Precision Measurement of Neutrino Oscillation Parameters with KamLAND

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Overview

- **History:**
  - Neutrinos and the Solar Neutrino Problem

- **KamLAND:**
  - Previous Results
  - Recent Improvements
  - Future Prospects
History of Missing Neutrinos

1933: Fermi develops theory of beta-decay, names the 'neutrino'.

1930: Pauli proposes neutral fermion.

1953 - 1959: Reines and Cowan detect neutrinos from nuclear reactors.

1968: Davis detects 1/3 expected Solar neutrinos.
What's wrong with the Sun?

Solar experiments continue to show deficit.

**Chlorine:**
- Homestake

**Gallium:**
- Sage
- Gallex/GNO

**Water-Cherenkov:**
- Kamiokande
- Super-K: $0.41 \pm 0.04$

SNO shows evidence for flavor-change!
Neutrino Oscillation

Neutrinos change character based on perspective!

Interaction eigenstates ≠ Mass eigenstates

\[ |\nu_e\rangle = \sum_{m_i} U_{ei}^* |\nu_i\rangle \]

Pontecorvo (1957): \n / anti-oscillation

Maki, Nakagawa, and Sakata (1962): Flavor oscillation

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{12}) \sin^2 \frac{\Delta m_{12}^2 L}{4E} \]

\[ \Delta m_{12}^2 = m_1^2 - m_2^2 \]

\[ \theta_{12} \text{ mixing angle} \]

\[ L \text{ is distance from source} \]

\[ E \text{ is neutrino energy} \]
What about Reactor neutrinos?

- Probe the Solar Neutrino Oscillation with Reactor Neutrinos
  - Need long baseline:

\[
L \sim L_{osc} \sim \frac{E(\text{MeV})}{\Delta m_{solar}^2 (\text{eV}^2)} \sim 100 \text{ km}
\]

<table>
<thead>
<tr>
<th>Solar experiments</th>
<th>Reactor experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrinos: $\nu_e$</td>
<td>Anti-neutrinos: $\bar{\nu}_e$</td>
</tr>
<tr>
<td>Distance: 1.5 x 10^8 km</td>
<td>Up to 100s km</td>
</tr>
<tr>
<td>Propagation: $\nu$'s travel through dense matter</td>
<td>Very little matter</td>
</tr>
<tr>
<td>Model prediction: Solar model</td>
<td>Reactor model</td>
</tr>
</tbody>
</table>
Reactor Neutrinos

Reaction Process: inverse $\beta$-decay

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

Threshold: 1.8 MeV

$$E_{e^+} \approx E_\nu - 0.8 \text{ MeV}$$
Oscillation Searches at Reactors

\[ E \approx 1 \text{ MeV}, \quad L_{\text{max}} \approx 1 \text{ km}, \quad \text{Sensitivity } \Delta m^2 \Rightarrow 10^{-3} \text{ eV}^2 \]

Measured spectra within \( \approx 2\% \) of expected

Signal rate falls \( 1/ L^2 \)
Surrounded by Reactors

~12% of global nuclear power

Nuclear Power Stations in Japan

86% of $\nu$ events from ~180 km

Kamioka
KamLAND Collaboration

- **University of Alabama**: J.Busenitz, T.Classen, C.Grant, G.Keefer, D. Leonard, D.McKee, A.Piepke
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- **TUNL**: H.J.Karwowski, D.Markoff, W.Tornow
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- **University of Tennessee**: W.Bugg, Y.Efremenko, Y.Kamyshkov, O.Perevozchikov
- **CEN Bordeaux-Gradignan**: F.Piquemal, J.-S.Ricol
KamLAND Detector

- 1 kton Scintillation Detector
  - 6.5m radius balloon filled with:
    - 20% pseudocumene (scint)
    - 80% dodecane (oil)
    - 1.5 g/L PPO (wavelength shifter)
  - 2.5m buffer region filled with oil
- 34% PMT coverage
  - 1325 17” fast PMTs
  - 554 20” large PMTs
- Water Cherenkov veto counter
Detector Construction
A View from the Inside
Needle in the Haystack

Trigger Rate: \(~50\) Hz

Radioactive Backgrounds: \(~10^6 / \text{day}\)

Cosmic Rays: \(~20000 / \text{day}\)

Reactor Neutrinos: \(~1 / \text{day}\)
Anti-neutrino Detection Method

Reaction Process: inverse $\beta$-decay

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

$$n + p \rightarrow d + \gamma$$

Look for the neutron!
Second event delayed by $\sim 200$ µs.

