Geo-neutrino Measurement with KamLAND

Hiroko Watanabe
Research Center for Neutrino Science (Tohoku Univ.)
for the KamLAND Collaboration
1. Introduction
2. Analysis Results
3. Summary
1. Introduction
2. Analysis Results
3. Summary
* Institutions:
5 from Japan
8 from US
1 from Europe
* ~50 collaborators
KamLAND

Kamioka Liquid Scintillator Anti-Neutrino Detector
(operated since 2002)

Kashiwazaki 159km
Shika 88km
Wakasa 146~192km
Hamaoka 200km

KamLAND

Kamioka Mine
1000m depth

neutralino
neutrino
cosmic ray

Water Cherenkov Outer Detector
* Muon veto

1,325 17inch + 554 20inch PMTs
* Photo coverage 34%

φ13m balloon
φ18m stainless tank

(125µ thickness)

* Dodecane (80%) Pseudocumene (20%) PPO (1.36 g/l)
* extremely low impurity ($^{238}$U: $3.5 \times 10^{-18}$ g/g, $^{232}$Th: $5.2 \times 10^{-17}$ g/g)
KamLAND
2000~

- Detector Features
  - Large volume & low backgrounds

- Physics
  - Different neutrino physics in a wide energy range

- Electron scattering: $\nu + e^- \rightarrow \nu + e^-$
- Inverse beta-decay: $\bar{\nu}_e + p \rightarrow e^+ + n$

- Solar neutrinos
- Reactor neutrinos
- Geo neutrinos
- Supernova neutrinos, etc.

- Observed energy [MeV]: 0.4, 1.0, 2.6, 8.5

- References:
  - PRC 84, 035804 (2011)
  - PRC 92, 055808 (2015)
  - Nature Geoscience 4, 647-651 (2011)
  - PRD 88, 033001 (2013)
  - PRL 100, 221803 (2008)
  - PRD 83, 052002 (2011)
136Xe loaded LS was installed in KamLAND

### Detector Features

KamLAND-Zen 400: 2011~2015
KamLAND-Zen 800: 2019~

### Physics

- 0ν2β can happen if neutrinos are Majorana.

KamLAND-Zen 800, 133 days: $T^\nu > 4 \times 10^{25}$ year (90% C.L.)

(®TAUP 2019)

Continue to use LS volume outside of mini-balloon to measure anti-neutrino signals
inverse-beta decay

\[ \begin{align*}
\nu_e & \rightarrow e^- + P + \gamma(0.511\text{MeV}) \\
\Delta T & = 200\mu\text{sec} \\
\text{thermal diffusion} & \rightarrow n + d
\end{align*} \]

Geoneutrinos

- Neutrino Application

- Direct measurement of radiogenic heat contribution

Neutrino Property Study

- Signature of neutrino oscillation
- Precise measurement of oscillation parameters
Geo-neutrino Flux at Kamioka

Contributions from each area
- 50%: distance < 500km
- 25%: distance < 50km
- 1~2%: from Kamioka mine

Important to understand Japanese geology

Recent study will be reported by N. Takeuchi, K. Ueki and S. Enomoto.
1. Introduction

2. Analysis Results

3. Summary
Data-set & Reactor Neutrinos

Reactor Neutrino Flux @Kamioka

March 2011 Earthquake

Period 1 : 1485.62 days
Period 2 : 1151.47 days
Period 3 : 1759.85 days

2013 data-set : 2991 days
4.90×10^{32} proton-year

2016 data-set : 3901 days
6.39×10^{32} proton-year

2019 data-set : 4397 days
7.20×10^{32} proton-year

+500 days of low-reactor phase from 2016 data-set

• PRD 88, 033001 (2013)
• Preliminary

+500 days

Preliminary

March 2011 Earthquake

2013 data-set : 2991 days
4.90×10^{32} proton-year

2016 data-set : 3901 days
6.39×10^{32} proton-year

2019 data-set : 4397 days
7.20×10^{32} proton-year

Period 1 : 1485.62 days
Period 2 : 1151.47 days
Period 3 : 1259.8 days
Period 3 : 1759.85 days

