Reactor $\bar{\nu}_e$ Disappearance at KamLAND
The KamLAND Collaboration


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Introduction

Reactor antineutrino experiments: look for a flux deficit at a distance $L$
Neutrino Oscillations

- Write the weak states $\nu_1$ as a linear combination of mass eigenstates $\nu_j$:

$$\nu_1 = \sum_j U_{\nu 1 j} \nu_j$$

- The $\nu_j$ evolve in time as:

$$\nu_j(t) = e^{-i(p \cdot x)} \nu_j(0) \approx e^{-i(m_j^2/2E)L} \nu_j(0)$$

- The probability of detecting flavor $\nu_l'$ at distance $L$ is:

$$P(\nu_1 \rightarrow \nu_1, \ldots, L) = | $$

- For 2 flavors (e.g. $\nu_e$, $\nu_\mu$) this simplifies:

$$P(\nu_e \rightarrow \nu_e, \nu_\mu, L) = |$$
Matter Effects

\[ n = 1 + \frac{2\pi N}{p^2} f_1(0) \]

\[ L_0 = \frac{2\pi}{\sqrt{2} G_F N_e} \]

\[ P(\nu_e \rightarrow \nu_\mu, L) = \sin^2 2\theta_m \sin^2 \frac{\pi L}{L_m} \]

\[ \tan 2\theta_m = \tan 2\theta (1 + \frac{L_{osc}}{L_0} \sec 2\theta) \]

\[ L_m \equiv L_{osc} \left[ 1 + \left( \frac{L_{osc}}{L_0} \right)^2 + 2 \frac{L_{osc}}{L_0} \cos 2\theta \right]^{-1/2} \]
Neutrino Mixing Parameters
Neutrinos On Earth

- Control source and detector

- Sun: \( L_0 \sim 200 \text{ km} \ll R_{\text{sun}} \); Rock: \( L_0 \sim 10^4 \text{ km} > R_{\text{earth}} \)
  Matter effects much less significant

- Neutrino beams: \( E \sim 100 \text{ MeV} \): sensitivity to solar neutrino problem requires \( L \sim 1000 \text{ km} \)

- Reactors: antineutrinos with \( E \sim \text{ MeV} \): \( L \) can be smaller but \( 4\pi \) source
Reactor Experiments

Nuclear reactor → \( \bar{\nu}_e \) → Detector

L
Reactors In Japan

55% of total flux from:

Kashiwazaki

Takahama

Ohi

80% of total flux from baselines 140-210 km

KamLAND uses the entire Japanese nuclear power industry as a long-baseline source

KamLAND

Neutrino Flux at KamLAND
$^{235}\text{U Fission}$

$^{235}\text{U} + n \rightarrow X_1 + X_2 + 2n$

92 protons and 142 neutrons are shared between $X_1$ and $X_2$

Stable nuclei with $A$ most likely from fission:

94 and 140

98 protons
136 neutrons

On average, 6 n must decay to 6 p to reach stable matter.
Reactor Output

- A typical large power reactor operates at \( \sim 3 \text{ GW}_{th} \)
- At 200 MeV / fission and 6 \( \nu_e \) / fission:

\[
6 \times 10^{20} \bar{\nu}_e \text{ emitted into } 4\pi \text{ each second}
\]
Only ~1.5 $\nu_e$ per fission are actually detected.
> 99.9% of ν are produced by fissions in $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$
Simulation Inputs

- Power: $0.962 	imes 10^{-4}$
- Pressure: $3.42 \times 10^{-3}$
- Flow: $1.11 \times 10^{-3}$
- Boron ppm: $1.41 \times 10^{-3}$
- T inlet: $1.52 \times 10^{-2}$
\( \nu_e \) Spectra

- For 235U, 239Pu, and 241Pu, nuebar spectra can be derived from \( \beta^- \) spectrum measurements. This is not easy, since there are many fission branches, each with a variety of \( \beta^- \)-decay branches.

- For 238U, which makes up 11\% of the yield, no spectra are available, so we must rely on calculations, which are accurate to only 10\%. 

