KamLAND Results

Kunio Inoue
(for the KamLAND collaboration)

Research Center for Neutrino Science, Tohoku University
E-mail: inoue@awa.tohoku.ac.jp

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First Results from KamLAND: Evidence for Reactor Antineutrino Disappearance


(KamLAND Collaboration)

1Research Center for Neutrino Science, Tohoku University, Sendai 980-8578, Japan
2Department of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama 35487
3Physics Department, University of California at Berkeley and Lawrence Berkeley National Laboratory, Berkeley, California 94720
4W.K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
5Physics Department, Drexel University Philadelphia, Pennsylvania 19104
6Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822
7Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803
8Physics Department, University of New Mexico, Albuquerque, New Mexico 87131
9Physics Department, Stanford University, Stanford, California 94305
10Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996
11Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708 and Physics Department at Duke University, North Carolina State University, and the University of North Carolina at Chapel Hill
12Institute of High Energy Physics, Beijing 100039, People’s Republic of China

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Solar Neutrino Measurements

SNO NC provided direct evidence of neutrino flavor transformation. $\phi_{\mu,e} = 3.41^{+0.66}_{-0.64}$ is 5.3$\sigma$ above zero.

The LMA is favored at $\sim 3\sigma$ level combining all results.

---

SNO

NC

ES

CC

SK

ES

8B

SSM

5.09$^{+0.44}_{-0.43}$ - 0.43

2.39$^{+0.24}_{-0.23}$ + 0.12

1.76$^{+0.06}_{-0.05}$ + 0.09

2.35$^{+0.02}_{-0.02}$ + 0.08

5.05$^{+1.01}_{-0.81}$ x 10$^{6}$/cm$^{2}$/sec

74.8 + 5.1 - 5.0 SNU

128 + 7 - 9 SNU

2.56$^{+0.23}_{-0.23}$ SNU

7.6 + 1.3 - 1.1 SNU

37Cl

SSM

74.8 + 5.1 - 5.0 SNU

128 + 7 - 9 SNU

2.56$^{+0.23}_{-0.23}$ SNU

7.6 + 1.3 - 1.1 SNU

---

B bore"
Can the LMA be verified with a different neutrino source?

Reactor neutrino measurements looked for a neutrino oscillation for more than 50 years.

\[ P = 1 - \sin^2 2\theta \sin^2 \left( 1.27 \frac{\Delta m^2 L}{E_\nu} \right) \]

\[ E_\nu \sim 5 \text{ MeV} \]

<table>
<thead>
<tr>
<th></th>
<th>mass (ton)</th>
<th>distance (km)</th>
<th>rate (ev/d)</th>
<th>Sensitive@ (eV2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHOOZ</td>
<td>5</td>
<td>1</td>
<td>24</td>
<td>6e−3</td>
</tr>
<tr>
<td>Palo Verde</td>
<td>12</td>
<td>0.8</td>
<td>220</td>
<td>8e−3</td>
</tr>
<tr>
<td>KamLAND</td>
<td>1000</td>
<td>~175</td>
<td>3</td>
<td>4e−5</td>
</tr>
<tr>
<td>BOREXINO</td>
<td>300</td>
<td>~800</td>
<td>0.1</td>
<td>8e−6</td>
</tr>
</tbody>
</table>

KamLAND verifies the LMA with "man-made" neutrinos.
Rich and Cheap Neutrino Source

Total man-made thermal output with nuclear power reactors in the world amounts to ~1.1 TW.

- Japan: 152 GW
- Asia w/o Japan: 60 GW
- Europe: 521 GW
- North America: 333 GW
- Others: 11 GW

It corresponds to $2 \times 10^{23}$ anti electron neutrino creation / sec.

High Population

70 GW (7% of world total) is generated at $175 \pm 30$ km distance from Kamioka site.

This high population provides $5 \times 10^6$/cm$^2$/sec of neutrino flux at Kamioka and it is measurable amount with an O(kiloton) underground detector.
80% of contribution comes from reactors located at ~200km from Kamioka.

