KamLAND Geoneutrino Study

1. Review of Previous Results
2. Recent Improvements
3. On-going Efforts and Prospects
4. Far Future Dreams

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KamLAND Collaboration
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KamLAND Experiment

- observes low energy anti-neutrinos in the Kamioka Mine, Hida, Japan
- consists of 1000ton Liquid Scintillator, surrounded by 1845 PMT's

- 2002 Jan: Start data taking
- 2002 Dec: Evidence for reactor neutrino disappearance (145 days)
- 2005 Jan: Evidence of reactor neutrino spectral distortion (514 days)
- 2005 Jul: Investigation of geoneutrinos (749 days)
- 2008 Jun: 1491 day data accumulated
KamLAND Detector

- Yields light on ionization (8000 photons / MeV)
- Mainly consists of only C and H

Liquid Scintillator

- PC: 20%  dodecane: 80%  PPO: 1.36 g/l

- Detector Center
  - Liquid Scintillator 1000 ton
  - Contained in plastic balloon

- Surrounded by
  - 17-inch PMT 1325
  - 20-inch  554

(PMT : Photo Multiplier Tube, a photo sensor)
Antineutrino Detection Method

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

\[ \tau \sim 210 \ \mu\text{sec} \]

\[ e^+ + e^- \rightarrow 2\gamma(0.511\text{MeV}) \]

\[ n + p \rightarrow d + \gamma(2.2\text{MeV}) \]

\[ E_{\text{threshold}} = 1.8 \ \text{MeV} \]

\[ E_{\text{prompt}} = E_{\nu_e} - 0.8 \ \text{MeV} \]

\[ E_{\text{delayed}} = 2.2 \ \text{MeV} \]

Two characteristic signals

Clear event identification

Great BG suppression
KamLAND Detector

Kamioka Mine

Japan Arc

KamLAND Inner View

KamLAND Outer View

Photo Multiplier Tube

Scintillator Container
LS Purification and Radioactive Impurity

Before

$U: \sim 10^{-10} \text{ g/g}$, $\text{Th}: <10^{-12} \text{ g/g}$, $K: 7 \times 10^{-11} \text{ g/g}$

After

$U: 3.5 \times 10^{-18} \text{ g/g}$, $\text{Th}: 5.2 \times 10^{-17} \text{ g/g}$, $K: 2.7 \times 10^{-16} \text{ g/g}$

measurable only by KamLAND itself!
Antineutrino Sources

HPE (U/Th) in the Earth

- ~50% from surrounding crust
- ~25% from mantle

\[ ^{238}\text{U} \rightarrow ^{206}\text{Pb} + 8\ ^{4}\text{He} + 6\ e^- + 6\bar{\nu}_e \]

\[ ^{232}\text{Th} \rightarrow ^{208}\text{Pb} + 6\ ^{4}\text{He} + 4\ e^- + 4\bar{\nu}_e \]
Reactor Neutrino Flux Calculation

Example of Reactor Operation Data

- **Japanese Reactors (95.5%)**: Operation data, including fuel burn-up, for each core are provided by operators.

- **Korean Reactors (3.4%)**: Flux are calculated based on published electrical output.

- **Other Reactors (1.1%)**: Nominal power is assumed.

**Neutrino Flux at KamLAND (no oscillation case)**

Total ~2% error (conservative)

- BSE composition by [McDonough1999]
- Crustal composition by [Rudnick et al. 1995]
- Crustal thickness by CRUST 2.0
- Uniform Mantle Model
- No U/Th in the Core

Expected Geoneutrino Flux
- U-Series
  \[2.3 \times 10^6 \text{ [1/cm}^2\text{/sec]}\]
- Th-Series
  \[2.0 \times 10^6 \text{ [1/cm}^2\text{/sec]}\]

With \(10^{32}\) target protons,
- U-Series
  32 events / year
- Th-Series
  8 events / year

Geoneutrino Origination Points
Detectable at KamLAND (MC)

