KamLAND

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for the KamLAND Collaboration
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In a Type II supernova, a huge burst of neutrinos is released, making the next Galactic supernova a greatly anticipated event. Neutrinos have already been playing an important role in our understanding of supernovae since the discovery of neutrinos from SN 1987A was located in the Large Magellanic Cloud at a distance of 50 kpc. A core-collapse supernova in the Milky Way would provide a larger flux of neutrinos and the physics of supernovae can be studied in much more detail. In the carbon-burning phase, the dominant mechanism for energy generation is the pair process, and neutrinos provide a significant fraction of the energy output. This data set has provided many insights into the properties of supernovae and the neutrino sector. Neutral-current cross sections are currently being measured in several experiments to provide further constraints on the neutrino masses and mixing angles.

The KamLAND Collaboration


* Institutions:
  4 from Japan
  12 from US
  1 from Europe

* ~50 collaborators

Sep. 2016 @Amsterdam
Kamioka Liquid Scintillator
Anti-Neutrino Detector
(operated since 2002)

1,000t Liquid Scintillator
- extremely low impurity
  \(^{238}\text{U}: 3.5 \times 10^{-18} \text{g/g}, \; ^{232}\text{Th}: 5.2 \times 10^{-17} \text{g/g}\)
- world’s largest LS detector!

1,879 Photomultiplier Tubes

* Photo coverage 34%
**KamLAND**

**Detector Features**
- Large volume & low backgrounds

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

\[
\begin{align*}
\text{inverse beta-decay} &: \bar{\nu}_e + p \rightarrow e^+ + n \\
electron scattering &: \nu + e^- \rightarrow \nu + e^- 
\end{align*}
\]

- Different neutrino physics in a wide energy range

**Observed Energy [MeV]**
- 0.4
- 1.0
- 2.6
- 8.5

**References**
- PRC 92, 055808 (2015)
- PRL 100, 221803 (2008)
- PRD 88, 033001 (2013)
- Nature Geoscience 4, 647-651 (2011)
- PRD 83, 052002 (2011)
KamLAND-Zen

**Detector Features**

- Zero Neutrino double beta decay search
- $^{136}$Xe loaded LS was installed in KamLAND (344 kg 90% enriched $^{136}$Xe installed so far)

**Physics**

- $0\nu 2\beta$ can happen if neutrinos are Majorana.
- Neutrino-less double beta decay
- World best limit on neutrino effective mass
  \[
  \langle m_{\beta\beta} \rangle < (61 - 165) \text{ meV}
  \]
  PRL 117, 082503 (2016)

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

Geoneutrinos: Neutrino Application

- Direct measurement of radiogenic heat contribution
- Signature of neutrino oscillation
- Precise measurement of oscillation parameters

Neutrino Property Study

Survival Probability

\[ S(E_p) = \frac{1}{1 + \frac{E_p}{E_0}} \]

Events/10keV
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Electron-antineutrino from natural radioactive decay

\[ \bar{\nu}_e \quad 4.1 \times 10^6 / \text{cm}^2 / \text{sec} \]

\( \beta \)-decay

- \( ^{238}U \rightarrow ^{206}Pb + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.7 \text{ MeV} \)
- \( ^{232}Th \rightarrow ^{208}Pb + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.7 \text{ MeV} \)
- \( ^{40}K \rightarrow ^{40}Ca + e^- + \bar{\nu}_e + 1.311 \text{ MeV} (89.28\%) \)

Energy threshold, 1.8 MeV

Only geo-neutrinos from \( U \) and \( Th \) are detectable

 Contributions from each part

- Crust: 70%
- Mantle: 27%
- Core: 0%
- Sediment etc.: 3%

Contributions from each area

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

Important to understand Japanese geology
Geo-neutrino Measurements with KamLAND

KamLAND
KamLAND-Zen

2005 Nature 03980
geo-neutrino first measurement

2011 N. Geo. 1205
radiogenic heat direct measurement

749 days
0.71×10^{32} proton-year
geo-nu event
28.0^{+15.6}_{-14.6} ev (56% error)

2135 days
3.49×10^{32} proton-year
geo-nu event
106^{+29}_{-28} ev (27% error)

2013 PRD 88, 03301 (2013)
include low reactor phase data
2991 days
4.90×10^{32} proton-year
geo-nu event
116^{+28}_{-27} ev (24% error)
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Current Data-set

Reactor Neutrino Flux @Kamioka

Data provided according to the special agreements between Tohoku Univ. and Japanese nuclear power reactor operators.

March ‘11 earthquake

all Japanese reactor-off period

Reactors
- Total
- Wakasa-bay
- Kashiwazaki
- Shika
- Hamaoka
- Korea
- Others

March '11 earthquake

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

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

- 1.3 times of 2013 data-set
- low-reactor operation period : ~3.5 years livetime
- all Japanese reactor-off period : ~2.0 years livetime

Precise understanding of reactor neutrino spectrum enhances geo-neutrino measurement.

PRD 88, 033001 (2013)

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

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

Reactor neutrino background is decreased significantly.

Preliminary

advantages

- low-reactor period
- geo-neutrino

Reactor neutrino background is decreased significantly.

