Recent KamLAND Results

• Introduction

• First KamLAND Reactor Antineutrino Analysis

• Recent KamLAND Results

• Future: Reactor and Solar Phases

• Conclusions
Motivation

- Situation several years ago:
  With MSW matter effects, solar neutrino oscillation constraints allowed several very different regions of mixing parameter space

- A reactor antineutrino experiment with a baseline ~200 km could measure or rule out LMA oscillation

- After first SNO results, global analyses of all solar data favored LMA
Reactor Antineutrinos

• Nuclear power plants produce electron antineutrinos $\bar{\nu}_e$ through the $\beta$-decay of fission fragments

• Antineutrinos detected through inverse $\beta$-decay:
  $\bar{\nu}_e + p \rightarrow e^+ + n$

• Prompt signal:
  positron ionization, annihilation
  $E_{\text{prompt}} = E_{\bar{\nu}} - 0.8 \text{ MeV}$

• Delayed signal:
  thermal neutron capture
  $E_{\text{delayed}} = 2.2 \text{ MeV (hydrogen)}$
  $\sim 200 \mu s$

Bruce Berger
Rencontres de Moriond - March 6, 2005
Why Japan?

Convenience!

Neutrino Convenience Store near Kamioka, Japan

“neutrino”
Why Japan?

KamLAND uses the entire Japanese nuclear power industry as a long-baseline source. 80% of flux from baselines 140-210 km
Effects of Oscillations

- Oscillations change both the rate and energy spectrum of detected events

\[ P_{ee} = 1 - \sin^2\theta \sin^2(1.27 \Delta m^2 L/E) \]

- Multiple reactors at different baselines complicate the signal

- Reactor operation data is critical!

Example spectra (L.A. Winslow)

Top: \( \Delta m^2 = 1.5 \times 10^{-4}, \tan^2\theta = 0.41 \) (‘LMA II’)

Bottom: \( \Delta m^2 = 0.7 \times 10^{-4}, \tan^2\theta = 0.41 \) (‘LMA I’)

*top 4 reactors at full thermal power only
KamLAND Detector

- 1 kton liquid scintillator
- Mineral oil buffer outside 120-µm nylon balloon
- 1879 PMTs
  - 1325 17" fast
  - 554 20" efficient
- Water Čerenkov
- Outer Detector
- Event position from light arrival times
  - ~20 cm resolution
- Event energy from total light yield
  - ~6.2%/[$E$(MeV)]$^{1/3}$ resolution
First Reactor Antineutrino Result

- Observed neutrino disappearance:

\[(N_{\text{obs}} - N_{BG})/N_{\text{no-osc}} = 0.611 \pm 0.085 \text{ (stat)} \pm 0.041 \text{ (syst)}\]

- Probability that 86.8 events would fluctuate down to 54 is < 0.05%

- “Standard” $\bar{\nu}_e$ propagation ruled out at the 99.95% confidence level
Rate + Shape Analysis

- Fit prompt (positron) energy spectrum above 2.6 MeV with full reactor information (power, fuel, flux), 2-flavor mixing
- Energy spectrum was consistent with constant suppression but the absence of distortions constrained oscillation parameters
Assuming CPT invariance:
- KamLAND rate analysis
  - confirms LMA
  - rules out all other regions
- Shape analysis further constrains LMA parameters
  - LMAI (lower)
  - LMAII (upper)

Best-fit values of mixing parameters are in the same region for both neutrinos and antineutrinos > test of CPT

- KamLAND constraints symmetric about $\tan^2\theta=1$ due to absence of matter effects
Latest KamLAND Result

Improvements since the first analysis:

• **More data:** Livetime increased from 145.1 to 515.1 days

• **Fiducial volume increased** from 5 to 5.5 m

• **Analysis improvements**
  - Vertex reconstruction, energy calibration, muon fitting, general understanding of the detector

• **Identification of a new background:** $^{13}\text{C}(\alpha,n)^{16}\text{O}$
13C(α,n)16O

• 13C(α,n)16O cross section ~10^-7

• KamLAND scintillator contains 210Pb a long-lived radon decay product

• 210Pb decay chain produces α’s 210Pb → 210Bi → 210Po → 206Pb + α

• Total α decays in dataset: (1.47 ± 0.20) x 10^9

• Produces fast neutron background is mostly below 2.6 MeV

• Most of the background above 2.6 MeV is from an excited state of 16O populated by 13C(α,n)16O* prompt 6 MeV gamma delayed neutron capture

• Largest background above 2.6 MeV: 10.3 ± 7.1 out of 17.8 ± 7.3
Latest KamLAND Result

- Second KamLAND reactor antineutrino paper
  (hepex-0406035; 6/13/2004; revised 11/1/2004; accepted by PRL)

- Statistical significance of disappearance: 99.998% (was 99.95%)

