KamLAND Results and Future

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KamLAND collaboration


@Laforet Zao Resort & Spa (Oct. 8, 2005)
KamLAND results and future

- Reactor results and future
- Geoneutrino results and future
- Solar neutrino future
  - $^7\text{Be}$
  - pep, CNO, low-energy $^8\text{B}$
- Other physics
  - Solar $\bar{\nu}_e$, supernova, and other high energy $\bar{\nu}_e$
  - Invisible decay of neutron
KamLAND Detector

- Detector location: old Kamiokande site
- 2700 m.w.e.

- 1000 ton liquid scintillator
  - 80% (dodecane) + 20% (pseudocumene)
  - + 1.52 g/l PPO
  - Housed in spherical plastic balloon

- 3000 m$^3$ stainless steel vessel
  - Filled with a mixture of paraffin oil and dodecane ($\Delta \rho = 0.04\%$)

- 1325 17-inch + 554 20-inch PMT's

- Commissioned in February, 2003

- Photocathode coverage: 22% → 34%
- Energy resolution at 1 MeV: 7.3% → 6.3%

- Water Cerenkov outer detector
Kamioka Liquid Antineutrino Detector

- Kevlar ropes
- Water tank
- Balloon
- Buffer oil
- Phototubes
- Liquid scintillator

- Prompt signal 0.9–8 MeV
- Delayed signal 2.2 MeV
- \( N_{\text{hit}} \)
- Time \( \sim 200 \mu s \)

Balloon 13 mØ
Reactor results

1st result: 162 ton-yr
(May 4 - Oct. 6, 2002)

2nd result: 766.3 ton-yr
(May 9, 2002 - Jan 11, 2004)

Exposure

Time

Data taking started

Today

Neutrino 2004

New from Results KamLAND

Today
First result: reactor neutrino disappearance


Disappearance: 99.95% C.L.
2nd result: spectral distortion


$L_0 = 180$ km
Determination of solar neutrino solution
Precise measurement of $\Delta m_{12}^2$
Reactor future

- Keep taking data: (statistical error) $\propto (\text{time})^{-1/2}$
- Reduction of the systematic error to keep (total error) $\sim \propto (\text{time})^{-1/2}$
  - All volume calibration instead of only along the vertical axis:
    - from July 2006, the “$4\pi$ system”
  - Better understanding of the detector, improving analysis tools
- See also posters
  - #56 T. Classen for energy scale
  - #57 D. Dwyer for oscillation analysis
  - #60 L. Hsu for Monte Carlo

<table>
<thead>
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<th>Systematic</th>
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<tbody>
<tr>
<td>Fiducial volume</td>
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<td>Energy threshold</td>
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<td>Efficiency of cuts</td>
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<td>Livetime</td>
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<td>Reactor power</td>
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<td>Fuel composition</td>
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<td>$\nu_e$ spectra</td>
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<td>Cross section</td>
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<tr>
<td>Total</td>
<td>6.5</td>
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3% rate error
1% scale error
3kt-yr data accumulation
“Geoneutrinos”

- Electron antineutrinos produced in the Earth’s interior (crust and mantle) by decays of $^{238}\text{U}$, $^{232}\text{Th}$, and $^{40}\text{K}$
- Decays of $^{238}\text{U}$, $^{232}\text{Th}$, and $^{40}\text{K}$: ~40% of Earth’s power
- Earth’s power: $\rightarrow$ plate tectonics, earthquakes, volcanoes, geomagnetism, …
- Origin and history of the Earth
- Pointed out since $\nu$ discovered (1950’s, G. Gamow, …)
Heat balance of the Earth

Heat flow measurement:

44 TW? (Pollack H.N. et al, Rev. Geophys 31, 267)

31 TW? (Hofmeister, A.M et al. Tectonophysics 395)

Radiogenic:

19 TW (McDonough et a. Chem. Geol. 120, 223)

= (?)

