jun. 2010 preliminary new result
- Sep. 2010 new result (hep-ex/1009.4771)

- **ν_x**
- **e^-**
- **ν_e**
- **p**
- **n**
- **γ**

- neutrino detection by electron scattering
- anti-neutrino detection by inverse beta-decay

- **ν_x**
- **e^-**
- **ν_e**
- **p**
- **n**
- **γ**

- prompt
- delayed

- mean capture time ~ 200 μsec on proton
Geologically Produced Antineutrinos

Antineutrino Flux

Window for KamLAND

beta-decay

\[ ^{238}\text{U} \rightarrow ^{206}\text{Pb} + 8^4\text{He} + 6e^- + 6\bar{\nu}_e + 51.7 \text{ MeV (100\%)} \]

\[ ^{232}\text{Th} \rightarrow ^{208}\text{Pb} + 6^4\text{He} + 4e^- + 4\bar{\nu}_e + 42.7 \text{ MeV (100\%)} \]

\[ ^{40}\text{K} \rightarrow ^{40}\text{Ca} + e^- + \bar{\nu}_e + 1.31 \text{ MeV (89.28\%)} \]

\[ ^{40}\text{K} + e^- \rightarrow ^{40}\text{Ar} + \nu_e + 1.51\text{MeV(10.72\%)} \]
**Reference Earth Model**

- **UCC**  
  U : 2.8 ppm / Th : 10.7 ppm

- **MCC**  
  U : 1.6 ppm / Th : 6.1 ppm

- **LCC**  
  U : 0.2 ppm / Th : 1.2 ppm

- **Oceanic crust**  
  U : 0.10 ppm / Th : 0.22 ppm

- **Continental crust**  
  U : 0.012 ppm / Th : 0.048 ppm

**Mantle = BSE (Primitive Mantle) − Crust**

- Th/U ~ 3.9
- Radiogenic heat ~ 16 TW

**Rudnick et al. (1995)**

- No U/Th in core

**Chondrite meteorite**
neutrino oscillation

\[ P(E, L) \sim 1 - \frac{1}{2} \sin^2 2\theta_{12} \quad \text{(constant suppression)} \]

50% of the total flux originates within 500 km
Radio-purity Upgrade in Geo Neutrino

Purification system in Kamioka mine in 2006

16 TW U/Th reactor
KamLAND 2005

remove ($\alpha$, n) BG to get higher S/N

~ 1.5 kilo-liter / hour

Likelihoods

Distillation $^{210}$Pb (Bi, Po), $^{40}$K,
$^{238}$U, $^{232}$Th, ...

$\alpha$-source

N$_2$ purge $^{85}$Kr, $^{39}$Ar, ...

Purification system in Kamioka mine in 2006

16 TW U/Th reactor
KamLAND 2005

remove ($\alpha$, n) BG to get higher S/N

~ 1.5 kilo-liter / hour
In the 2nd purification, we succeeded in keeping the LS boundary by the precise density control.
Background Estimation

13C(α, n)16O

natural abundance 1.1%

Q = 2.2MeV

16O

α

13C

prompt γ (6.1MeV) or e⁺e⁻ (6.0MeV)

recoil proton

6.130MeV 3− 6.049MeV 0+

1st excited state 2nd excited state

16O

prompt γ (2.22MeV)

12C(n, nγ)12C

in-situ calibration with 210Po13C

KamLAND data

ground state

1st excited state

2nd excited state

210Po13C source

(1) dominant BG source (α, n) has been reduced by down to ~ 1 / 20

(2) determination of the cross section is improved by in-situ calibration

uncertainty: 11% for ground state

LS purification

1st 2nd

2007. 5 ~ 2008. 7 ~

210Po

214Bi

85Kr

2007. 5 ~ 2008. 7 ~

(1st 2nd)

12C(n, nγ)12C

Q = 2.2MeV

prompt γ (4.4MeV)