50% within 500km
25% from Mantle

KamLAND
Australia
Greenland
Antarctic
South America

[Image of Earth with KamLAND, Australia, Greenland, and South America marked, showing 50% within 500km and 25% from Mantle]
KamLAND Antineutrino Spectrum (expected)

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

\[ E_{\text{threshold}} = 1.8 \text{ MeV} \]

\[ E_{\text{prompt}} = E_{\nu_e} - 0.8 \text{ MeV} \]

Neutrino Property Study

- Signature of Neutrino Oscillation
- Precision Measurement of Oscillation Parameters

Geoneutrinos: Neutrino Application
- Direct measurement of HPE in the Earth
  [Nature 436, 499 (2005)]
Expected Rate and Spectrum

- Fiducial Volume: 408 ton
- Live-time: 749 days
- Efficiency: 68.7%

Expected Geoneutrinos
- U-Series: 14.9
- Th-Series: 4.0
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Backgrounds
- Reactor: 82.3 ± 7.2
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- Reactor: 82.3 ± 7.2
- \((\alpha,n)\): 42.4 ± 11.1
- Accidental: 2.38 ± 0.01
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KamLAND Observation

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BG total: 127.4 ± 13.3

Observed: 152
First Geoneutrino Result  [Nature 436, 499 (2005)]

- Number of Geoneutrinos: 28.0
- 99% C.L. upper limit: 70.7 events
- Significance 95.3% (1.99-sigmas)

- KamLAND is insensitive to U/Th ratio
  → adopt U/Th \sim 3.9 from Earth science

- Fiducial Volume: 408 ton
- Live-time: 749 days
- Efficiency: 68.7%

Spectrum Shape Analysis (likelihood)

Earth Model Prediction

Discrimination of U and Th
Flux Prediction from Earth Models

- Scale Bulk Composition
- Fix Crustal Composition, Parameterize Mantle

Heat Production

Bulk Earth Model Constraint

Fully Radiogenic Upper Limit

Geoneutrino Flux [1/cm²/sec]

U+Th Mass [kg]
Comparison with Earth Model Predictions

- Consistent with BSE model predictions
- 99% C.L. upper limit too large to be converted to heat production (No Earth models applicable)
Updates

- $(\alpha,n)$ BG error reduced
  - New cross section data
  - Proton quenching measurement
  - PoC calibration
  $(\alpha,n)$ error: 26% $\Rightarrow$ 11%

- Systematic error reduced
  - Full-volume calibration
  FV error: 4.9% $\Rightarrow$ 1.8%

- Analysis improved
  - Enlarged fiducial volume
  - Optimal selection cuts
  FV radius: 5.0 m $\Rightarrow$ 6.0 m
  Efficiency: 69% $\Rightarrow$ 78%(U) / 69%(Th)

- More data accumulated
  Livetime: 749 $\Rightarrow$ 1491 day

*Full-Volume Calibration*

\[7.09 \times 10^{32} \text{ proton} \cdot \text{year}\]
\[\downarrow\]
\[24.4 \times 10^{32} \text{ proton} \cdot \text{year}\]
Updated Results [PRL 100, 221803 (2008)]

- Number of Geoneutrinos: $73 \pm 27$ (36% error ← 56% previous)
- Still consistent with model prediction
56% ⇒ 36% error reduction becoming comparable with BSE (20% error)
99% C.L. upper limit is approaching to the total terrestrial heat
On-Going Effort

LS Distillation in Progress
⇒ removes radioactivity by $10^{-5}$

we remove these
Distillation Apparatus

• Three distillation column (each for PC, Dodecane, PPO)
• Vacuum distillation (ex PPO: ~0.3 kPa, ~180°C)
• Can process ~ 1 ton/hour (~ 1 month for full volume)

• Designed for $10^{-5}$ BG reduction for solar $^7$Be observation
First Distillation Campaign (Nov 2006 ~ Aug 2007)

BG reduction only 20%~80%

- Insufficient control of distillation conditions
- Rn / Kr leaks
- Unwanted mix of purified / non-purified LS
Second Purification Campaign (May 2008~)

- Leaks fixed
- Airtight chamber built
- Procedure reexamined
- Fine temp. control
- More density difference
- ...