If adopted for oscillation search

\[
P = 1 - \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 L/E_\nu \right)
\]

\[
\frac{\pi/2}{2}
\]

Typical distance 175km
Typical energy 5MeV

Sensitive @ $\Delta m^2 \sim 4 \times 10^{-5} eV^2$

Just on the LMA solution!
Fission Rate

Only 4 fissile nuclei contribute to reactor power outputs.

\[ ^{235}\text{U} \quad 201.8 \text{ MeV} \]
\[ ^{238}\text{U} \quad 205.0 \text{ MeV} \]
\[ ^{239}\text{Pu} \quad 210.3 \text{ MeV} \]
\[ ^{241}\text{Pu} \quad 212.6 \text{ MeV} \]

Normalization to the total fission rate is well defined by the measured thermal power output at much better than 2\% level.

Contribution of each nuclei evolves as fuel burns (burn up effect). Burn up effect can be accurately calculated knowing history of thermal power, fraction of new fuel and \(^{235}\text{U}\) enrichment. Systematic error to the neutrino event rate is much smaller than 1\%. 
Burn up Effect at Kamioka

As fuel burns, the contribution of Pu increases in a single reactor core. However, considering the real situation (brand new fuel is only one third or a quarter and many cores are contributing), composition change is very tiny. Even Pu contribution changes by 10%, neutrino event rate changes by only 5%.
Fission Neutrino Spectra

Neutrino spectra are obtained by conversion of experimentally measured beta decay spectra except $^{238}\text{U}$ which doesn't break up with thermal neutrons.

Error in neutrino event rate is dominated by error of major fission nucleus, $^{235}\text{U}$, and total error from spectrum is 2.25%.

Experimental measurements

Theoretical calculation
Clear 2 fold delayed coincidence Signature

\[ \bar{\nu}_e + p \rightarrow e^+ + n \quad \Rightarrow \quad n + p \rightarrow D + \gamma (2.22437\, \text{MeV}) \]

Capture time 210 \( \mu \text{sec} \) (KamLAND)

Theoretical uncertainty of neutrino cross section calculation is only 0.2\% for the entire reactor neutrino energy spectrum.

Order(1/M) calculation

P. Vogel and J.F. Beacom hep-ph/9903553

Outer Radiative Correction

A. Kurylov, M.J. Ramsey-Musolf and P. Vogel

\[ \times 10^{-42} \, \text{cm}^2 \]

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

\[ E_{\nu} = 1.806\, \text{MeV} \]

neutrino energy (MeV)
## Ambiguity of Neutrino Event Rate

### Conservative Accumulation of Various Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Power Output</td>
<td>2%</td>
</tr>
<tr>
<td>Burn up Effect</td>
<td>1%</td>
</tr>
<tr>
<td>Long Life Beta Nuclei</td>
<td>0.65%</td>
</tr>
<tr>
<td>Time Lag of Beta Decay</td>
<td>0.28%</td>
</tr>
<tr>
<td>Korean Reactors</td>
<td>0.3%</td>
</tr>
<tr>
<td>Other Reactors</td>
<td>0.35%</td>
</tr>
<tr>
<td>Neutrino Spectra</td>
<td>2.25%</td>
</tr>
<tr>
<td>Cross Section</td>
<td>0.2%</td>
</tr>
<tr>
<td><strong>Total Systematic Error</strong></td>
<td><strong>3.3%</strong></td>
</tr>
</tbody>
</table>

Overall Calibration has been done with Bugey-3 (15m) experiment.

\[
\frac{\sigma_f}{\sigma_{V-A}} = 98.7\% \pm 1.4\% \pm 2.7\% \quad (\text{Phys.Lett.B338}(1994)383)
\]
Systematic errors achieved by middle baseline experiments