Cooling of core, solidification of outer core, … (originates from initial gravitational energy)
The expected $^{238}\text{U}$, $^{232}\text{Th}$, and $^{40}\text{K}$ decay chain electron anti-neutrino energy distribution. KamLAND can only detect electron antineutrinos to the right of the vertical dotted black line; hence it is insensitive to $^{40}\text{K}$ electron antineutrinos.
152 events observed
“signal” $25 \pm^{19}_{18}$

Geoneutrino results

Data-set:
749.1 days

Fiducial:
5 m radius

$13C(\alpha, n)16O$
$42 \pm 11$

reactor $80.4 \pm 7.2$
Systematic uncertainty

$232\text{Th}$

$238\text{U}$

Total BG $127.0 \pm 13.1$

$E_v = E_{\text{prompt}} + 0.8 \text{MeV}$
Rate + shape analysis

U/Th = 3.9 (in mass ratio) (“definitely” expected in BSE model (“chondritic”))

Best fit:

(NU, NTh) = (3, 18)

Total number of geo-ν in dataset NU + NTh

Relative intensity (U and Th)

BSE model
U/Th ratio is fixed
Geoneutrino future: $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reduction

$$T_{1/2} = 22.3 \text{y} \quad 2^{10}\text{Pb} \rightarrow 2^{10}\text{Bi} \rightarrow 2^{10}\text{Po} \rightarrow 2^{06}\text{Pb}$$

- Reduction of systematic error: currently going on
- Reduction of $^{210}\text{Pb}$: near future (see “solar neutrino future” next)
Geoneutrino future – reduction of systematic uncertainty of $^{13}\text{C}(\alpha,n)^{16}\text{O}$

- Use new data of cross section of $^{13}\text{C}(\alpha,n)^{16}\text{O}$:
  (Harissopulos et al. (2005), systematic error 20% → 4%)

- Measurement of events below 0.9 MeV:
  (almost pure sample of $^{13}\text{C}(\alpha,n)^{16}\text{O}$, currently consistent with the estimated rate, → measurement ongoing for more statistics)

- Measurement of the visible energy of neutron events:
  - quenching effect of the scintillator
  - $(\text{visible energy}) / (\text{real energy}) \sim 1/4$ for protons recoiled by neutrons from $^{13}\text{C}(\alpha,n)^{16}\text{O}$ (calculation from $\alpha$ quenching)
  - no direct measurement exists, so conservative uncertainties assumed
  - → direct measurement (next slide)
Energy scale of neutron events – measurement using monochromatic neutrons

OKTAVIAN @ Osaka Univ.
14.1-MeV monochromatic neutron beam
Geoneutrino future

\[ \frac{(N_U - N_{Th})}{(N_U + N_{Th})} \]

Th/U \approx 3.9

BSE model

best fit

KamLAND-II

NU + N_{Th} vs. (N_U - N_{Th})/(N_U + N_{Th})

CL 68.3%
CL 95.4%
CL 99.7%

CL 68.3%
CL 95.4%
CL 99.7%
Solar neutrino future

\( SSM\ BP04 \) observation “before oscillation”

- \( ^8\text{B} \): precisely measured
- \( \text{pp} \): constrained by luminosity
- \( ^7\text{Be} \): key to understand total pp-chain


Fig. from Nucl. Phys. B 149 (2005) 13
Solar neutrino future

KamLAND single spectra

Solar $^7\text{Be}$
Reduction of $^{210}\text{Pb}, \ 85\text{Kr}$ by $10^{-5}$

→ KamLAND “solar $\nu$ phase”

$T_{1/2} = 22.3\text{y}$

$^{210}\text{Pb} \rightarrow 210\text{Bi} \rightarrow 210\text{Po} \rightarrow 206\text{Pb}$

$T_{1/2} = 10.8\text{y}$

$^{85}\text{Kr} \rightarrow 85\text{Rb}$

$\nu$ $^3\text{He} (\alpha, n) 16\text{O}$

Obstacles for solar $^7\text{Be} (^{210}\text{Bi}, 85\text{Kr}, 210\text{Po})$, and antineutrino (reactor and geoneutrino) physics ($210\text{Po}$)
Distillation + $N_2$ purge

