Reactor Based Neutrino Oscillations

Patrick Decowski
UC Berkeley
Few MeV anti-neutrinos: Energy too low to produce $\mu$ or $\tau$
$\rightarrow$ disappearance experiments
Oscillation Searches with Reactors

Reactors have played an important role in early history of neutrinos and in $\nu$ oscillation search: 1953 - Present

Poltergeist
(Reines & Cowan 1955)

- Many different experiments
  - Baselines up to 1km
  - No evidence for $\bar{\nu}$ disappearance

$N_{\text{obs}} / N_{\text{no-osc}}$ vs Distance (m)
The stable products most likely from Uranium fission:

\[ ^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n \]

Together 98 protons and 136 neutrons

6 neutrons have to $\beta$-decay to reach stable matter: \( 6\bar{\nu}_e / \text{fission} \)
99.9% of $\overline{\nu}_e$ produced by just 4 fission elements

- Provided by Reactor companies
  - Chiefly function of thermal power
  - Weak function of water inlet T: 10% error $\rightarrow \sim 0.15\%$ rate change
Detected Reactor Spectrum

1.8MeV threshold in inverse beta decay

In practice only 1.5 neutrinos/fission detected
Reactor spectra

- Reactor anti-neutrino spectra measured at short baseline:
  - Gösgen (1986)
  - Bugey (1995)

Agreement of measured with expected: ~2%

- No near detector necessary!
Suppression of Spectrum

Neutrino oscillations change both overall normalization ('rate') and shape
Anti-Neutrino Detection Method

Reaction Process: inverse $\beta$-decay

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

Scintillator is target and detector

- Distinct two-step signature:
  - prompt event: positron
    \[ E_\nu \approx E_{e^+} + 0.8 \text{ MeV} \]
  - delayed event: neutron capture after $\sim 210\mu s$
    - 2.2 MeV gamma

Delayed coincidence: good background rejection
Chooz and Palo Verde didn't see evidence for neutrino oscillations involving $\bar{\nu}_e$ down to $10^{-3}$ eV$^2$

Atmospheric neutrino oscillations are mainly $\nu_\mu - \nu_\tau$
## Reactor and Accelerators Complementary

### Terrestrial Neutrinos:

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Accelerator</th>
</tr>
</thead>
<tbody>
<tr>
<td>E $\sim$ few MeV</td>
<td>E $\sim$ few GeV</td>
</tr>
<tr>
<td>- Can probe small $\Delta m^2$</td>
<td>- Good mass sensitivity requires large $L$</td>
</tr>
<tr>
<td>- Disappearance only: weak sensitivity to $\sin^2 2\theta$</td>
<td>- Appearance possible, strong sensitivity to $\sin^2 2\theta$</td>
</tr>
<tr>
<td>- Isotropic neutrino emission, detector has to scale with $L^2$</td>
<td>- 'Collimated' beam</td>
</tr>
</tbody>
</table>

### Diagram:

- [Graph showing neutrino oscillation data]

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M.P. Decowski / UCB
The KamLAND Collaboration


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80 Members from 12 Institutions

M.P. Decowski / UCB
KamLAND uses the entire Japanese nuclear power industry as a long-baseline source.

80% of flux from baselines 140-210 km
KamLAND Detector

- 1 kton Scintillation Detector
  - 6.5m radius balloon filled with:
    - 20% pseudocumene (scint)
    - 80% dodecane (oil)
  - 2.5m buffer region filled with oil
- 34% PMT coverage
  - ~1300 17” fast PMTs
  - ~550 20” large PMTs
- Multi-hit, deadtime-less electronics
- Water Cerenkov veto counter
Building the Steel Sphere
Event Display

Through going muon

The low-energy anti-neutrino events are far less spectacular!
Position Reconstruction

Position resolution ~ 25 cm.
Vertex reconstruction based on photon arrival times.

\begin{itemize}
\item $^{68}\text{Ge}$ : 1.012 MeV ($\gamma + \gamma$)
\item $^{65}\text{Zn}$ : 1.116 MeV ($\gamma$)
\item $^{60}\text{Co}$ : 2.506 MeV ($\gamma + \gamma$)
\item AmBe : 2.20, 4.40, 7.6 MeV ($\gamma$)
\end{itemize}
Energy Calibration

\[ \Delta E/E \sim 7.5\% / \sqrt{E} \]
\[ \Delta E_{\text{syst}} = 2.1\% \text{ for positrons} \]

Energy varies by < 0.5\% over the fiducial volume
Trigger Efficiency

Prompt Trigger: 200 PMT hits (~0.7MeV)

Delayed Trigger: 120 hits for 1msec after prompt trigger
Anti-neutrinos are also produced in the earth's crust from U/Th decays

\[ E_{\nu(geo)} < 2.49 \text{ MeV} \]

\[ E_{\text{prompt}} > 2.6 \text{ MeV} \text{ avoids the geo neutrino background} \]
Muon rate is ~0.3 Hz, muons can produce neutrons and radioactive isotopes.