Delayed coincidence: good background rejection
Calibration / Reconstruction

- Not Just a Calorimeter!
- Event Reconstruction
  - Position -> Use Relative PMT Firing Times
  - Energy -> Use PMT Charges, corrected for position
  - Verify with calibration sources

\[ \sigma = 7\% / \sqrt{E} \]
Imaging the Detector

High singles rate at neck and bottom (stainless steel)

Singles mostly at balloon boundary (Radioactive backgrounds and external gammas)
Backgrounds: Accidentals

Two singles accidentally mimic delayed-coincidence

Reduce accidental rate:

\[ R_p, R_d < 5.5 \text{ m} \quad \Delta R < 2 \text{ m} \quad \Delta T < 1 \text{ ms} \]

\[ 2.6 < E_p < 8.5 \text{ MeV} \quad 1.8 < E_d < 2.6 \text{ MeV} \]
Cosmic rays are easy to veto, but muon spallation creates radioactivity throughout the detector.
Spallation

- Muon Rate: \(~0.32\) Hz
- High Rate / Short Lifetime:
  - Free n (\(t_c=209\) us)
  - \(^{12}\)B (\(t_{1/2}=20.2\) ms), \(^{12}\)N (\(t_{1/2}=11.0\) ms)
- \(\beta\)-\(\alpha\) decay: Also emits neutron!
  - \(^{9}\)Li (\(t_{1/2}=178.3\) ms)
  - \(^{8}\)He (\(t_{1/2}=119.0\) ms)
Spallation Light

All muons

Extra light from spallation is visible.

Veto detector for 2s after 'spallation muon'

pre-$^{12}$B

pre-$^{9}$Li
Muon Reconstruction

- **Problem:** Check Muon Fitter?
- **Tests:**
  - Use MUSIC simulation
  - Compare with spallation
Backgrounds: $^{13}\text{C}(\alpha,n)$

High energy $\alpha$ can produce a delayed-coincidence.

$^{210}\text{Po} \rightarrow ^{206}\text{Pb} + \alpha(5.3 \text{ MeV})$

$\sim 1 \text{ in } 10^7! \rightarrow \alpha + ^{13}\text{C} \rightarrow n + ^{16}\text{O}$

$n,p$ scatters

$^{12}\text{C}(n,n)^{12}\text{C}^*(4.4 \text{ MeV}) \rightarrow \gamma$

$\rightarrow n + ^{16}\text{O}^*(6.0 \text{ MeV}) \rightarrow e^+ + e^-$

$\rightarrow n + ^{16}\text{O}^*(6.1 \text{ MeV}) \rightarrow \gamma$

Estimated spectrum
Systematics and Efficiency

Efficiency:
- Delayed-Coincidence: 0.90
- Muon Veto: 0.90

Systematics:

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial Volume</td>
<td>4.7</td>
</tr>
<tr>
<td>Reactor power</td>
<td>2.1</td>
</tr>
<tr>
<td>Energy threshold</td>
<td>2.3</td>
</tr>
<tr>
<td>Fuel composition</td>
<td>1.0</td>
</tr>
<tr>
<td>Efficiency of cuts</td>
<td>1.6</td>
</tr>
<tr>
<td>$\bar{\nu}_e$ spectra [5]</td>
<td>2.5</td>
</tr>
<tr>
<td>Livetime</td>
<td>0.06</td>
</tr>
<tr>
<td>Cross section [7]</td>
<td>0.2</td>
</tr>
<tr>
<td>Total systematic error</td>
<td>6.5</td>
</tr>
</tbody>
</table>
Past Results

![Graph showing past results of particle production](image-url)
Oscillation Signature

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{12}) \sin^2 \frac{\Delta m_{12}^2 L}{4E} \]

Single source oscillation in L/E

Distortion from multiple sources
KamLAND Results

Signature of Neutrino Oscillation

\[ \Delta m^2 = 8.3 \times 10^{-5} \text{ eV}^2 \quad \text{and} \quad \tan^2 \theta = 0.41 \]
Recent Improvements

- Increase statistics
- Reduce Volume Uncertainty
- Characterize ($\alpha,n$) Background
- Reduce Energy Threshold / Optimize Cuts
Improvement: Statistics

period for "2nd result" updated

515 days 976 days

total 1491 days

3x previous runtime
Improvement: $4\pi$ Calibration

Full-volume calibration

3cm radial bias: ~2% volume uncertainty
Improvement: $^{13}\text{C}(\alpha,n)$

Calibration using $^{210}\text{Po}-^{13}\text{C}$ source
- Improved understanding of largest background
- Reduce energy threshold below 2.6 MeV
Backgrounds: Geo-neutrino

