KamLAND current status & future prospects

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Workshop on Next Generation Nucleon Decay and Neutrino Detectors
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Muon detector

Inner detector PMTs

Pure water

Buffer Oil

Liquid scintillator (LS) $(\text{CH}_{1.97})$

Balloon

Stainless steel tank $(\varnothing 18\text{m})$

914t

13m

20m

Low-energy event

Muons event

ID Hit Charge

ID Hit Charge

[p.e.]
New improved anti-neutrino data analysis

**reactor-v study** *PRL* (2005)

**geo-v study** *Nature* (2005)

This plot is for **Prompt-Delayed pairs** separated by $\Delta T<1\text{ms}$, and $\Delta R<2\text{m}$. In new analysis variable selection criteria allowed to suppress **accidentals** effectively and to perform **combined analysis** using a $0.9$-$8.5\text{MeV}$ energy range and a $6\text{m}$ fiducial volume.
Selection of anti-neutrino events

Effect from accidentals

\(^{208}\text{Tl}\) and \(^{40}\text{K}\) \(\gamma\)-rays

For each bin in \(E_{\text{prompt}}\) there are \(R_p\), \(R_d\), \(E_d\), \(\Delta T\), \(\Delta R\) parameters.

Muon cuts include full volume \(2s\) veto after a showering muon, \(3m\) cylinder cut along track of a non-showering muon for \(2s\) to suppress the \(^9\text{Li}\) correlated background.

Prompt energy 2.2-2.3MeV

\[ \text{Lratio} = \frac{f_v}{f_v + f_{\text{acc.}}} \]

accidentals (off-time data)

anti-neutrinos (MC)

\[ S/\sqrt{S+N} \] maximum

\[ \text{Lratio} > 0.967 \]
The red (black) points show vertex location of correlated events with and without the selection cut. Left figure shows Prompt, and right figure Delayed events. Anti-neutrino events are distributed uniformly, while accidentals located near the balloon edge.
Estimation of the fiducial volume uncertainty

The fiducial volume (FV) uncertainty, 1.8%, was determined by using the off-axis calibration system and uniformly distributed $\mu$-induced $\beta$-emitter $^{12}$B events. For comparison, the 4.7% FV uncertainty was used for the 2$^{nd}$ KamLAND result.

off-axis calibration system was used to deploy $^{241}$Am$^{9}$Be, $^{210}$Po$^{13}$C, $^{60}$C, $^{68}$Ge, and $^{203}$Hg sources outside of the detector central axis to study vertex reconstruction biases at distances up to 5.75m away from the detector center. This confirmed that the new Tohoku vertex fitter, in addition to improved vertex resolution ($21\text{cm} \to 12\text{cm}$ at $1\text{MeV}$), reconstructs event's position with a bias < 3cm.
Calculation of the expected \((\alpha, n)\) background

\(^{210}\text{Po} \ 5.3\text{MeV} \ \alpha\)-particle interaction on \(^{13}\text{C}\):

(g.s.) \(\alpha + ^{13}\text{C} \rightarrow ^{16}\text{O} + n\ (3-7\text{MeV})\)

\[ n + ^{12}\text{C} \rightarrow ^{12}\text{C} + n + \gamma \ (4.44\text{MeV}) \]

(1\(^{\text{st}}\)) \(\alpha + ^{13}\text{C} \rightarrow ^{16}\text{O}^* \ (6.05\text{MeV}) + n\ (0-0.5\text{MeV})\)

(2\(^{\text{nd}}\)) \(\alpha + ^{13}\text{C} \rightarrow ^{16}\text{O}^* \ (6.13\text{MeV}) + n\ (0-0.5\text{MeV})\)

1\(^{\text{st}}\) (2\(^{\text{nd}}\)) excited states of \(^{16}\text{O}\) decay to \(e^-e^+\) (\(\gamma\)-ray)

all these reactions produce correlated events not distinguishable from anti-neutrino signals

\(\text{Expected number of events:}\)

ground state \(163.3 \pm 18.0\)

excited states \(18.7 \pm 3.7\)

\textbf{Compared to the 2\(^{\text{nd}}\) KamLAND result:}

Error for g.s. reduced: \(32\% \rightarrow 11\%\)

Error for exc. st. reduced: \(100\% \rightarrow 20\%\)

10\% energy scale error was removed
The anti-neutrino energy spectrum

Data taken between March 9, 2002 and May 12, 2007, the 2881 ton-year exposure is used. This is KamLAND only result (no SNO data included) with U/Th geo-ν contributions being free parameters. Scaled spectrum with no oscillations included is excluded at a 5.2σ level, χ² / NDF = 63.9/17, (while 5σ is a formal requirement for discovery of a phenomenon).
The $L_0/E_{\nu_e}$ oscillation plot ($L_0=180\text{km}$)