**Palo Verde**

<table>
<thead>
<tr>
<th>systematic</th>
<th>Method 1 (%)</th>
<th>Method 2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e+ efficiency</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>n efficiency</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>$\bar{\nu}_e$ flux prediction</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>$\bar{\nu}_e$ selection cuts</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>$B_{pn}$ estimate</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>10</strong></td>
<td><strong>8</strong></td>
</tr>
</tbody>
</table>

**CHOOZ**

<table>
<thead>
<tr>
<th>parameter</th>
<th>relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>reaction cross section</td>
<td>1.9</td>
</tr>
<tr>
<td>number of protons</td>
<td>0.8</td>
</tr>
<tr>
<td>detection efficiency</td>
<td>1.5</td>
</tr>
<tr>
<td>reactor power</td>
<td>0.7</td>
</tr>
<tr>
<td>energy absorbed per fission</td>
<td>0.6</td>
</tr>
<tr>
<td><strong>combined</strong></td>
<td><strong>2.7%</strong></td>
</tr>
</tbody>
</table>

*KamLAND goal* 5% ?
Expected anti-electron neutrino event at Kamioka

- Reactor event rate
  - 980 ev/yr/kton

- Geo-neutrino rate
  - 50 ev/yr/kton

- Strong spectrum distortion at the LMA solution enables a precise parameter determination.
Brief History of KamLAND

1997 April  start KamLAND project
1998 April  dismantle Kamiokande
2000 April  complete stainless vessel
2000 September  finish PMT installation
2001 February  complete balloon deployment
2001 September  complete oil filling
2001 October  electronics arrival
2001 Nov 26  first muon event
2002 Jan 22  start data acquisition?
2002 Dec 6  first results .....  
2003 Jan 27  appear on PRL
KamLAND Schematics

Liquid Scintillator
- 20% PseudoCumene
- 80% dodecane
- 1.5g/l PPO
- 8,000 photons/MeV
- L = 10 m @ 400 nm
- $\rho_{LS}=0.780 \text{ g/cm}^3$

Buffer Oil
- 50% dodecane
- 50% isoparaffin
- $\rho_{LS}/\rho_{BO}=1.0004$

PMTs
- 1325 17" PMTs $\sigma \sim 1 \text{ nsec}$
- 22% coverage
- (554 20" PMTs $\sigma \sim 5 \text{ nsec}$)
- (34% coverage)

Energy Resolution
- $\sigma/E \sim 7.5%/\sqrt{E} \text{ (MeV)} \sim 320 \text{ p.e./MeV}$
- ($\sigma/E \sim 6%/\sqrt{E} \text{ (MeV)} \sim 500 \text{ p.e./MeV}$)

Vertex Resolution
- $\sigma \sim 25 \text{ cm} @ 1 \text{ MeV}$
Front End Electronics

Analog Transient Waveform Digitizer

dual x 3 gain x 10bits x 128depth

Hit out

Esum

threshold 0.5 mV
1/3 p.e.

5x10^6 gain

sliding capture window
with 1.556ns step and 1.556x4ns width

PMT signal

capture gate

128 x 3 analog buffer + fast ADC

A

ATWD

High gain

Middle gain

Low gain

B

ATWD

G1 G5 G2 G6 G3 G7 G4 G8
KamLAND Waveform Display
Run/Subrun/Event : 113/0/1499
UT: Sun Feb 24 15:49:19 2002
TimeStamp : 3146704014
TriggerType : 0xfffffa21 / 0xfffff0002
Time Difference 16.7 msec
NumHit : 1155
Channel : 1110 AH(13) AM(13) AL(13)
Multi Photon Analysis

KamLAND Waveform Display
Run/Subrun/Event : 113/0/304
UT: Sun Feb 24 15:49:05 2002
TimeStamp : 2578169707
TriggerType : 0x3a10 / 0x2
Time Difference 64.5 sec
NumHit : 1124
Channel : 3 BH(11)

leading edges
found pulses
Trigger scheme

Digital # of hits information are acquired from all individual boards.
FPGA issues a trigger based on # of hits.
Very complex trigger criteria can be set in principle.

