KamLAND: Measuring Terrestrial and Solar Neutrinos

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Measuring Neutrino Oscillation using Reactors
Neutrino Oscillation

The flavor eigenstates that neutrinos are born in, may not necessarily be the mass eigenstates:

\[ |\nu_l\rangle = \sum_{i=1}^{3} U_{li} |\nu_i\rangle; \quad l = e, \mu, \tau \]

where,

\[
U_{MNSP} = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\]

Maki, Nakagawa, Sakata, Pontecorvo

\[
= \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta_D} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta_D} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

atmospheric/accelerator \( \nu \)  
reactor/accelerator \( \nu \)  
solar/reactor \( \nu \)

Assuming that the neutrinos are moving relativistically through space:

\[ |\nu_i\rangle = e^{-i \frac{m_i^2 L}{2E}} |\nu_i(L = 0)\rangle \]

We will only consider two neutrino oscillation here.
Neutrino Oscillation

The flavor eigenstates that neutrinos are born in, may not necessarily be the mass eigenstates:

\[ |\nu_l\rangle = \sum_{i=1}^{3} U_{li} |\nu_i\rangle; \quad l = e, \mu, \tau \]

where,

\[ U_{MNSP} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \]

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\[ = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_D} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_D} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

Assuming that the neutrinos are moving relativistically through space:

\[ |\nu_i\rangle = e^{-i\frac{m_i^2 L}{2E}} |\nu_i(L = 0)\rangle \]

We will only consider two neutrino oscillation here
Few MeV anti-neutrinos, energy too low to produce $\mu$ or $\tau$ → disappearance experiments

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2 L}{E} \]
In practice, only 1.5 neutrinos/fission detectable

Calculated spectrum has been verified to 2% accuracy in past reactor experiments

No near detector necessary!
Anti-Neutrino Detection Method

Reaction process: Inverse beta decay

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

\[
n + p \rightarrow d + \gamma
\]

Scintillator is both target and detector

- Distinct two step process:
  - prompt event: positron
    \[
    E_{\bar{\nu}_e} \simeq E_{prompt} + 0.8\text{MeV}
    \]
  - delayed event: neutron capture after \(\sim 210\mu s\)
    - 2.2 MeV gamma

**Delayed coincidence: good background rejection**
\( \nu_e \) from 53 Reactor Cores in Japan

70 GW (7% of world total) is generated at 130-220 km distance from Kamioka.

Reactor neutrino flux: \(~6 \times 10^6\) cm\(^{-2}\)s\(^{-1}\)

Effective distance \(~180\) km

Distance from Kamioka:
- Mt. Ikenoyama
- 1000m rock
- \(\approx 2700\) mwe

Geographical coordinates:
- long. 137°18′43.495″
- lat. 36°25′35.562″
- alt. 358 m
KamLAND detector

- 1 kton Scintillation Detector
  - 6.5m radius balloon filled with:
    - 20% Pseudocumene (scintillator)
    - 80% Dodecane (oil)
    - PPO
  - 34% PMT coverage
    - ~1300 17” fast PMTs
    - ~550 20” large PMTs
- Multi-hit, deadtime-less electronics
- Water Cherenkov veto counter
KamLAND Physics Capabilities

0.4 1.0 2.6 8.5 Energy [MeV]

neutrino electron elastic scattering
\[ \nu + e^- \rightarrow \nu + e^- \]

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

- Neutrino Astrophysics
  - Verification of SSM
- Geoneutrinos

- Neutrino Geophysics
  - Study of earth heat model
- Solar neutrino
  - PRL 90 021802 (2003)

- Neutrino Physics
  - Precision measurement of oscillation parameters
- Neutrino Cosmology
  - Verification of universe evolution, SSM
- Supernova, relic neutrino, solar anti-neutrinos etc.
- KamLAND Physics Capabilities

Future
Low background phase
Systematic Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial volume</td>
<td>4.7</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>0.1</td>
</tr>
<tr>
<td>Reactor thermal power</td>
<td>2.1</td>
</tr>
<tr>
<td>Fuel composition</td>
<td>1.0</td>
</tr>
<tr>
<td>Anti-neutrino spectra</td>
<td>2.5</td>
</tr>
<tr>
<td>Cross section</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Total uncertainty</strong></td>
<td>6.5</td>
</tr>
</tbody>
</table>

Future improvements

Recent Full Volume calibration will help us bring down the largest syst. uncert.

