New from KamLAND

Neutrino 2004
Paris

Results
The KamLAND Collaboration

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Nuclear reactors are very intense sources of $\bar{\nu}_e$ deriving from beta-decay of the neutron-rich fission fragments.

Yield:
- $200\text{MeV} / \text{fission}$
- $6\bar{\nu}_e / \text{fission}$

Look for a deficit of $\bar{\nu}_e$ and spectral distortions at a distance $L$. 
A specific signature is provided by the inverse-β reaction

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

\[ \tau \approx 200 \, \mu s \]

\[ p + n \rightarrow d + \gamma (2.2 \, \text{MeV}) \]

Event tagging by coincidence in time, space and energy of the neutron capture

\[ E_{\bar{\nu}} \text{measurement} \]

\[ E_{\bar{\nu}} \cong T_{e^+} + T_n + (M_n - M_p) + m_{e^+} \]

Threshold: \( E_{\bar{\nu}} > 1.8 \, \text{MeV} \)

→ only \( \sim 1.5 \) antineutrinos/fission can be detected
The $\bar{\nu}_e$ energy spectrum

Reactor $\nu_e$ spectrum (a.u.)

Observed spectrum (a.u.)
Neutrino 2004
New Results from KamLAND

~1 km high
Mt Ikenoyama
Neutrino 2004 New Results from KamLAND

KamLAND:
Kamioka Liquid scintillator
AntiNeutrino Detector

- 1 kton liq. Scint. Detector in the Kamiokande cavern
- 1325 17" fast PMTs
- 554 20" large area PMTs
- 34% photocathode coverage
- H₂O Cerenkov veto counter
The completed detector, looking up
Scintillator is a blend of 20% pseudocumene and 80% dodecane.

Different density paraffines are used to tune the density of buffer to $4 \times 10^{-4}$ of that of the scintillator.

PPO concentration is 1.52 g/l in scintillator.
### Many reactors contribute to the antineutrino flux at KamLAND

<table>
<thead>
<tr>
<th>Site</th>
<th>Dist (km)</th>
<th>Cores (#)</th>
<th>$P_{\text{therm}}$ (GW)</th>
<th>Flux ($\text{cm}^{-2} \text{s}^{-1}$)</th>
<th>Rate noosc $^*$ ($\text{yr}^{-1} \text{kt}^{-1}$)</th>
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<tbody>
<tr>
<td>Japan</td>
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<td>Kashiwazaki</td>
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<td>Ohi</td>
<td>179</td>
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<td>Takahama</td>
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<tr>
<td>Fukushima1</td>
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<td>14.2</td>
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<td>Tokai2</td>
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<td>Onagawa</td>
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<td>Ikata</td>
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<td>Tomari</td>
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<td>3.3</td>
<td>$2.3 \times 10^3$</td>
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<td>South Korea</td>
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<td>Kori</td>
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<td>4</td>
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<tr>
<td>Wolsong</td>
<td>709</td>
<td>4</td>
<td>8.2</td>
<td>$7.1 \times 10^3$</td>
<td>4.3</td>
</tr>
<tr>
<td><strong>Total Nominal</strong></td>
<td><strong>70</strong></td>
<td><strong>181.7</strong></td>
<td><strong>1.3 \times 10^6</strong></td>
<td><strong>803.8</strong></td>
<td></td>
</tr>
</tbody>
</table>

$^*$ $E_{\nu} > 3.4 \text{MeV}$

$E_{\text{prompt}} > 2.6 \text{MeV}$

**Detailed power and fuel Composition calculation used**

**From electrical power Japanese average fuel used**

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**Neutrino 2004**

**New Results from KamLAND**
## A brief history of KamLAND

<table>
<thead>
<tr>
<th>Event</th>
<th>Dates</th>
<th>Live time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Start data taking</strong></td>
<td>Jan 2002</td>
<td>-</td>
</tr>
<tr>
<td><strong>Run A</strong> <em>(data-set of 1st paper)</em></td>
<td>Mar 9 - Oct 6 2002</td>
<td>145.4*</td>
</tr>
<tr>
<td><strong>Electronics upgrade &amp; 20” PMT commissioning</strong></td>
<td>Jan/Feb 2003</td>
<td>-</td>
</tr>
<tr>
<td><strong>Run B</strong></td>
<td>Oct - Jan 11 2004</td>
<td>369.7</td>
</tr>
<tr>
<td><strong>Data-set presented here</strong>†</td>
<td>Mar 9, 2002 - Jan 11, 2004</td>
<td>515.1</td>
</tr>
</tbody>
</table>