+500 days
Livetime: 4397 days

Candidate: 1167 ev

Background Summary

<table>
<thead>
<tr>
<th>Decay</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>⁹Li</td>
<td>4.4 ± 0.1</td>
</tr>
<tr>
<td>Accidental</td>
<td>121.9 ± 0.1</td>
</tr>
<tr>
<td>Fast neutron</td>
<td>&lt; 4.1</td>
</tr>
<tr>
<td>¹³C(α, n)¹⁶O</td>
<td>211.6 ± 23.3</td>
</tr>
<tr>
<td>Reactor $\bar{\nu}_e$</td>
<td>629.0 ± 34.4</td>
</tr>
<tr>
<td>Total</td>
<td>966.9 ± 41.8</td>
</tr>
</tbody>
</table>
Livetime: 1760 days
Candidate: 110 ev

- Geo-neutrino / Background
  = 66.3 ev / 50.3 ev ~1.3
- We clearly measured geo-neutrino spectrum.
  \[\rightarrow\] better understanding of U, Th each contribution
Energy Spectrum, U and Th Geo-neutrino Contributions

Th/U Fixed (3.9)

- Data - BG - all data best-fit reactor $\bar{\nu}_e$
- Background subtracted data
  - backgrounds: all data best-fit
  - weighted average by each period’s livetime
- U • Th contributions
  - all data best-fit with Th/U fixed analysis

Good agreement

Preliminary

![Graph showing energy spectrum with data points and fitted curves for Th and U geo-neutrinos, along with background subtraction and weighted average consideration.]

Events / 0.1MeV vs. $E_p$ (MeV)
**Rate + Shape + Time Analysis (1)**

### Preliminary

#### Ratio Free

<table>
<thead>
<tr>
<th></th>
<th>[event]</th>
<th>[TNU]</th>
<th>Flux [$\times 10^5$ cm$^{-2}$s$^{-1}$]</th>
<th>0 signal rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>best-fit</td>
<td>model</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>123.3 +41.2/-39.1</td>
<td>23.3 +7.8/-7.4</td>
<td>17.9 +6.0/-5.7</td>
<td>22.0</td>
</tr>
<tr>
<td>Th</td>
<td>41.6 +24.6/-24.7</td>
<td>8.1 +4.8/-4.8</td>
<td>20.0 +11.9/-11.9</td>
<td>18.6</td>
</tr>
</tbody>
</table>
Rate + Shape + Time Analysis (2)

(a) Preliminary

- Earth model prediction
- EPSL 258, 147 (2007)

Best-fit: $(N_U, N_{Th}) = (122, 42)$

$N_{U} + N_{Th} = 164$

(b) Preliminary

<table>
<thead>
<tr>
<th>Ratio Fixed</th>
<th>[event]</th>
<th>[TNU]</th>
<th>Flux [$\times 10^6$ cm$^{-2}$s$^{-1}$]</th>
<th>0 signal rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_U + N_{Th}$</td>
<td>$168.8 \pm 26.3/-26.5 (15.6%)$</td>
<td>32.1 $\pm 5.0/-5.0$</td>
<td>$3.6 \pm 0.6/-0.6$</td>
<td>4.1</td>
</tr>
</tbody>
</table>
geoscientific findings from measurement results

* Th/U Mass Ratio
* Radiogenic Heat
* Mantle Signal
Th/U Mass Ratio

Th/U mass ratio = 3.9

- Chondrite data: (1.06-6.42)
- BSE models: (3.58-4.2)

Best fit
- Th/U = 5.3 \pm 6.0_{-3.6}
- Th/U < 18.5 (90% C.L.)

ref) 2016 preliminary
- Th/U = 4.1 \pm 5.5/-3.3, <17.0 (90% C.L.)