The KamLAND and CHOOZ data plotted as $\text{Ratio} = (N_{\text{obs}} - N_{\text{bg}})/(N_{\text{exp}})$, where $N_{\text{obs}}$ is number of observed events, $N_{\text{exp}}$ is number of expected in no oscillation case, $N_{\text{bg}}$ is number of expected $^9\text{Li}, (\alpha, n)$, and accidental background events.
The $L_0/E_\nu$ oscillation plot: LMA 0, I, II vs data

The 2nd KamLAND result was obtained for the $E_\nu > 3.4\text{MeV}$ to avoid the geo-$\nu$ background, while data below 3.4MeV has a power to distinguish between different LMA regions. New analysis excluded alternative solutions (LMA 0, LMA II) by more than $4\sigma$. 
New result for oscillation parameters

New feature of this analysis: KamLAND substantially improves mixing angle measurement. Solar data has no effect on the $\Delta m^2$ measurement.

KamLAND+SNO:

$\Delta m^2 = 7.59^{+0.20}_{-0.21} \times 10^{-5} \text{eV}^2$

$\tan^2 \theta = 0.49^{+0.07}_{-0.05}$

KamLAND only:

$\Delta m^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5} \text{eV}^2$

$\tan^2 \theta = 0.56^{+0.14}_{-0.09}$
Expected geo-neutrino signal at KamLAND

Area within 500km gives $\frac{1}{2}$ of the total expected geo $\nu$ flux at the KamLAND location.

Geo-neutrinos carry information about the absolute amount and distribution of the U/Th/K in the crust, mantle and core. This information may help to understand mechanisms of Earth formation, and its dynamics.
The second geo-neutrino result

The Rate+Shape+Time data analysis were performed with the SNO result included to improve precision on the mixing angle. The Th/U mass ratio was fixed at 3.9.

Result: 39.4^{+14.4}_{-14.3} TNU while previous result published in Nature was 57.4^{+32.0}_{-30.0} TNU (TNU = event / 10^{32} target-proton per year)
KamLAND Purification System

- Distillation goal is to remove $^{210}$Pb, $^{40}$K, and Th/U
- pure $N_2$ purge goal is to remove $^{85}$Kr, $^{39}$Ar, and $^{222}$Rn
Background reduction after the 1st stage of purification

About 1700m$^3$ of the KamLAND scintillator were purified. Due to mixing between purified and non-purified scintillator purification effect is smaller than needed for the $^7$Be observation. The upper part of the detector is filled with scintillator after a 2nd pass through the system.

The distribution of events with energy 0.45-0.7MeV (mostly $^{85}$Kr $\beta$-decays)
Detector upgrade towards the solar neutrino detection

95% of the $^{11}$C nuclei are produced in $^{12}$C+$\mu \rightarrow ^{11}$C+n reaction. Detection of the neutron after muon should allow to veto a small part of the detector volume until $^{11}$C decays and reduce background for measurement of the pep and CNO solar neutrinos. Technique was successfully tested in KamLAND but new electronics is needed to improve veto efficiency.

A new **deadtime-free** data acquisition electronics was developed for the solar pep/CNO neutrino observation with KamLAND. It aims to detect all neutrons produced by muons. The number of neutrons after a muon can reach 60~100, and therefore capability of collecting multiple signals is crucial.
Sensitivity to the SN neutrinos after purification

elastic scattering: $\nu_x + p \rightarrow \nu_x + p$

sum of all neutrino flavors

Signal from 1.5MeV proton corresponds to $\sim 250$keV of Visible energy in KamLAND

The proton-recoil energy spectrum in KamLAND from SN ($3\times10^{53}$ergs) at 10kpc from PRD 66, 033001 (2002). Background reduction at the low energy region, a large detector mass, and high H/C ratio makes KamLAND a unique tool for the SN neutrino detection.
Search for neutrino-less double $\beta$-decay in KamLAND

One of the possible scenario of the more distant future of KamLAND is a search for neutrino-less double $\beta$-decay (e.g. $^{150}$Nd, $Q=3.367\text{MeV}$).

Simulations show how KamLAND data would look like if KKDC claim about the neutrino mass is true.

**To do:**
- develop a new liquid scintillator with a high light yield, understand energy resolution well, study background ($^{208}$Tl internal + external), etc
Conclusion

- The “reactor” phase is over with 4.1 years of the detector livetime.
- KamLAND measured $\Delta m^2 = 7.59 \times 10^{-5} \text{eV}^2$ with a 2.8% uncertainty.
- KamLAND improved measurement of $\theta_{12} \approx 35$ degrees.
- Purification of the scintillator has been started. More work is needed.
- Main goals after the purification: $^7\text{Be}$, CNO, pep solar neutrinos, geo-$\nu$, a new window for the SN neutrinos detection (via proton recoil).
- More distant goals: search for neutrino-less double $\beta$-decay, direction sensitive detection of the geo-and-reactor neutrinos with a $^6\text{Li}$ loaded scintillator.