12C

prompt (4.4MeV)

in-situ calibration with 210Po13C

KamLAND data

ground state

1st excited state

2nd excited state

210Po13C source

(1) dominant BG source (α, n) has been reduced by down to ~ 1 / 20

(2) determination of the cross section is improved by in-situ calibration

uncertainty: 11% for ground state
Stability of Event Reconstruction

Time variation of $^{60}\text{Co}/^{68}\text{Ge}$ energy  Time variation of $^{12}\text{B}/^{12}\text{N}$ event ratio

Z dependence of energy deviation  Z dependence of vertex deviation
### Systematic Uncertainty

<table>
<thead>
<tr>
<th>Data-set</th>
<th>livetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>(DS-1) Mar. 9, 2002 - May 12, 2007 (pre-purification data-set)</td>
<td>1486 days</td>
</tr>
<tr>
<td>(DS-2) May 12, 2007 - Nov. 4, 2009 (post-purification data-set)</td>
<td>669 days</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Detector related</th>
<th>Reactor related</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fiducial volume</strong></td>
<td><strong>νe spectra</strong></td>
</tr>
<tr>
<td>1.8% / 2.5%</td>
<td>2.4% / 2.4%</td>
</tr>
<tr>
<td><strong>Energy scale</strong></td>
<td><strong>Reactor power</strong></td>
</tr>
<tr>
<td>1.1% / 1.3%</td>
<td>2.1% / 2.1%</td>
</tr>
<tr>
<td><strong>L-selection eff.</strong></td>
<td><strong>Fuel composition</strong></td>
</tr>
<tr>
<td>0.7% / 0.8%</td>
<td>1.0% / 1.0%</td>
</tr>
<tr>
<td><strong>OD veto</strong></td>
<td><strong>Long-lived nuclei</strong></td>
</tr>
<tr>
<td>0.5% / 0.5%</td>
<td>0.3% / 0.4%</td>
</tr>
<tr>
<td><strong>Cross section</strong></td>
<td><strong>Time lag</strong></td>
</tr>
<tr>
<td>0.2% / 0.2%</td>
<td>0.01% / 0.01%</td>
</tr>
</tbody>
</table>

| 2.3% / 3.0% | 3.3% / 3.4% |

**Total systematic uncertainty (DS-1 / DS-2) : 4.1% / 4.5%**
Reactor Neutrino Status
Observed Energy Spectrum: 0.9 MeV - 8.5 MeV

exposure: 4126 ton-year (1.4 × 2881 ton-year for “KamLAND 2008”)

Geo neutrinos

Selection efficiency

KamLAND data
no-oscillation
best-fit osci.
accidental
\( ^{13}C(\alpha,n)^{16}O \)
best-fit Geo \( \nu_e \)
best-fit osci. + BG
+ best-fit Geo \( \nu_e \)

Observed events
No osci. expected
Background (w/o geo neutrino)
Observed events

3-flavor best-fit

\[ \tan^2 \theta_{12} = 0.436^{+0.102}_{-0.081} \]
\[ \Delta m^2_{21} = 7.49^{+0.20}_{-0.20} \times 10^{-5} \text{ eV}^2 \]
\[ \sin^2 \theta_{13} = 0.032^{+0.037}_{-0.037} \]

free parameter: geo neutrinos
(U, Th) = (82, 26) events

Geo-neutrinos from U and Th are unconstrained
L/E plot

\[ P = \frac{\text{observed} - \text{B.G.}}{\text{no osci. expected}} \]

\( L_0 : \) a fixed baseline (180 km)

KamLAND data covers almost 2 cycle of oscillation

\[ \text{characteristic of neutrino oscillation} \]
KamLAND: 3-flavor oscillation analysis

\[ P_{ee}^{3\nu} = \cos^4 \theta_{13} P_{e'e'}^{2\nu} + \sin^4 \theta_{13} \]

survival probability

matter effect

atmospheric oscillation length is completely averaged out

\[ \Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5} \text{ eV}^2 \]