- Data now show shape distortion at 99.6% significance
Rate vs. Flux

- KamLAND can't turn the reactors off to measure backgrounds and confirm directly that the signal is from reactors
- However, the reactor antineutrino flux has varied significantly during KamLAND operation
- Consistent with reactor antineutrinos
L₀/E Plot

- Oscillation depends on L/E
  KamLAND doesn’t measure L, but the flux distribution has a strong peak
  A typical value L₀=180 km is used
  This is really a 1/E plot
  Oscillations smeared out in 1/E

- Goodness of fit:
  0.7% - decay
  1.8% - decoherence
  11.1% - oscillation
  (0.4% - constant suppression)

- Data prefer oscillation to other hypotheses
Latest KamLAND Result

- KamLAND data in agreement with global fits to solar neutrino results
- KamLAND alone now measures $\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5} \text{ eV}^2$
- Global analysis of KamLAND plus solar data gives $\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5} \text{ eV}^2$ and $\tan^2 \theta = 0.40^{+0.10}_{-0.07}$
Rate analysis and mixing angle determination are now systematics limited.

6.5% systematic uncertainty dominated by 4.7% fiducial volume systematic.

Building a “4π” calibration system to directly calibrate vertex reconstruction in the full fiducial volume. We currently only have calibration along the vertical axis.

Δm² resolution comes from distortions in the energy spectrum, which are not as sensitive to our systematics > still statistics limited.

4π sketch
Reactor Experiment Future

- New Shika cores starting 2006
  - Significant flux increase at 88 km, near first oscillation minimum
  - Should have larger rate suppression for these neutrinos

- Other physics measurements:
  Geoneutrinos: antineutrinos produced by the $\beta$-decay of U and Th in the earth
  - Large $^{13}C(\alpha,n)^{16}O$, accidental backgrounds
  - Paper forthcoming
  Spallation production of neutrons, delayed-coincidence backgrounds e.g. $^9$Li, other product e.g. $^{12}$B
  - Understanding these processes is important for future experiments e.g. reactor measurement of $\theta_{13}$

Higher-energy antineutrinos
Nucleon decay
KamLAND Solar Phase

Goal is a direct measurement of the solar $^7$Be neutrino flux

Tough measurement:
- single ES event
- need very low background to statistically extract the signal

Solar Standard Model (SSM)
$^7$Be prediction is at the ~10% level
- This measurement is not expected to improve the determination of mixing parameters
- Measurement will improve the SSM

$^7$Be neutrino energy is below the MSW transition
- survival probability is different than $^8$B $\nu$
  seen by Super-K, SNO
- verification of MSW effect

John Bahcall
KamLAND Solar Phase

- KamLAND scintillator has very low U, Th levels from initial purification, but other contaminants must be reduced substantially:
  - ~$10^6$: $^{85}$Kr - present in atmosphere, from N2 bubbling
  - ~$10^5$: $^{210}$Pb, $^{210}$Bi - from radon contamination

<table>
<thead>
<tr>
<th>Background</th>
<th>Current Level</th>
<th>$^7$Be Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}$U</td>
<td>$3.5 \times 10^{-18}$ g/g</td>
<td>OK</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>$5.2 \times 10^{-17}$ g/g</td>
<td>OK</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>$2.7 \times 10^{-16}$ g/g</td>
<td>~$10^{-18}$ g/g</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>0.7 Bq/m$^3$</td>
<td>1$\mu$Bq/m$^3$</td>
</tr>
<tr>
<td>$^{210}$Pb</td>
<td>~$10^{-20}$ g/g</td>
<td>$5 \times 10^{-25}$ g/g</td>
</tr>
</tbody>
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- A great deal of R&D progress on purification approaches: distillation, adsorption, heating

- Upgrade project approved in Japan, receiving major funding
  - Construction of initial purification system to be complete by March 2006
KamLAND Solar Phase

- Signal and backgrounds:
  - $^7$Be signal now $\sim 10^6$ below backgrounds:
    - $^{85}$Kr, $^{210}$Bi $\beta$, $^{210}$Po $\alpha$

- Other benefits of purification:
  - Eliminates $^{13}$C($\alpha,n$)$^{16}$O background for reactor antineutrinos, geoneutrinos
  - Enhances supernova signals by adding singles detection below 1MeV
Conclusions

KamLAND made the first observation of reactor antineutrino disappearance

Current KamLAND results show disappearance at the 99.998% CL and spectral shape distortion at 99.6%.

“Solar” oscillation mixing results have gone from allowed regions spanning many orders of magnitude to parameter measurement

Reactor results will continue to improve

KamLAND is gearing up to measure solar $^7$Be neutrinos

KamLAND public data release: http://www.awa.tohoku.ac.jp/KamLAND/datarelease/2ndresult.html Individual candidate energies, etc.