Previous Results

3 baselines at Goesgen

Bugey3 (short baseline)

a) “first principles” calculation
b) best prediction (uses $\beta$-spectra where possible and calculation for U$^{238}$)
Previous Results

![Graph showing the relationship between Nobs/Nexp and distance to reactor (m). The graph includes data points for various locations such as ILL, Savannah River, Bugey, Rovno, Goesgen, Krasnoyarsk, Palo Verde, and Chooz.]
Previous Results

KamLAND

MSW LMA Region

Distance to Reactor (m)

N_{obs}/N_{exp}
Event Signature

Coincidence signal: detect
- **Prompt**: $e^+$ energy + annihilation \(\gamma\)
- **Delayed**: n-capture \(\gamma\)

Average \(\Delta t = 210 \mu s\)
The KamLAND Detector

- Chimney
- Calibration Device
- Liquid Scintillator (1 kton)
- Containment Vessel (diam. 18 m)
- LS Balloon (diam. 13 m)
- Photo-Multipliers
- Buffer Oil
- Outer Detector
- Outer Detector PMT
KamLAND Trigger

Coincidence, prescale threshold: 120 PMT's hit
Singles threshold: 200 PMT's hit
Muons: all tubes hit

Calibration triggers

Inner Detector Triggers

Nsum
Nent = 536885
Mean = 245.2
RMS = 140.9

preliminary
Waveform Analysis

**Blue**: raw data
**red**: pedestal
**green**: pedestal subtracted
KamLAND Data

Event Display:
through-going muon
color is pulseheight
all tubes illuminated
KamLAND Data

Stopped muon
KamLAND Data

Cherenkov ring from “edge clipper”
KamLAND Data

Low-energy event

color is time
Calibrations

Radioactive gamma sources inserted in detector to calibrate energy and position reconstruction
Reconstruction Performance

Energy estimation from radioactive source calibrations

$$\sigma = 7.5\% / \sqrt{E (MeV)}$$

$R = 5.0\, m$ radius fiducial volume estimation from spallation neutron uniformity

$E (MeV)$

$\Delta E/E$

Events/Bin

$R = 5.0\, m$

$R/6.5\, m^3$

(b)
Event Selection

- Time correlation: $0.5 \mu s < \Delta t < 660 \mu s$
- Vertex correlation: $\Delta r < 1.6$ m
- Delayed event energy: $1.8$ MeV $< E_{\text{del}} < 2.6$ MeV
- Spherical fiducial volume: $R < 5$ m

Total efficiency: $78.3 \pm 1.6 \%$
Residual accidental background: $< 10^{-5}$ / day
Cosmogenic Backgrounds

Muons leave neutrons which can fake the signal
• Veto detector for 2 ms after muons

Muons also create longer lived (> 100 ms) neutron emitters
• Veto 3m cylinder around muon track for 2 s
• For high energy muons (> 3 GeV), veto entire detector for 2 s

Muon track reconstruction reveals the balloon boundary
Cosmogenic Backgrounds

Residual correlated background: $0.0068 \pm 0.0059$ events/day
Prompt/Delayed Event Energies

Delayed Energy (MeV) vs. Prompt Energy (MeV)

(delayed energy window)

Jason Detwiler  SSI 2003
Livetime: 145.1 days (162 ton·yrs)
Expected signal (no osc.): $86.8 \pm 5.6$ events
# Systematic Uncertainties

Estimated Contributions to the Systematic Uncertainty (%):

<table>
<thead>
<tr>
<th>Component</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Scintillator Mass</td>
<td>2.13</td>
</tr>
<tr>
<td>Fiducial mass ratio</td>
<td>4.06</td>
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<tr>
<td>Energy threshold</td>
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</tr>
<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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<td>Time lag</td>
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<tr>
<td>Antineutrino spectra</td>
<td>2.48</td>
</tr>
<tr>
<td>$\bar{\nu}_e p$ cross section</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Total systematic error 6.42%
Expected $86.8 \pm 5.6 (0.94 \pm 0.85 \text{ bg})$, observed 54
Event Spectrum

2.6 MeV (analysis threshold)

KamLAND data
- no oscillation
- best-fit oscillation

$\sin^2 2\theta = 1.0$
$\Delta m^2 = 6.9 \times 10^{-5} \text{eV}^2$

- geo neutrinos
- accidentals

Prompt Event Energy (MeV)
Fit to Oscillation Parameters

All contours at 95% CL

Backgrounds fixed but geoneutrino signal floated for fit

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

• KamLAND observed, for the first time, antineutrino disappearance at \( > 4\sigma \)

• Interpreted in terms of neutrino oscillations and assuming CPT invariance, this result

  – excludes all solar neutrino oscillation solutions except LMA

  – is in perfect agreement with LMA
Future Prospects

• Livetime has increased by a factor of ~2 since our first publication

• 50% reduction of flux in 2003 will allow for on-off analysis

• With any luck, KamLAND may observe spectral distortions, truly verifying neutrino oscillations

• Other physics results to come soon, including solar $\nu_e$, geonuetrinos, neutron production...