KamLAND scintillator:
- 80% dodecane ($C_{12}H_{26}$)
- 20% pseudocumene (1,2,4-$(CH_3)_3-C_6H_3$),
- 1.5-g/l PPO (2,5-Diphenyloxazole, 2,5-(C$_6$H$_5$)$_2$-C$_3$HNO)

Dirty scintillator

Clean scintillator

Boiling points

$^{210}$Pb$^{n+}$

PPO

Dodecane

Pseudocumene

$^{85}$Kr

$^{222}$Rn

$N_2$ purge
Distillation–R&D since 2004

Real system:
~ 1.5 kilo-liter/hr (design flow rate)
Construction starting August, 2006
R&D using $^{212}\text{Pb}$ instead of real $^{210}\text{Pb}$

- In KamLAND: $^{222}\text{Rn} \rightarrow ^{218}\text{Po} \rightarrow ^{214}\text{Pb} \rightarrow ^{214}\text{Bi} \rightarrow ^{214}\text{Po} \rightarrow ^{210}\text{Pb} \rightarrow ^{210}\text{Bi} \rightarrow ^{210}\text{Po} \rightarrow ^{206}\text{Pb}$
- Pb removal R&D: $^{220}\text{Rn} \rightarrow ^{216}\text{Po} \rightarrow ^{212}\text{Pb} \rightarrow ^{212}\text{Bi} \rightarrow ^{212}\text{Po} \rightarrow ^{208}\text{Pb}$

$^{212}\text{Pb}$ is tagged by $^{212}\text{Bi}$-$^{212}\text{Po}$ ($T_{1/2} = 299$ ns)

- $^{212}\text{Pb}$ decay curve ($T_{1/2} = 10.6$ hr)

- Both $^{212}\text{Pb}$ and $^{210}\text{Pb}$ are Po daughter:
  - molecular forms in the scintillator are expected to be similar
Example of PPO distillation

$^{212}$Pb decay curve

Before distillation

After distillation

$\sim 4 \times 10^{-4}$ reduction achieved

$\sim 10^{-4} \sim 10^{-5}$ reduction has been achieved also for dodecane, and pseudocumene distillation

* See also poster #28 G. Keefer
Toward “solar $\nu$ phase”

- Excavation of a new mine tunnel for the distillation system
  (completed: Fall, 2005)
- New computer system for data acquisition and storage of larger data
  (installed: Winter, 2005)
- New electric power ~ 1MW for the distillation system
  (power line construction going on: June, 2006)
- Design of the distillation system
  (almost done: June, 2006)
- Construction of the N$_2$ generator and purge system
  (partly done, will complete in September 2006)
- Construction of distillation system
  (August - September, 2006)
- Construction of “miniLAND” (1-ton detector to measure $^{222}$Rn level after purification, down to $\sim$1 mBq/m$^3$ ($\approx \mu$Bq/m$^3$ for $^{210}$Pb))
- Construction of Kr detector (see also poster #30 C. Mauger)
Toward “solar $\nu$ phase” (continued)

- Engineering run of the distillation system
- Real purification of the KamLAND scintillator
  (this will take a few months …)
- Observation of the solar $^7$Be neutrinos

Control room for the distillation system in the newly excavated mine tunnel
Solar neutrino future

After $\sim 3 \times 10^{-5}$ reduction of $^{210}$Pb and $^{85}$Kr

![Graph showing neutrino events vs. visible energy]
pep and CNO neutrinos

Even after successful $^{210}$Pb, $^{85}$Kr reduction, at KamLAND depth 2,700 m.w.e., spallation $^{11}$C ($T_{1/2} = 20.4$ min.) is a serious background ...