*Was 145.1 with old analysis

A limited range of baselines contribute to the flux of reactor antineutrinos at Kamioka

Over the data period Reported here

Korean reactors 3.4±0.3%
Rest of the world +JP research reactors 1.1±0.5%
Japanese spent fuel 0.04±0.02%
Vertexing is performed using timing from the 17” PMTs.
Tagged cosmogenics can be used for calibration

Fit to data shows that $^{12}\text{B}$:$^{12}\text{N} \sim 100:1$

- $^{12}\text{B}$$\bullet$\hspace{1cm}$\tau=29.1\text{ms}$\hspace{1cm}Q=13.4\text{MeV}$
- $^{12}\text{N}$\hspace{1cm}$\tau=15.9\text{ms}$\hspace{1cm}Q=17.3\text{MeV}$

Chi2 / ndf = 650.3 / 495
const  = 48.38 ± 0.3711
B12    = 3.166e+04 ± 208.1
decay time [msec] = 29.76 ± 0.2706
Energy calibration uses discrete $\gamma$ and $^{12}\text{B}/^{12}\text{N}$

$\sigma/E \sim 6.2\%$ at 1MeV

Carefully include Birks law, Cherenkov and light absorption/optics to obtain constants for $\gamma$ and e-type depositions
Estimate of total volume and fiducial fraction

flow meter meas.
purification tank meas.
3,000 m³ tank meas.

spallation neutrons

${}^{12}\text{B}/{}^{12}\text{N}$
Fraction of volume inside the fiducial radius verified using $\mu$-produced $^{12}\text{B}/^{12}\text{N}$ and n (assumed uniform)
Selecting antineutrinos, $E_{\text{prompt}} > 2.6 \text{MeV}$

- $R_{\text{prompt, delayed}} < 5.5 \text{ m}$
- $\Delta R_{e-n} < 2 \text{ m}$
- $0.5 \mu\text{s} < \Delta T_{e-n} < 1 \text{ ms}$
- $1.8 \text{ MeV} < E_{\text{delayed}} < 2.6 \text{ MeV}$
- $2.6 \text{ MeV} < E_{\text{prompt}} < 8.5 \text{ MeV}$

Tagging efficiency 89.8%

...In addition:
- 2s veto for showering/bad $\mu$
- 2s veto in a $R = 3\text{m}$ tube along track

Dead-time 9.7%
<table>
<thead>
<tr>
<th>Systematic</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scintillator volume</td>
<td>2.1</td>
</tr>
<tr>
<td>Fiducial fraction</td>
<td>4.2</td>
</tr>
<tr>
<td>Energy threshold</td>
<td>2.3</td>
</tr>
<tr>
<td>Cuts efficiency</td>
<td>1.6</td>
</tr>
<tr>
<td>Live time</td>
<td>0.06</td>
</tr>
<tr>
<td>Reactor $P_{thermal}$</td>
<td>2.1</td>
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<tr>
<td>Fuel composition</td>
<td>1.0</td>
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<tr>
<td>Time lag</td>
<td>0.01</td>
</tr>
<tr>
<td>Antineutrino spectrum</td>
<td>2.5</td>
</tr>
<tr>
<td>Antineutrino x-section</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td>6.5</td>
</tr>
</tbody>
</table>
Results

Observed events 258
No osc. expected 365±24(syst)
Background 7.5±1.3

<table>
<thead>
<tr>
<th>Background</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidentals</td>
<td>2.69±0.02</td>
</tr>
<tr>
<td>$^8$He/$^9$Li</td>
<td>4.8±0.9</td>
</tr>
<tr>
<td>$\mu$-induced n</td>
<td>&lt;0.89</td>
</tr>
<tr>
<td>Total</td>
<td>7.5±1.3</td>
</tr>
</tbody>
</table>