Current trigger condition

Prompt : Nhit >200 (~0.7MeV)
Delayed: Nhit >120 (~0.4MeV) for 1 msec after prompt

<table>
<thead>
<tr>
<th>Trigger rate</th>
<th>~25 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data size</td>
<td>~400GB/day (online format)</td>
</tr>
<tr>
<td></td>
<td>~150GB/day (off line format)</td>
</tr>
<tr>
<td></td>
<td>~10GB/day (waveform analysis)</td>
</tr>
</tbody>
</table>

Trigger threshold is limited by the data size, but it is sufficiently low for the reactor neutrino observation.
Typical Penetrating Muon

KamLAND Event Display
Run/Subrun/Event : 110/0/19067
UT: Sat Feb 23 15:10:54 2002
TimeStamp : 3416793063
TriggerType : 0x7210 / 0x2
Time Difference 10.1 msec
NumHit/Num/Num2/NumHitA : 1315/199/1327/77
Total Charge : 9.02e+05 (1.17e+03)
Max Charge (ch) : 3.54e+03 (210)
Cherenkov Ring from Clipping Muon

KanLAND Event Display
Run/Subrun/Event : 110/0/3772
UT: Sat Feb 23 15:17:50 2002
TimeStamp : 4363651980
TriggerType : 0x3210 / 0x2
Time Difference 4.13 msec
NumHit/Num/Num2/NumHitA : 468/177/427/45
Total Charge : 3.05e+03 (471)
Max Charge (ch): 882 (46)
Chi2 / ndf = 107 / 56
const. = 766 ± 4.975
N0 = 6.506e+04 ± 392.9
capture time = 212.3 ± 0.7455
Spallation B12/N12 Distribution

Balloon Radius

Fiducial

Spallation B12/N12 $R^3$ Distribution

Events/bin

Balloon Radius

Fiducial

$+0.16 \pm 3.34\% \rightarrow \pm 3.5\%$
Achieved Systematic Errors

<table>
<thead>
<tr>
<th>Category</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS total mass</td>
<td>2.13%</td>
</tr>
<tr>
<td>Fiducial/Total</td>
<td>4.06%</td>
</tr>
<tr>
<td>Energy Threshold</td>
<td>2.13%</td>
</tr>
<tr>
<td>Reactor Power</td>
<td>2.05%</td>
</tr>
<tr>
<td>Fuel Composition</td>
<td>1.0%</td>
</tr>
<tr>
<td>Time Lag</td>
<td>0.28%</td>
</tr>
<tr>
<td>Neutrino Spectra</td>
<td>2.48%</td>
</tr>
<tr>
<td>Cross Section</td>
<td>0.2%</td>
</tr>
<tr>
<td>Live Time</td>
<td>0.07%</td>
</tr>
<tr>
<td>Delayed Tag</td>
<td>2.06%</td>
</tr>
</tbody>
</table>

Total Error: 6.42%

1171 ± 25 m$^3$
Requirements for Radioactive Impurities

* Reactor Neutrino
  LS: $^{238}\text{U}/^{232}\text{Th}/^{40}\text{K}/^{222}\text{Rn}$  
  BO: $^{232}\text{Th}$  
  $10^{-15}, 10^{-13}, 10^{-14}$ g/g, $1\text{mBq/m}^3$  
  $10^{-12}$ g/g

* Geo-neutrino
  LS: $^{238}\text{U}/^{232}\text{Th}/^{40}\text{K}/^{222}\text{Rn}$  
  BO: $^{238}\text{U}/^{232}\text{Th}/^{40}\text{K}/^{222}\text{Rn}$  
  $10^{-14}, 10^{-15}, 10^{-15}$ g/g, $100\text{mBq/m}^3$  
  $10^{-13}, 10^{-13}, 10^{-14}$ g/g, $1\text{mBq/m}^3$