Range of radioactive sources: $^{203}\text{Hg}$, $^{68}\text{Ge}$, $^{60}\text{Co}$, $^{241}\text{Am}$, $^{9}\text{Be}$, $^{210}\text{Po}$, $^{13}\text{C}$

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Best-fit oscillation:

$$\tan^2 \theta = 0.46$$

$$\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5} \text{eV}^2$$
Ratio of measured to expected no-oscillation spectrum

\[ P_{ee} = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2}{4} \frac{L}{E} \right) \]
KamLAND + Solar Results

Solar Experiments are sensitive to $\theta$

KamLAND is most sensitive to $\Delta m^2$

Including SNO salt results:

$$\tan^2 \theta = 0.45^{+0.09}_{-0.07}$$

$$\Delta m^2 = 8.0^{+0.6}_{-0.4} \times 10^{-5} eV^2$$
Statistics not good enough to make firm statements on correlation or georeactor

Georeactor < 19TW at 90% C.L.
Can KamLAND Detect a Nuclear Test?

North Korea tested a nuclear device on Oct 9, 2006: can KamLAND detect a test of a nuclear weapon?

- Assume a test of a Hiroshima size bomb (~15kton TNT) or ~10 kg of fissile material
  - Larger bombs are detectable by other means
- Further assume:
  - All material is fully fissioned
  - Distance is ~1000km from KamLAND (across the Japanese Sea)
- Typical 3GW (thermal) reactor has a few tons of fissile material burned up in a cycle of ~18months → 10kg/day
- KamLAND measures anti-neutrinos from 53 1GW size reactors, at an avg. distance of ~200km → rate of ~1 anti-neutrino/day

A small nuclear device will generate <0.001 of an additional anti-neutrino event in KamLAND
Geoneutrino Results

EARTHLY POWERS
Geoneutrinos reveal Earth's inner secrets
Radioactive decays: $^{40}$K, $^{232}$Th, $^{238}$U must contribute a significant fraction.

Anti-neutrinos from $^{232}$Th and $^{238}$U decays visible in KamLAND.

Reactor neutrinos main background.

Use KamLAND to measure radiogenic heat contribution.

Total Earth heat-flow: 30–40TW

Where does the heat come from?

**Heat-flow**

- Radioactive decays: $^{40}$K, $^{232}$Th, $^{238}$U must contribute a significant fraction.
- Anti-neutrinos from $^{232}$Th and $^{238}$U decays visible in KamLAND.
- Reactor neutrinos main background.
- Use KamLAND to measure radiogenic heat contribution.

Total Earth heat-flow: 30–40TW

Where does the heat come from?
Geoneutrino Results

- For 749 days of livetime
- “Rate” result
  - Observed: 152 events
  - Background: $127 \pm 13$ ev
  - Geoneutrinos: $25^{+19}_{-18}$
- “Shape” result
  - Central value: 28
  - ~2 sigma effect

Current data limit radiogenic heat to < 160TW
KamLAND Future: Low Background Phase
Solar $^7$Be Measurement

Test the Standard Solar Model:

- Mono-energetic $^7$Be lines
- $^7$Be neutrino flux is the largest uncertainty in SSM
Testing LMA-MSW

- Test LMA-MSW
  - For $^8$B neutrinos matter resonance largest effect
  - For $^7$Be vacuum oscillations is most important
- What happens in the transition region? Sensitivity to new physics
- Need a ~5% measurement
Internal Background

Detect through elastic scattering:

- Electron scattering: **no** delayed coincidence to suppress backgrounds
- Singles Spectrum in KamLAND
  - 4m Fiducial Volume cut suppresses external $^{40}$K and $^{208}$Tl
Main background sources in the solar $^7$Be analysis window:

- From $^{210}$Pb: $^{210}$Bi & $^{210}$Po
- $^{85}$Kr
## Purification Levels

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$T_{1/2}$</th>
<th>Current Concentration</th>
<th>Goal</th>
<th>Purification Level</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{210}$Pb</td>
<td>22.5 yr</td>
<td>$10^{-20}$ g/g</td>
<td>$10^{-25}$ g/g</td>
<td>$10^{-5}$</td>
<td>Distillation</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>$10^9$ yr</td>
<td>$1.9\times10^{-16}$ g/g</td>
<td>$10^{-18}$ g/g</td>
<td>$10^{-2}$</td>
<td>Distillation</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>11 yr</td>
<td>700 mBq/m$^3$</td>
<td>1 $\mu$Bq/m$^3$</td>
<td>$10^{-6}$</td>
<td>N$_2$ purging</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>$10^9$ yr</td>
<td>$3.5\times10^{-18}$ g/g</td>
<td>$10^{-18}$ g/g</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>$10^{10}$ yr</td>
<td>$5.2\times10^{-17}$ g/g</td>
<td>$10^{-16}$ g/g</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{222}$Rn</td>
<td>3.8 days</td>
<td>&lt;1 mBq/m$^3$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
After $10^{-6}$ reduction in $^{210}\text{Pb}$ and $^{85}\text{Kr}$