10^{-6} reduction of $^{210}$Pb, $^{85}$Kr assumed
$^{11}$C off-line rejection

muon + neutron tagging (Galbiati et al., hep-ph/0411002)

Most of $^{11}$C are created by

\[ ^{12}\text{C} + X \rightarrow ^{11}\text{C} + n + Y + \cdots \]

\[ X = \gamma, n, p, \pi^{-}, \pi^{+}, e, \mu \]

\~ 95\% of $^{11}$C reaction produce neutrons

3-fold coincidence

(1) muon - (2) neutron (capture time $\sim 210$ $\mu$sec)
- (3) $^{11}$C (lifetime = 29.4 min)
$\mu - n - ^{11}\text{C}$ events in KamLAND data

$(\Delta L < 50 \text{ cm, } \#n_{\text{detected}} > 0)$

$\tau = 29.4 \text{ min}$
Problem: electronics dead time after large $\mu$ signal $\rightarrow$ missing neutrons

$^{11}$C without neutrons (5%)

Veto by $\mu$ only? $\rightarrow$ better $\mu$ fitter with better understanding of $\mu$ events

See also poster: #55 L. Winslow for muon tracker
Low-energy $^8$B neutrino–MSW distortion

- If $^{208}$Tl ($\beta + \gamma$, $Q = 5$ MeV) reduced enough
- $\rightarrow ^{232}$Th reduction needed (distillation works?)

KamLAND: low-energy frontier

from Pena-Garay
Solar $\bar{\nu}_e$, other high energy $\bar{\nu}_e$

PRL 92 (2004) 071301
see also talk by A. Friedland (this morning)

- $\nu_e / SSM-^8B$
  - $< 2.8 \times 10^{-4}$
  - (90 % C.L.)

- Supernova search: almost no B.G.

- See also poster #111 K. Ishii for supernova search

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FIG. 2. Energy distribution of the final event candidates. The tail from reactor $\bar{\nu}_e$ events is visible below 8 MeV.
Invisible nucleon decay
\( n \rightarrow \text{inv.}, \ \text{nn} \rightarrow \text{inv.} \)

- For example, \( n \rightarrow 3\nu, \ \text{nn} \rightarrow 2\nu \) (GUT or other new phys. beyond SM)
- s-shell neutron disappearance from \( ^{12}\text{C} \rightarrow \) highly excited \( ^{11}\text{C}^*, \ ^{10}\text{C}^* \)
- After single neutron disappearance from \( ^{12}\text{C} \) (s shell)
  1. \( ^{11}\text{C}^* \rightarrow ^{10}\text{C} \text{ g.s.} + n \)
  2. \( ^{11}\text{C}^* \rightarrow ^{10}\text{C}^* + n \rightarrow ^{10}\text{C} \text{ g.s.} + n + \gamma \) (3.35 MeV)
- After two neutron disappearance from \( ^{12}\text{C} \) (s shell)
  1. \( ^{10}\text{C}^* \rightarrow ^{9}\text{C} \text{ g.s.} + n \)
  2. \( ^{10}\text{C}^* \rightarrow ^{9}\text{C}^* + n \rightarrow ^{8}\text{B} \text{ g.s.} + p + n \)
- All 4 modes should appear as triple coincidence events.
  \( \rightarrow \) very low background search
- \( \tau(n \rightarrow \text{inv.}) > 5.8 \times 10^{29} \text{ yr} \) (90% C.L.) (factor \( \sim 3 \) improvement)
- \( \tau(\text{nn} \rightarrow \text{inv.}) > 1.4 \times 10^{30} \text{ yr} \) (90% C.L.) (factor \( >10^4 \) improvement)
- See also poster: #110 T. Miletic
Summary

- **Reactor neutrino:**
  - Data taking is going well and will continue
  - All volume calibration is starting soon

- **Geoneutrino:**
  - Efforts to reduce systematic error of B.G.

- **Solar neutrino:**
  - Toward “solar ν phase” ($^{210}$Pb, $^{85}$Kr reduction by $10^{-5}$)
  - Distillation will start in September 2006

- Thank you very much and please keep encouraging KamLAND