* Solar $^7\text{Be}$ neutrino
  Day/Night
  LS: $^{238}\text{U}/^{232}\text{Th}/^{40}\text{K}/^{222}\text{Rn}$  
  BO: $^{238}\text{U}/^{232}\text{Th}/^{40}\text{K}/^{222}\text{Rn}$  
  $10^{-15}, 10^{-15}, 10^{-17}$ g/g, $100\text{mBq/m}^3$  
  $10^{-13}, 10^{-13}, 10^{-15}$ g/g, $1\text{mBq/m}^3$

Others
  LS: $^{238}\text{U}/^{232}\text{Th}/^{40}\text{K}/^{222}\text{Rn}$  
  BO: $^{238}\text{U}/^{232}\text{Th}/^{40}\text{K}/^{222}\text{Rn}$  
  $10^{-16}, 10^{-16}, 10^{-18}$ g/g, $10\text{mBq/m}^3$  
  $10^{-14}, 10^{-14}, 10^{-16}$ g/g, $100\text{mBq/m}^3$

Acceptable mine dust  
  100mg (LS), 10g (BO)
$^{214}\text{Bi} \quad \beta^+ \quad T_{1/2} = 7.687\text{MeV} \quad T = 237\text{ms}$

$^{214}\text{Po}$

$\Delta T = 223 \pm 7\text{ µsec}$
$^{212}$Bi $\rightarrow ^{212}$Po $\beta^{-} E_{\beta} = 5.789$ MeV $\tau = 0.431$ ms

$^{212}$Po $\beta^{-}$

$426 \pm 18$ nsec
## Impurities in the LS

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Activity</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{222}\text{Rn}$</td>
<td>$0.03 \mu\text{Bq/m}^3$</td>
<td>$^{214}\text{Bi} \rightarrow ^{214}\text{Po} (\tau = 237 \mu\text{sec})$</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>$(3.5 \pm 0.5) \times 10^{-18} \text{ g/g}$</td>
<td>$^{214}\text{Bi} \rightarrow ^{214}\text{Po} (\tau = 237 \mu\text{sec})$</td>
</tr>
<tr>
<td>$^{232}\text{Th}$</td>
<td>$(5.2 \pm 0.8) \times 10^{-17} \text{ g/g}$</td>
<td>$^{212}\text{Bi} \rightarrow ^{212}\text{Po} (\tau = 0.431 \mu\text{sec})$</td>
</tr>
<tr>
<td>$^{40}\text{K}$</td>
<td>$&lt; 2.7 \times 10^{-16} \text{ g/g}$</td>
<td>single rate</td>
</tr>
<tr>
<td>$^{85}\text{Kr}$</td>
<td>$\sim 1 \text{Bq/m}^3$</td>
<td>single rate/delayed coincidence</td>
</tr>
<tr>
<td>$^{210}\text{Po}$</td>
<td>$\sim 100 \text{mBq/m}^3$</td>
<td>single rate</td>
</tr>
</tbody>
</table>

## Impurities on the balloon

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Activity</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{222}\text{Rn}$</td>
<td>$4.0 \times 10^{-4} \text{Bq}$</td>
<td>$^{214}\text{Bi} \rightarrow ^{214}\text{Po} (\tau = 237 \mu\text{sec})$</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>$3.1 \times 10^{-8} \text{g}$</td>
<td>$^{214}\text{Bi} \rightarrow ^{214}\text{Po} (\tau = 237 \mu\text{sec})$</td>
</tr>
<tr>
<td>$^{232}\text{Th}$</td>
<td>$9.7 \times 10^{-4} \text{Bq}$</td>
<td>$^{212}\text{Bi} \rightarrow ^{212}\text{Po} (\tau = 0.431 \mu\text{sec})$</td>
</tr>
</tbody>
</table>

Reactors: $10^{-13} \text{g/g}$ for reactor, $10^{-16} \text{g/g}$ for solar.