KamLAND best-fit is consistent with chondrite data and BSE models.

ref) chondrite data
Radiogenic Heat

Radiogenic Heat from $^{238}\text{U} + ^{232}\text{Th}$ (TW)

- Fully Radiogenic
- High Q
- Middle Q
- Low Q

2019 Preliminary Result

- KamLAND 68.3% C.L.
- $\nu$ Flux ($10^6 \text{cm}^2\text{s}^{-1}$)

- Radiogenic Heat: $12.4^{+4.9}_{-4.9}$ TW

- Ref) Crust (U+Th) ~7 TW
- Mantle (U+Th) ~5.4 TW

[BSE models]

- High Q
  - based on balancing mantle viscosity and heat dissipation

- Middle Q
  - based on mantle samples compared with chondrites

- Low Q
  - based on isotope constraints and chondritic models

Enomoto et al. EPSL 258, 147 (2007)
Measured Geo-neutrino Flux and Model Expectations

- **Model**
  - mantle (assuming Middle Q)
  - crust

- **Contributions from the other isotopes** [Arevalo Jr. et al., 2009; Enomoto, 2006] (4.3 TW) are subtracted from the total heat flow [Davies and Davies, 2010] (47 ± 2 TW).

- **238U and 232Th contributions are tested separately.**

- **Estimated data have excesses from crustal contributions.**

- **Present-day contributions from individual heat producing elements can determine past radiogenic heat through the history of the Earth.**

---

**S. Enomoto, Earth Moon and Planets, 99(1), 131-146 (2006)**
Mantle Signal: KamLAND & Borexino Results

KamLAND

\[
S(\text{Mantle}) = S(\text{Observation}) - S(\text{Crust, Model})
\]

\[
= 3.60^{+0.56}_{-0.57} \times 10^6 \text{ cm}^{-2}\text{s}^{-1} - 2.93^{+0.29}_{-0.29} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}
\]

\[
= 0.67^{+0.63}_{-0.64} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}
\]

\[
\rightarrow 6.0^{+5.6}_{-5.7} \text{ TNU}
\]

- High Q model is rejected with >2 \(\sigma\)
- Mantle signal (median value)
  
  \[
  23.7^{+10.7}_{-10.1} \text{ events}
  \]

Borexino

- Mantle signal
  
  \[
  21.2^{+9.6}_{-9.1} \text{ TNU}
  \]

- Recent approach of geo-neutrino flux calculation model
  - indicating there is significant systematic uncertainty (60-70 %)
  - trying to understand sources of uncertainties

N. Takeuchi et al. (PEPI 6222, 2019)


The KamLAND experiment measures anti-neutrino from various sources over a wide energy range.

Preliminary results are presented.

- Low-reactor operation period:
  - ~4.8 years (40% of total livetime)
- Clear energy spectrum of geo-neutrino → better understanding of U, Th each contribution
- Geo-neutrino event measurement with 15.6% uncertainty
- Geoscience discussion
  - Th/U mass ratio: 5.3 ± 0.6 ± 3.6, consistent with chondrite data and BSE models
  - Radiogenic heat: 12.4 ± 4.9 TW (Mantle+Crust, U+Th), consistent with Middle Q and Low Q models
  - Separated test of $^{238}$U and $^{232}$Th geo-neutrinos → power to determine past radiogenic heat through the Earth’s history
  - Mantle signal: 0.67 ± 0.63 ± 0.64 × 10$^6$ cm$^{-2}$s$^{-2}$ → * High Q is rejected with >2σ
    * depends on estimation of crust contribution

Future Prospects:

- KamLAND continues to measure geo-neutrinos with low-reactor backgrounds stably
- Better understanding of crust contribution → helps further estimation of mantel signals
- Multi-sight measurements
- Ocean Bottom Detector has strong power to measure mantle contribution directly. Poster by H. Watanabe, K. Ueki et al