Goal: $S/B = \sim 6:1$
• Distillation into separate components: Pseudocumene (PC), Dodecane (NP) & PPO
  - 80% PC, 20% Dodecane, 1.52g/l PPO
• Liquid Scintillator (LS) is fed from KamLAND into a small (2m³) holding tank
- Distillation into separate components: Pseudocumene (PC), Dodecane (NP) & PPO
  - 80% PC, 20% Dodecane, 1.52g/l PPO
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Pseudocumene distillation in first tower

- Boiling point: 60 degC, operating pressure ~2kPa
- Output: ~0.25t/hr of PC
- Remainder sent to next tower
• Dodecane is distilled in the 2nd tower
  • Boiling point: ~100 degC, operating pressure ~2kPa
  • Output: ~1.0t/hr of dodecane

• Remainder in the distillation tower is further concentrated and sent to PPO tower

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• PPO is the final step in distillation
  • Boiling point: \( \sim 190 \) deg C at 0.6kPa operating pressure
  • Output: 1.5kg/h
  • Remainder is disposed of
- Liquid scintillator is (re)blended from PC, NP and PPO
- Monitor temperature and density
• Final step is N₂ purging of the Liquid Scintillator
• Radon Removal
System installed in the mine in 2006
Liquid Scintillator Monitoring

- Liquid Scintillator will be monitored during purification
  - Light attenuation properties
  - Rn concentration in LS
    - miniLAND (small scintillator detector monitoring BiPo coincidences)
    - Electrostatic collection after trapping
  - $^{85}$Kr concentration in a trap
- Monitoring of mechanical properties (fragile balloon)
  - Precision corioli flow meters will monitor input/output flow rates
  - Muon rates in the detector (long time average)

*KamLAND will remain operational during purification*

- Most sensitive background monitoring tool!
Status of Distillation System

- System was installed in Fall 2006
- Engineering runs are being conducted
- Pseudocumene and Dodecane towers are successfully tested and have been run stably for several weeks
- PPO tower operates as expected, but not yet stable
- No degradation in LS after purification observed
- **Plan** once full stable operation achieved:
  - Introduce 2\(m^3\) of purified LS into KamLAND
  - Introduction of 50\(m^3\) of purified LS
  - One full volume exchange of LS (approx. 2 months)

Schedule driven by blasting in Kamioka for the XMASS cavity at the end of July - no operation during blasting
Other Measurements that will Benefit

Reactor Analysis:

Geoneutrino Analysis:

Even a modest purification level will eliminate the $^{13}C(\alpha, n)^{16}O$ background $\rightarrow$ largest BG for reactor analysis.
- KamLAND will measure SN antineutrinos through CC with inverse beta decay
  \[ \bar{\nu}_e + p \rightarrow e^+ + n \]

- KamLAND can also observe neutrinos from a SN via NC proton scattering
  \[ \nu_x + p \rightarrow \nu_x + p \]

- This process would be the only model independent method capable of determining the total energy and \( \nu_x \) temperature.

- KamLAND requires a factor of \( \sim 10 \) reduction in background at low energy to achieve this sensitivity.

- Also detection through NC \(^{12}\text{C}\) excitation
  \[ \nu_x + ^{12}\text{C} \rightarrow \nu_x + ^{12}\text{C}(15.11\text{MeV}) \]

- Narrow peak at 15 MeV in the E spectrum
Supernova Detection

Assuming 1kt FV and a “Standard Supernova”:

<table>
<thead>
<tr>
<th>Reaction</th>
<th># Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_e + p \rightarrow e^+ + n$</td>
<td>~300</td>
</tr>
<tr>
<td>$\nu_x + p \rightarrow \nu_x + p$ (for 0.2MeV thr)</td>
<td>~270</td>
</tr>
<tr>
<td>$\nu_x + ^{12}C \rightarrow \nu_x + ^{12}C(15.11\text{MeV})$</td>
<td>~60</td>
</tr>
</tbody>
</table>

Current KamLAND SN threshold is at ~0.7MeV due to DAQ rate limitations

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• KamLAND results strengthen support for “neutrino disappearance” and LMA-MSW as the solution to the Solar Neutrino Problem

• Precision measurements: best-fit KamLAND+Solar oscillation parameters are: \( \Delta m^2 = 8.0^{+0.6}_{-0.4} \times 10^{-5} \text{eV}^2 \) \( \tan^2 \theta = 0.45^{+0.09}_{-0.07} \)

• Geoneutrino detection: new tool to investigate the Earth

• **Future**: Low background phase
  
  • Measurement of solar \(^7\text{Be}\) neutrinos: is solar oscillation only LMA-MSW? Investigating SSM
  
  • *Reactor and geoneutrino* measurements will continue with significantly lower backgrounds

  • Lower supernova threshold to \( \sim 0.2\text{MeV} \)

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**Invitation:**

10:45AM R15.00001 Measuring \(^8\text{B}\) Solar Neutrino Elastic Scattering with KamLAND, LINDLEY A. WINSLOW

(The KamLAND Collaboration)

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