Yellow: After muon in 150µs-10ms
Red: apply ΔL< 3m cut

np-capture(2.22MeV)
nC-capture(4.95MeV)

N12, B12

Visible energy [MeV]
Backgrounds

• Significant reduction of backgrounds due to:
  – Delayed coincidence
  – 5m fiducial volume cut
  – Analysis prompt energy threshold
  – Muon veto and cuts around muon tracks

• Remaining backgrounds mainly due to spallation products

<table>
<thead>
<tr>
<th>Source</th>
<th>#ev in dataset</th>
</tr>
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<tbody>
<tr>
<td>accidental</td>
<td>0.0086±0.0005</td>
</tr>
<tr>
<td>$^9\text{Li}/^8\text{He}$ ($\beta,n$)</td>
<td>0.94±0.99</td>
</tr>
<tr>
<td>fast neutron</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>Total Background</td>
<td>0.95±0.99 ev</td>
</tr>
</tbody>
</table>
Fiducial Volume

\[ \Delta V_{\text{fid}} / V_{\text{fid}} = 4.6\% \]

408 ton out of 1125 ton
$\bar{\nu}_e$ Event Selection

- Inverse $\beta$ - decay selection
  - $E_{\text{prompt}} > 2.6$ MeV
  - $0.5 < \Delta T < 660$ $\mu$ sec
  - $\Delta R < 1.6$ m
  - $1.8 < E_{\text{delay}} < 2.6$ MeV

- Spallation event cut
  - $\Delta T_\mu < 2$ sec, $\Delta E_\mu > 3$ GeV or $\Delta R_\mu < 3$ m

- Fiducial selection
  - $R < 5$ m: 408 ton $\rightarrow$ $3.46 \times 10^{31}$ free protons

- Tagging efficiency: 78.3%

- $^8$He, $^9$Li: 11.4% dead time

Data Sample: Mar. 4 - Oct. 6, 2002
$\rightarrow$ 162 ton$\cdot$yr (145.1 live days)
Prompt and delayed energies after applying all cuts, except for the delayed energy cut.

\[ \gamma \text{ from } n + ^{12}\text{C} \] (0.5% prob)
## Systematic Uncertainties

For analysis threshold of $E > 2.6$ MeV:

<table>
<thead>
<tr>
<th></th>
<th>%</th>
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<tr>
<td>Total LS mass</td>
<td>2.1</td>
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<td>Fiducial mass ratio</td>
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<tr>
<td>Energy threshold</td>
<td>2.1</td>
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<tr>
<td>Efficiency of cuts</td>
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<tr>
<td>Live time</td>
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<tr>
<td>Reactor power</td>
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<td>Fuel composition</td>
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<tr>
<td>Time lag</td>
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<tr>
<td>$\bar{\nu}_e$ spectra</td>
<td>2.5</td>
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<tr>
<td>$\bar{\nu}_e$ cross section</td>
<td>0.2</td>
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</tbody>
</table>

Tot. Syst. uncertainty: 6.4 %
### Observed Number of Events

#### “Rate” Analysis:

<table>
<thead>
<tr>
<th>Final sample:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{e^+} &gt; 2.6\text{MeV}$</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>No-osc Expected</th>
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<tbody>
<tr>
<td>$86.8 \pm 5.6 \text{ ev}$</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.95 \pm 0.99 \text{ ev}$</td>
</tr>
</tbody>
</table>

$$\frac{N_{\text{obs}} - N_{\text{BG}}}{N_{\text{no-osc}}} = 0.611 \pm 0.085 \text{ (stat)} \pm 0.041 \text{ (syst)}$$

Inconsistent with $1/R^2$ flux dependence at 99.95% CL
Ratio of Measured to Expected Flux

Comparing to mixing parameters from global fit of all solar data (pre KamLAND)

LMA:
\[ \Delta m^2 = 5.5 \times 10^{-5} \text{ eV}^2 \]
\[ \sin^2 2\theta = 0.833 \]

Fogli et al., PRD 66 (2002)
Data prefers spectrum deformation at 93% CL

Data and (scaled) no-oscillation compatible at 53% CL
Neutrino Oscillations

Best fit:
\[ \Delta m^2 = 6.9 \times 10^{-5} \text{ eV}^2 \]
\[ \sin^2 2\theta = 1.0 \]

95% C.L.

\( E_{\text{prompt}} > 2.6 \text{ MeV} \)
Geo Neutrinos

40TW radiogenic heat model

Going down in spectrum to 0.9MeV and treat geo fluxes as free parameters:
- 4 events from U decay
- 5 events from Th decay
LMA is the solution

Assuming CPT invariance: Only LMA region left; SMA, LOW, VAC solutions excluded...
Global Analysis

LMA split into two regions...

G. Fogli et al. hep-ph/0212127
Which LMA solution is it?

LMA-1

LMA-2
Thermal Power Distribution

Thermal Power Flux (W/cm$^2$)

Survival $E_{vis} > 2.6$MeV

LMA parameters: (0.84, 1.4e-4), (0.84, 7e-5), (0.84, 3e-5)

80% of Total Contribution

M.P. Decowski / UCB
Safety Problems at Japanese Reactors Begin to Erode Public's Faith in Nuclear Power

By HOWARD W. FRENCH (NYT) 1320 words

TOKYO, Sept. 15 -- The reports of safety lapses, fraudulent repairs and cover-ups at Japan's largest nuclear power company began with a trickle but have resounded into an industry nightmare.