Inconsistent with simple $1/R^2$ propagation at 99.995% CL

$$(\text{Observed-Background})/\text{Expected} = 0.686±0.044(\text{stat})±0.045(\text{syst})$$

Caveat: this specific number does not have an absolute meaning in KamLAND, since, with oscillations, it depends on which reactors are on/off

(766.3 ton·yr, ~4.7× the statistics of the first paper)
2003 saw a substantial dip in reactor antineutrino flux
Good correlation with reactor flux

90% CL

Expected for no oscillations

χ^2=5.4/4

Fit constrained through known background

χ^2=2.1/4

~0.03 for 3TW hypothetical Earth core reactor

But a horizontal line still gives a decent fit with χ^2=5.4/4
Very clean measurement

Expect 1.5 n\(^{-12}\text{C}\) captures

Accidental background
Energy spectrum now adds substantial information

Best fit to oscillations:
\[ \Delta m^2 = 8.3 \cdot 10^{-5} \text{ eV}^2 \]
\[ \sin^2 2\theta = 0.83 \]

Straightforward \( \chi^2 \) on the histo is 19.6/11

Using equal probability bins \( \chi^2/\text{dof}=18.3/18 \) (goodness of fit is 42%)

A fit to a simple rescaled reactor spectrum is excluded at 99.89% CL (\( \chi^2=43.4/19 \))
Neutrino 2004 New Results from KamLAND

\[ \Delta m^2 = 8.3 \cdot 10^{-5} \text{ eV}^2 \]

\[ \sin^2 2\theta = 0.83 \]

LMA2 excluded at 99.6\% CL

"LMA0" disfavored at 94\% CL
\[ \Delta m^2 = 8.3 \cdot 10^{-5} \text{ eV}^2 \]

\[ \sin^2 2\theta = 0.83 \]

First KamLAND result

\[ \Delta m^2 = 6.9 \times 10^{-5} \text{ eV}^2 \]

\[ \sin^2 2\theta = 1.0 \]

Neutrino 2004

New Results from KamLAND
A shape-only fit gives similar results.

\[ \Delta m^2 = 8.3 \cdot 10^{-5} \text{ eV}^2 \]

\[ \sin^2 2\theta = 0.98 \]
KamLAND uses a range of L and it cannot assign a specific L to each event. Nevertheless, the ratio of detected/expected for $L_0/E \ (\text{or } 1/E)$ is an interesting quantity, as it decouples the oscillation pattern from the reactor energy spectrum.

![Graph showing the ratio of $L_0/E$ against $L_0/E$ (km/MeV). The graph includes KamLAND data points, a best-fit oscillation curve, and a hypothetical single 180km baseline experiment. The analysis threshold is marked at 2.6MeV. There is no oscillation expectation marked with a dashed green line.]
More exotic, non-oscillations models for the antineutrino channel start being less favored by data.

Decay* excluded at 95% CL

Decoherence† excluded at 94% CL

Combined solar $\nu -$ KamLAND 2-flavor analysis

$\Delta m^2_{12} = 8.2^{+0.6}_{-0.5} \times 10^{-5} \text{ eV}^2$

$\tan^2 \theta_{12} = 0.40^{+0.09}_{-0.07}$
Conclusions

KamLAND reactor exposure: 766.3 ton·yr (470% increase)

Data consistent with large flux swings in 2003

Spectrum distortions now quite significant, shape-only very powerful

Best KamLAND fit to oscillations $\Delta m=8.3 \cdot 10^{-5}$ eV$^2$, $\sin^22\theta=0.83$

LMA2 is now excluded

Together with solar $\nu$

$$\Delta m_{12}^2 = 8.2^{+0.6}_{-0.5} \times 10^{-5} \, eV^2; \tan^2 \theta_{12} = 0.40^{+0.09}_{-0.07}$$

Welcome to precision neutrino physics!