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Reactor neutrino background is decreased significantly.
- Reactor neutrino experiments reported that there was an excess of events in the region of 4-6 MeV.
  - Daya Bay, RENO, Double Chooz

- Reactor neutrino spectrum for KamLAND analysis
  2013 paper: Huber + Mueller & Bugey-4 normalisation
  2016 preliminary: Daya Bay measurement result
  \[ \sigma_f (\text{cm}^2/\text{fission}) = (5.92 \pm 0.12) \times 10^{-43} \] (uncertainty: 2.03%)

- We confirmed that:
  - 4-6 MeV excess has no impact on the geo-neutrino results.
  - Effect of reactor spectrum uncertainty is much smaller than the statistical uncertainty of geo-neutrino events.
The geo-event rate for each group is plotted at the exposure-weighted expected event rate within the group. The efficiency-corrected best-fit value of spectra per fission of these isotopes introduced a $^{239}$Pu fission rates is measured to within 2%. Only four isotopes thermal power generation used for the normalization of the and reshuffling data for all Japanese commercial reactors. The best-fit values from the global oscillation analysis:

The data are grouped according to periods of similar expected reactor are calculated from the reference model [17]. The vertical bands correspond to data periods not used in the analysis. In the right panel of (a), preliminary Preliminary Preliminary

- Backgrounds:
  - LS purification $\rightarrow$ non-neutrino backgrounds reduction
  - Earthquake $\rightarrow$ reactor neutrino reduction
- Constant contribution of geo-neutrino
  
  Time information is useful to extract the geo-neutrino signal
Energy Spectrum (0.9-2.6 MeV)

2016 Preliminary Result

Livetime : 3900.9 days

Candidate : 1130 ev

Background Summary

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^9\text{Li}$</td>
<td>3.4 ± 0.1</td>
</tr>
<tr>
<td>Accidental</td>
<td>114.0 ± 0.1</td>
</tr>
<tr>
<td>Fast neutron</td>
<td>&lt; 4.0</td>
</tr>
<tr>
<td>$^{13}\text{C}(\alpha, n)^{16}\text{O}$</td>
<td>205.5 ± 22.6</td>
</tr>
<tr>
<td>Reactor $\bar{\nu}_e$</td>
<td>618.9 ± 33.8</td>
</tr>
<tr>
<td>Total</td>
<td>941.8 ± 40.9</td>
</tr>
</tbody>
</table>
Livetime: 1259.8 days 2016 Preliminary Result

We measured clear distribution of geo-neutrino events.

best-fit : Period 3 analysis
Rate + Shape + Time Analysis (1)

**NU vs NTh**

- Earth model prediction: EPSL 258, 147 (2007)
- Ratio fixed

### 2016 Preliminary Result

#### Ratio fixed

<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>128 +46/-39</td>
<td>27.1 +9.8/-8.3</td>
<td>20.8 +7.5/-6.4</td>
<td>22.0</td>
</tr>
<tr>
<td>Th</td>
<td>32 +27/-23</td>
<td>6.9 +5.9/-5.0</td>
<td>17.2 +14.5/-12.5</td>
<td>18.6</td>
</tr>
</tbody>
</table>
Rate + Shape + Time Analysis (2)

(a) Preliminary

best-fit \((N_U, N_{Th}) = (130, 34)\)

\(N_U + N_{Th} = 164\)

model prediction : Enomoto et al. EPSL 258, 147 (2007)

(b) Preliminary

<table>
<thead>
<tr>
<th>event</th>
<th>Flux ([\times 10^6 \text{ cm}^{-2}\text{s}^{-1}])</th>
<th>0 signal rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>U+Th</td>
<td>(164 \pm 28/-25 (17%))</td>
<td>34.9 (+6.0/-5.4)</td>
</tr>
</tbody>
</table>
- According to geochemical studies, $^{232}$Th is more abundant than $^{238}$U. Mass ratio (Th/U) in bulk silicate Earth is expected to be around 3.9.

Models: 3.58-4.2

- Chondrite samples analysis: 1.06-6.42
  Fall statistics for the meteorites identified and catalogued since 980 A.D.

- Geo-neutrino observed rate can be converted to amount of Th & U assuming homogeneous distribution. Independent & direct measurement of entire Earth

滑 from McDonough, 2015, in Ehime
Th/U Mass Ratio (2)

Th/U = 4.1 $^{+5.5}_{-3.3}$

Th/U < 17.0 (90% C.L.)

ref) 2013 paper Th/U < 19 (90% C.L.)

Best fit

We have a sensitivity of Th/U mass ratio of entire Earth.

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

ref) chondrite data


Earth Model Comparison

2016 Preliminary Result

- Geodynamical
- Geochemical
- Cosmochemical

KamLAND 68.3% C.L.

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

$\overline{V}_e$ Flux ($\times 10^6$ cm$^2$s$^{-1}$)

- Geodynamical based on balancing mantle viscosity and heat dissipation
- Geochemical based on mantle samples compared with chondrites
- Cosmochemical based on isotope constraints and chondritic models

[BSE composition models]
Uncertainty of Geo-neutrino Flux Measurement

- Uncertainty of geo-neutrino flux measurement is decreased at the same level of our expectation.
- Measurement uncertainty gets close to uncertainty of Earth model prediction.
- It is important to improve accuracy of Earth model prediction, especially crust modelling.

PRD 88, 03301 (2013)

- ~21%

2016 Preliminary

- best fit with \( \pm 1\sigma \)
- \( 3.9 +0.7 -0.6 \times 10^6 \) /cm\(^2\)/s : ~18%

* uncertainty of Earth model prediction : 20%
The KamLAND experiment measures anti-neutrino from various sources over a wide energy range.

Preliminary results are presented.
- Low-reactor operation period: ~3.5 years (33% of total livetime), clear energy spectrum of geo-neutrino
- Geo-neutrino event measurement with 17% uncertainty (164 $^{+28}_{-25}$ ev). It is consistent with our expectation.
- Geoscience discussion
  - Th/U mass ratio: 4.1 $^{+5.5}_{-3.3}$, consistent with chondrite data and BSE models
  - Observed flux: consistent with models, but started to disfavour cosmochemical model

Measurement uncertainty gets close to the uncertainty of Earth model prediction.

Next target:
- Estimation of geo-neutrino contribution from mantle
- Better understanding of crust model