Reactor flux is temporarily ~50% of maximum
Rate vs flux measurement, study backgrounds
### Operating Records of Nuclear Power Plants in May

<table>
<thead>
<tr>
<th>Power Plant</th>
<th>Reactor Type</th>
<th>Gross Capacity (MWe)</th>
<th>Availability Factor</th>
<th>Capacity Factor</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Operating hours [h]</td>
<td>[%]</td>
<td>Generated output [MWh]</td>
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<tr>
<td>Tokai-Daini (II)</td>
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<td>744</td>
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<tr>
<td>Tsuruga-3</td>
<td>PWR</td>
<td>870</td>
<td>744</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Remarks:
- Shutdown due to periodic inspection (25. Apr.–) for Tokai-Daini (II)
- Shutdown due to periodic inspection (8. Sep. 2002–) for Tsuruga-1
- Shutdown due to periodic inspection (22. May–) for Tomari-1
- Shutdown due to periodic inspection (31. Mar.–) for Fukushima I-1
- Shutdown due to periodic inspection (2. Dec. 2002–) for Fukushima II-1
- Shutdown due to periodic inspection (11. Nov.–) for Kashiwazaki Kariwa-1
- Planned shutdown (15. Apr.–) for Fukushima II-2
- Shutdown due to periodic inspection (7. Jan.–) for Hamaoka-1
- Shutdown due to periodic inspection (14. Apr.–) for Shika-1
- Shutdown due to periodic inspection (10. Dec. 2002–) for Mihama-1
- Shutdown due to periodic inspection (1. Feb.–) for Takahama-1
- Shutdown due to periodic inspection (3. Sep. 2002–) for Mihama-2
- Shutdown due to periodic inspection (10. Mar.–) for Takahama-2
- Shutdown due to periodic inspection (10. Aug. 2002–) for Takahama-3
- Shutdown due to periodic inspection (7. Jan.–) for Tsuruga-3
- Shutdown due to periodic inspection (1. Mar.–) for Fukushima II-3
- Shutdown due to periodic inspection (27. Jan.–9. May) for Kashiwazaki Kariwa-6
- Planned shutdown (29. Mar.–) for Mihama-3
- Shutdown due to periodic inspection (26. Apr. 2002–) for Hamaoka-2
- Shutdown due to periodic inspection (20. Feb.–) for Shika-1
- Shutdown due to periodic inspection (4. Sep. 2002–) for Shika-1

37% of total Capacity!
Average Baseline

Weighted mean of distance from each reactor to KamLAND used thermal power flux

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

**Phase I:**

Reactor anti-neutrinos:

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

\(E_{\text{thr}} = 1.8\text{MeV}\)

**Phase II:**

\(^7\text{Be} \) Solar neutrinos:

\[ \nu_e + e^- \rightarrow \nu_e + e^- \]

\(E_{\text{thr}} = 200\text{keV}\)
## Liquid Scintillator Impurities

<table>
<thead>
<tr>
<th>Compound</th>
<th>Reactor Requirement</th>
<th>Solar Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{222}$Rn</td>
<td>0.03 µB/m$^3$</td>
<td>$^{214}$Bi-$^{214}$Po (237 µs)</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>$(3.5 \pm 0.5) \times 10^{-17}$ g/g</td>
<td>$10^{-13}$ g/g</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>$(5.2 \pm 0.8) \times 10^{-18}$ g/g</td>
<td>$10^{-13}$ g/g</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>$&lt; 2.7 \times 10^{-16}$ g/g</td>
<td>$10^{-14}$ g/g</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>~1 Bq/m$^3$</td>
<td>singles rate / delayed coincidence</td>
</tr>
<tr>
<td>$^{210}$Pb</td>
<td>~100 mBq/m$^3$</td>
<td>singles rate</td>
</tr>
</tbody>
</table>

Requirement

For Solar Phase, need O(6) improvement in purification
$\theta_{13}$ Experiments

MNS Matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric, K2K  Reactor, Accelerator  Solar, KamLAND

$\theta_{23} \sim 45^\circ$  \hspace{2cm} $\theta_{13} < 10^\circ$  \hspace{2cm} $\theta_{12} \sim 30^\circ$

Look for subdominant oscillation, need <1% accuracy → 2 detector solution

K.M.Heeger this afternoon
Conclusions

- Completes 50 years of reactor neutrino studies
- Strong evidence for $\bar{\nu}_e$ disappearance over a 100 km scale
- Solar neutrino oscillation confirmed by KamLAND using completely independent source of neutrinos and technique
- LMA is the solution to the solar neutrino problem
  - Global analysis splits LMA into 2
- Neutrino oscillation now seen from 4 different sources:
  - Solar (SNO, Homestake, ...)
  - Atmospheric (SuperK)
  - Accelerator (K2K)
  - Reactor (KamLAND)