Anti-neutrinos produced in the earth's crust from U/Th decays

$E_{(\text{geo})} < 2.49 \text{ MeV}$
Improvement: L-cut

Problem: Accidentals dominate signal at low energies

Solution: Vary cuts based on prompt event energy

Bin candidates:
- Radius
- $\Delta R$
- $\Delta t$
- Energy

Reject bins with low S/N ratio
Improvement: Energy Threshold

Likelihood Ratio:
\[ L = \frac{P_v}{P_v + P_{\text{acc}}} \]

- All Candidates
- Candidates After L-selection

\[ L_{\text{cut}}(E_p) \] chosen at maximum \( S/\sqrt{(S+B_{\text{acc}})} \)

**Efficiency**

\[ \Delta R \text{ [cm]} \]

\[ \Delta t \text{ [\mu s]} \]

\[ E_{\text{prompt}} \text{ (MeV)} \]
### Systematic Uncertainties

<table>
<thead>
<tr>
<th>Detector Related [%]</th>
<th>Reactor Related [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial Volume</td>
<td>Spectrum</td>
</tr>
<tr>
<td>Energy Scale</td>
<td>Reactor Power</td>
</tr>
<tr>
<td>L-cut</td>
<td>Fuel Composition</td>
</tr>
<tr>
<td>Cross section</td>
<td>Long-lived nuclei</td>
</tr>
</tbody>
</table>

- Fiducial Volume: 1.8%
- Energy Scale: 1.5%
- L-cut: 0.6%
- Cross section: 0.2%
- Spectrum: 2.4%
- Reactor Power: 2.1%
- Fuel Composition: 1%
- Long-lived nuclei: 0.3%

**Total Systematic Uncertainty: 4.1%**
# Background Summary

<table>
<thead>
<tr>
<th>Background</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidentals</td>
<td>80.5 ± 0.1</td>
</tr>
<tr>
<td>$^9\text{Li}/^8\text{He}$</td>
<td>13.6 ± 1.0</td>
</tr>
<tr>
<td>Fast neutron &amp; Atmospheric $\nu$</td>
<td>&lt;9.0</td>
</tr>
<tr>
<td>$^{13}\text{C}(\alpha,\text{n})^{16}\text{O}$ G.S.</td>
<td>157.2 ± 17.3</td>
</tr>
<tr>
<td>$^{13}\text{C}(\alpha,\text{n})^{16}\text{O}^{12}\text{C}(\text{n},\text{n}\gamma)^{12}\text{C}$ (4.4 MeV $\gamma$)</td>
<td>6.1 ± 0.7</td>
</tr>
<tr>
<td>$^{13}\text{C}(\alpha,\text{n})^{16}\text{O}$ 1$^{\text{st}}$ exc. state (6.05 MeV e$^+e^-$)</td>
<td>15.2 ± 3.5</td>
</tr>
<tr>
<td>$^{13}\text{C}(\alpha,\text{n})^{16}\text{O}$ 2$^{\text{nd}}$ exc. state (6.13 MeV $\gamma$)</td>
<td>3.5 ± 0.2</td>
</tr>
<tr>
<td>Total excluding geo-neutrinos</td>
<td>276.1 ± 23.5</td>
</tr>
<tr>
<td>Geo-neutrino decays U+Th [8]</td>
<td>56.8+13.3</td>
</tr>
</tbody>
</table>
Combined Spectral Analysis

Best Fit:
\[ \Delta m^2 = 7.58 \times 10^{-5} \text{ eV}^2 \]
\[ \tan^2 \theta = 0.56 \]

Geo-neutrino events:
39.3 U
29.4 Th

Threshold moved to 0.9 MeV
Neutrino Oscillation

More than one full cycle!

Reference Baseline: $L_0 = 180$ km

Geo-neutrino from Earth model

Preliminary

(Events – BG)

No Osc. Exp.
Oscillation Parameters

Previous regions now excluded

KamLAND only

\[ \tan^2 \theta = 0.56^{+0.14}_{-0.09} \]
\[ \Delta m^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5} \text{ eV}^2 \]

Precision value for $\Delta m^2$
KamLAND Future

Purification: reduce radioactive backgrounds
- Improve Reactor and Geo-neutrino measurements
- If reduction reaches $10^{-6}$: $^7$Be Solar Neutrinos

High-Energy Anti-neutrinos

Spallation physics