As of Sep 2008
Prospects

Assuming:
• $10^{-4}$ reduction of $^{210}$Pb
• 749 days livetime

If combined with the current 1491 day data,
• Error is reduced: from 36% to 25% (error is dominated by reactor neutrinos)
• Significance: 99.992% (3.96 sigmas)
Prospects after Purification

749 days after purification, combined with current 1491 day data

- Measurement error is comparable with Earth model predictions
- 99% C.L. limit can exclude some “upper limit” models

99% upper limit
1.6 times above BSE

25% uncertainty
KamLAND (Kamioka/Japan) Limitations?

after purification (MC)

Reactor neutrino event rate

Geo / Reactor Event Ratio

KamLAND

Borexino

SNO+

Kamioka (137.31E, 36.42N)
Geoneutrinos: 36.6
(Mantle Origin): 10.3
Reactor Neutrinos: 252.8

GranSasso (14.00E, 42.00N)
Geoneutrinos: 48.5
(Mantle Origin): 10.2
Reactor Neutrinos: 24.5

Sudbury (278.00E, 47.00N)
Geoneutrinos: 52.1
(Mantle Origin): 10.2
Reactor Neutrinos: 37.6
Far Future Dreams: Directional Sensitivity

- Rejection of reactor BG
- Mantle under continental crust
- Earth tomography ??

Recoiled neutron remembers direction

Problems:
- Thermalization blurs the info
- Gamma diffusion spoils the info
- Reconstruction resolution is too poor

Wish List:
- large neutron capture cross-section
- (heavy) charged particle emission and
- good resolution detector (~1cm)
If

- 20 mm vertex displacement
- 10 mm vertex fluctuation
- Perfect resolution

• horizontal distribution further improves separation
Towards Directional Sensitivity

$^6\text{Li}$ loading helps preserving directional information

- Large neutron capture cross-section: 940 barn
- $^6\text{Li} + n \rightarrow \alpha + T$: no gamma-ray emission
- Natural abundance 7.59%

Li 2.0 wt% ($^6\text{Li}$ 0.15wt%) Angular Resolution (MC)

Various chemical forms for Li loading are being tested…
Li Loaded Liquid Scintillator

Current candidate:
PC + PPO + POE + LiBr + H₂O

POE: surfactant

Goal (minimal):
• 2.0 wt% Li
• Transparency >70 cm @ 400 nm
• Light yield ~90% of KamLAND LS

Current:
• 0.8 wt% Li
• Transparency 65 cm @ 400 nm
• Light yield 46% of KamLAND LS

Li capture ratio v.s. Li wt% (MC)

⇒ ~2.0 wt% Li is sufficient
Towards Directional Sensitivity 2

\(~1\)M pixel imaging can achieve 1 cm resolution
  - Proper optics need to be implemented
  - Sensitivity to 1 p.e. and high-speed readout required

First step for LS imaging…(150cc test bench)
Optics Development

As of Dec 2007 (AAP2007 Paris)

Muon Event ???

Isotope Decay Event ???

Muon

17 photons
8.08 ± 0.222 cm

60Co compton e
Current Achievement

- 17 mm vertex displacement
- 20 mm vertex fluctuation
- 10 mm resolution

Next step:
20 litter test bench near reactor (~10m)

Optical Design

- 15 mm resolution
- 326 mm depth of field
- 0.10% photo collection
Another Updates: Reactors Stopped

- July 2007: Earthquake hit the world largest reactors (Kashiwazaki)
- March 2007: Earthquake hit the closest reactors (Shika)

⇒ ~40% reactor flux reduced
Summary

• KamLAND, low-energy antineutrino detector,
  – determined oscillation parameters precisely
  – made first experimental investigation on geoneutrinos

• Recent updates with more stat. and less syst. err.,
  – reduced geoneutrino measurement error from 54% to 36%
  – Upper limit is comparable with Earth model limits

• Further LS purification is in progress
  – will reduce error to ~25%
  – Measurement error will be comparable with Earth models

• R&D for directional sensitivity underway