Best-Fit

\[ \tan^2 \theta_{12} = 0.436^{+0.102}_{-0.081} \]

\[ \sin^2 \theta_{13} = 0.032^{+0.037}_{-0.037} \]

(< 0.094 at 90\% C.L.)
Oscillation Parameters: 2- and 3-flavor

2-flavor analysis

\[ \Delta m_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5} \text{ eV}^2 \]
\[ \tan^2 \theta_{12} = 0.446^{+0.034}_{-0.031} \]

3-flavor analysis

\[ \Delta m_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5} \text{ eV}^2 \]
\[ \tan^2 \theta_{12} = 0.450^{+0.037}_{-0.031} \]
\[ \sin^2 \theta_{13} = 0.020^{+0.016}_{-0.016} \]
Geo Neutrino Status (Preliminary)
Event rate time variation: 0.9 MeV - 2.6 MeV

expected event rate (best-fit oscillation, BG estimation, Earth Model)

pre-purification update correlation

Constant contribution above the estimated reactor neutrino + non-neutrino background in 0.9 < E < 2.6 MeV region

Time information is useful to extract the geo neutrino signal
Observed Energy Spectrum: 0.9 MeV - 2.6 MeV

4126 ton-yr data-set (2135 days)

Rate analysis
(0.9 < E < 2.6 MeV)

841 candidates

$^9$Li $2.0 \pm 0.1$

Accidental $77.4 \pm 0.1$

Fast neutron $< 2.8$

$(\alpha, n) 165.3 \pm 18.2$

Reactor $\nu 484.7 \pm 26.5$

BG total $729.4 \pm 32.3$

excess $111^{+45}_{-43}$ events

Null signal exclusion (rate) $99.55\%$ C.L.

Rate + Shape + Time analysis

best-fit (U, Th) = (65, 33)

w/ solar osci. constraint
Rate + Shape + Time analysis

best-fit
(U, Th) = (65, 33)

0 signal is rejected at 99.997% C.L. (> 4σ C.L.)

Ngeo = 106^{+29}_{-28} events
Fgeo = 4.3^{+1.2}_{-1.1} \times 10^6 \text{ /cm}^2/\text{sec}
(38.3^{+10.3}_{-9.9} \text{ TNU})
Radiogenic Heat and Flux

Multi-site measurements have just started!

Fully-radiogenic model

Radiogenic heat production = Surface heat flow
(scale U and Th amount in mantle assuming fixed crustal contribution)
Test of Fully-Radiogenic Model

- The observed flux is consistent with the 16 TW model prediction
- Fully-radiogenic models start to be disfavored

KamLAND only 2.4σ C.L. KamLAND + Borexino 2.3σ C.L.
Future Prospects
KamLAND-Zen Experiment

**Why use Xe?**
- Isotopic enrichment, purification established
- Soluble to LS more than 3 wt%, easily extracted
- Slow 2νββ (T_{1/2} > 10^{22} years) requires modest energy resolution

**Xenon loaded LS**
- dodecane 80%
- pseudo-cumene 20%
- PPO 1.36 g/liter
- Xenon 3.0 wt%

**Zero Neutrino Double Beta (0νββ)**

R. S. Raghavan PRL72 1411 (1994)

**KamLAND LS**
- dodecane 80%
- pseudo-cumene 20%
- PPO 1.36 g/liter
- Xenon 3.0 wt%

**neutrino-less double beta decay search with ^{136}\text{Xe} LS**
KamLAND2-Zen Experiment

KamLAND2-Zen

chimney enlargement

capability to accommodate CANDLES, CdWO4, NaI and others

LS renewal

KL LS 8,000 photon/MeV
standard LS 12,000 photon/MeV x1.4

Winstone Cone

photo-coverage > x2
photon collection > x1.8

target sensitivity

~ 20 meV / 5 years

KamLAND-Zen (400 kg $^{136}$Xe)