Solar: $10^{-13} \text{g/g}$ for reactor, $10^{-16} \text{g/g}$ for solar, $1 \mu\text{Bq/m}^3$ for impurities on the balloon.
Accidental Background
off time (10 ms ~ 20 sec)

1.81 ± 0.08
at E ≥ 0.9 MeV
0.0086 ± 0.0005
at E ≥ 2.6 MeV
Capture Time
= 195 ± 39 μsec

Fast Neutron

Fiducial 5m
< 0.17 (OD muon)
< 0.33 (rock)

Total < 0.5
# Spallation

<table>
<thead>
<tr>
<th></th>
<th>T1/2</th>
<th>decay</th>
<th>Hagner et al.</th>
<th>measured at KamLAND</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>expected rate</td>
<td>/day/kton</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11C</td>
<td>20.38min</td>
<td>0.96 β⁺</td>
<td>1039±106</td>
<td></td>
</tr>
<tr>
<td>10C</td>
<td>19.26s</td>
<td>1.9 β⁺, 0.72 γ</td>
<td>139±15</td>
<td></td>
</tr>
<tr>
<td>total neutron</td>
<td></td>
<td></td>
<td>1317±195.6</td>
<td>1157.6±7(stat)</td>
</tr>
<tr>
<td>8He/9Li</td>
<td>0.12/0.18s</td>
<td>10.6/13.6 β⁻</td>
<td>2.4±0.5</td>
<td>4.7±1.3</td>
</tr>
<tr>
<td>7Be</td>
<td>53.3d</td>
<td>0.478 γ (10%)</td>
<td>21.4±2.9</td>
<td></td>
</tr>
<tr>
<td>11Be</td>
<td>13.80s</td>
<td>11.5 β⁻</td>
<td>&lt;2.4</td>
<td></td>
</tr>
<tr>
<td>8Li</td>
<td>0.84s</td>
<td>16.0 β⁻</td>
<td>5.0±2.9</td>
<td></td>
</tr>
<tr>
<td>6He</td>
<td>0.81s</td>
<td>3.5 β⁻</td>
<td>18.9±2.1</td>
<td></td>
</tr>
<tr>
<td>8B</td>
<td>0.77s</td>
<td>13.7 β⁺</td>
<td>7.9±1.4</td>
<td></td>
</tr>
<tr>
<td>9C</td>
<td>0.13s</td>
<td>16.0 β⁺</td>
<td>5.5±1.8</td>
<td></td>
</tr>
</tbody>
</table>

**Backgrounds to be carefully rejected**

\[ ^8\text{He} \rightarrow ^8\text{Li} + \beta^- \quad (84\%) \]
\[ ^7\text{Li} + \beta^- + n \quad (16\%) \]
\[ ^9\text{Li} \rightarrow ^9\text{Be} + \beta^- \quad (50\%) \]
\[ ^8\text{Be} + \beta^- + n \quad (50\%) \]
$dQ \geq 10^6 \text{ p.e.}$

~0.02 by spallation cut
(totals ~ 55)

$dQ < 10^6 \text{ p.e., } L < 300 \text{ cm}$

~0.007 by spallation 2sec cut
(totals : $16 \pm 14$)
Muon Track Efficiency

$\mu + ^{12}\text{C} \rightarrow n + \text{Nuclei}$

$L < 300\text{cm} \ 93.6\%$

$dQ < 10^6\text{p.e.}$

$dQ < 10^6\text{p.e.}, L > 300\text{cm}$

$1.1 \pm 1.0 \text{ at } E \geq 0.9\text{MeV}$

$0.94 \pm 0.85 \text{ at } E \geq 2.6\text{MeV}$

by tracking efficiency 93.6$\%$
Event Selection

(1) Fiducial Cut  
   radius < 5m, 3.46e31 free protons

(2) timing correlation  
   0.5<\text{dt}<660\mu\text{sec}, \tau=212\mu\text{sec}