KamLAND2-Zen (1,000 kg $^{136}$Xe)

w/ improved energy resolution

useful also for geo neutrino measurement

$\Delta m^2_{\text{atm}} > 0.30$ meV$^2$

KKDC claim

$\Delta m^2_{\text{sol}} > 0.50$ meV$^2$

inverted hierarchy

$\Delta m^2_{\text{atm}} > 0.00$ meV$^2$

$\Delta m^2_{\text{sol}} > 0.00$ meV$^2$

$\Delta m^2_{\text{atm}} > 0.00$ meV$^2$

$\Delta m^2_{\text{sol}} > 0.00$ meV$^2$

$\Delta m^2_{\text{atm}} > 0.00$ meV$^2$

$\Delta m^2_{\text{sol}} > 0.00$ meV$^2$

$\Delta m^2_{\text{atm}} > 0.00$ meV$^2$

$\Delta m^2_{\text{sol}} > 0.00$ meV$^2$

$\Delta m^2_{\text{atm}} > 0.00$ meV$^2$

$\Delta m^2_{\text{sol}} > 0.00$ meV$^2$

$\Delta m^2_{\text{atm}} > 0.00$ meV$^2$

$\Delta m^2_{\text{sol}} > 0.00$ meV$^2$

$\Delta m^2_{\text{atm}} > 0.00$ meV$^2$

$\Delta m^2_{\text{sol}} > 0.00$ meV$^2$

$\Delta m^2_{\text{atm}} > 0.00$ meV$^2$

$\Delta m^2_{\text{sol}} > 0.00$ meV$^2$
Super-KamLAND(-Zen) Experiment

Toward further improvement of KamLAND-Zen

- Increase the pressure of Xe ×4 at 30 m depth
- Increase number of photo electrons ×3.3
- Reduce $^{10}$C BG by multiple vertex identification 1/10 reduction
- Target $^{136}$Xe mass 400 kg → 40 tons ×100 $200M$ (highest cost)

sensitivity ~ 7.6 meV → normal hierarchy?

1 ~ 5 meV

Another possibility is “high statistics” LS detector

geo neutrino ~ 1000 events / 50 kton / yr

→ flux at < 10% accuracy

but ...

effect from local geology ~ 10%

precise subtraction of the crustal contribution is more important
Summary

- Anti-neutrino results in KamLAND are improved.
  - Observed flux is fully consistent with Earth model
  - Fully-radiogenic model starts to be disfavored
  - Data-set: 2881 ton-yr → 4126 ton-yr
  - Reactor power reduction
  - Improved radio-purify by LS purification
  - \((\alpha, n)\) B.G. reduction \(\sim 1 / 20\)

- Reactor-neutrino (available at hep-ex/1009.4771)
  - Three-flavor oscillation analysis is presented
    - \(\tan^2 \theta_{12} = 0.450_{-0.031}^{+0.037}\)
    - \(\Delta m^2 = 7.50_{-0.20}^{+0.19} \times 10^{-5} \text{ eV}^2\)
    - \(\sin^2 \theta_{13} = 0.020_{-0.016}^{+0.016}\)

- Geo-neutrino (preliminary result)
  - Observed flux is fully consistent with Earth model
  - Fully-radiogenic model starts to be disfavored
  - Observed geo-neutrino event
    - Flux \(106_{-28}^{+29} \text{ events}\)
    - \(4.3_{-1.1}^{+1.2} \times 10^6 /\text{cm}^2/\text{sec}\)
  - (mass Th/U = 3.9)
• Multi-site measurements have just started!

• Multi-site measurements and/or a measurement on the oceanic crust (e.g. Hawaii) will be important to advance “neutrino geophysics”.

Future Prospects

• KamLAND-Zen starts in 2011 with 400 kg $^{136}$Xe, aiming at the effective mass ~ 50 meV.

• KamLAND, KamLAND-Zen, ... experiments will continue to measure the geo neutrino flux including future detector improvements.