(3) vertex correlation  
   dr<1.6m

(4) delayed energy  
   1.8<E<2.6\text{MeV}

(5) thermometer cut  
   r>1.2m
   detection efficiency 78.3%

(6) spallation cut  
   t<2\text{sec}, dQ>10^6\text{p.e.}
   t<2\text{sec}, dr<3\text{m}, dQ<10^6\text{p.e.}
   dead time = 11.4%

(7) energy threshold  
   E_{\text{vis}}>2.6\text{MeV}

Expected Signal Rate  
   0.60 \text{ ev/day}
Data Summary from March 4 through October 6, 2002 (145.1 live days)

Eprompt > 2.6 MeV

Expected neutrino: $86.8 \pm 5.6$
Expected BG: $0.95 \pm 0.99$
Observed: 54

$R = 0.611 \pm 0.085 \text{(stat)} \pm 0.041 \text{(syst)}$
99.95% CL. disappearance

Eprompt > 0.9 MeV

Expected neutrino: $124.8 \pm 7.5$
Expected BG: $2.91 \pm 1.12$ (+ ~9 geo–nu)
Observed: 85

$R = 0.586$
Rate + Shape Analysis

Eprompt $>2.6$ MeV

Best fit $@ (\sin^2 2\theta, \Delta m^2) = (1.0, 6.9 e^{-5} eV^2)$

Two bands overlap with the LMA solution.

Preference to the maximal mixing is not strong.

Eprompt $>0.9$ MeV

Best fit $@ (\sin^2 2\theta, \Delta m^2) = (0.91, 6.9 e^{-5} eV^2)$

Geo-nu's are treated as free parameters.

No significant statistical contribution from low energy.

Contours are quite consistent with 2.6 MeV analysis.

Nothing funny in the low energy region.
Geo-neutrinos ??

A model

- crust: U 1.8 ppm
- mantle: U 0.01 ppm
- Th/U: 3.6

16 TW heat flow
~9 events in our data

Best fit with 0.9 MeV rate + shape analysis (0.91, 6.9e-5)

- U: 4 events
- Th: 5 events

~40 TW consistent with 16 TW at 1 sigma
0~110 TW at 95% C.L.

No meaningful sensitivity yet but hinted?
Geo-neutrino

The graph shows the distribution of neutrino events per MeV per kiloton per year as a function of visible energy (MeV) and distance (km). The processes involving thorium and uranium are depicted separately.

- **Thorium**
  - Peak energy: 1.5 MeV
  - Distance: 2 km

- **Uranium**
  - Peak energy: 2.5 MeV
  - Distance: 3 km

The integrated event rate is shown for different depths, with crust and mantle layers indicated.

- **Crust**
  - Event rate: 40 events per 1000 ton/year

- **Mantle**
  - Event rate: 10 events per 1000 ton/year
\[ E_{\text{th}} = 2.6 \text{MeV} \]

\[ E_{\text{th}} = 0.9 \text{MeV} \]
Parameter Determination

Precise $\Delta m^2$ will be provided by KamLAND. But, a precise solar pp-neutrino measurement looks to be important for the mixing angle determination.
Summary

KamLAND observed evidence of neutrino disappearance at 99.95% CL.
(54 observed, 86.8±5.6 expected, 0.95±0.99 BG)

\[ R = 0.611 ± 0.085 \text{(stat)} ± 0.041 \text{(syst)} \]

All oscillation solutions but the LMA solution for the solar neutrino problem are excluded. On the other hand, a terrestrial experiment with man–made neutrino source finally confirmed the solar neutrino problem and verified the solution.

Geo–neutrino indication is seen. More statistics will give total earth radio–heating.

Opening of "Neutrino Geophysics"

KamLAND gets into a precision measurement of oscillation parameters. One more year data may drastically improve the allowed range of \( \Delta m^2 \).

Stay in Tune!