PROCEEDINGS OF SCIENCE

KamLAND

Junpei Shirai∗†
Research Center for Neutrino Science, Tohoku University
E-mail: shirai@awa.tohoku.ca.jp

In this talk following two points are presented which KamLAND has made a special contribution to the studies of neutrinos and the related field; 1) Discovery of the reactor antineutrino oscillation and the precise measurement of the oscillation parameters which lead to a complete solution to the solar neutrino problem, and 2) the first challenge of the detection of the geologically produced antineutrinos (geoneutrinos) which initiated "Neutrino Geoscience".

XVII International Workshop on Neutrino Telescopes
13-17 March 2017
Venezia, Italy

∗Speaker.
†The talk was made for Prof. Atsuto Suzuki who initiated and promoted KamLAND experiment as the group representative.

PoS(NEUTEL2017)003

1. Before KamLAND

Since the last years in 1960s, there was a longstanding solar neutrino problem (SNP), that is, the observed solar neutrino flux is significantly smaller than the prediction of the standard solar model (SSM). Only half or one third of the predicted flux was observed by three kinds of experiments with different thresholds; the chlorine experiment by R.Davis, Kamiokande with water Cherenkov detector by M.Koshiba and two Gallium experiments (SAGE and Gallex/GNO). Physicists considered seriously that the only possibility to reconcile the experiments with the theory was the neutrino oscillation caused by the finite masses of neutrinos, that is, the produced electron neutrinos in the center of the Sun transform to other types of neutrinos which evade the detection.

From the late 1990s to the early 2000s SNO experiment in Canada showed the transformation by detection of three kinds of interactions (CC: $\nu_e + d \rightarrow e^- + p + p$, NC: $\nu_x + d \rightarrow \nu_x + p + n$ and ES: $\nu_x + e^- \rightarrow \nu_x + e^-$) using heavy water target [1]. The initial results on CC reaction [2] in 2001 combined with the Super-Kamiokande experiment [3] strongly indicated the flavor transformation of the solar neutrinos. Although the results are consistent with the neutrino oscillation with the parameters in the so-called large mixing angle (LMA) region, there was no single experiment which uniquely determine the solution. A decisive blow was needed.

On the other hand, study of neutrinos with reactors has a long history. Reactors produce huge amount of electron antineutrinos by beta decays of neutron-rich fission fragments of the fuel elements like ^{235}U, ^{239}Pu, ^{238}U and ^{241}Pu. Six beta decays in average occur per fission of the nuclei generating $\sim$200MeV energy. Thus, a commercial power reactor of typical thermal energy output of 3 GW$_{th}$ produces 5.6×10^{20} pure electron antineutrinos per second. The electron antineutrinos are detected by the delayed coincidence events of the inverse beta decay (IBD) reaction, $\overline{\nu}_e p \rightarrow e^+ n$. The reaction with the delayed coincidence technique has been used in experiments with liquid scintillator (LS) detectors since the discovery of neutrinos by F.Reines and C.Cowan. It has quite excellent capability of identification and energy determination of the $\overline{\nu}_e$ with almost complete rejection of backgrounds. Figure 1 shows the expected reactor $\overline{\nu}_e$ interaction rate without neutrino oscillation (a), $\overline{\nu}_e$ flux generated in a reactor (b) and the IBD cross section (c) [4]. Neutrino oscillation would be observed by smaller event rate than prediction and by spectral distortion.

Among many experimental challenges done until 1990s, Chooz [5] and Palo Verde [6] set the detectors at around 1km from the reactors using several tons to over 10 tons of LS. If Δm^2 was around 10^{-3} eV^2, then the oscillation could be observed with the maximum mixing angle. No evidence was found for neutrino oscillation as presented in Figure 2.

During the time significant improvement was made in the prediction of the reactor antineutrino flux and the spectrum. This was made by measuring spectra of the beta rays emitted from the fission products of ^{235}U, ^{239}Th and ^{241}Pu irradiated by thermal neutrons, and by conversion of the measured spectra into the $\overline{\nu}_e$ spectra. Agreement of the prediction and the measurement was better than 2%. To significantly improve the sensitivity to the reactor $\overline{\nu}_e$ oscillation, it was considered essential to carry out an experiment by taking much longer baseline using reactors with much higher neutrino flux and much bigger LS detector, however this seemed unfeasible.

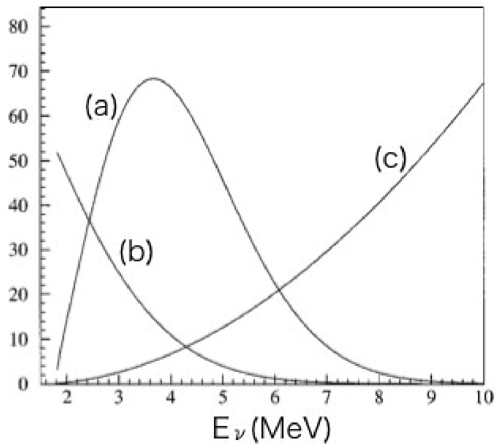

Figure 1: (a) Expected spectra of the reactor $\overline{\nu}_e$ interaction without neutrino oscillation, (b) Reactor $\overline{\nu}_e$ flux, and (c) Cross section of IBD reaction as a function of the $\overline{\nu}_e$ energy [4].

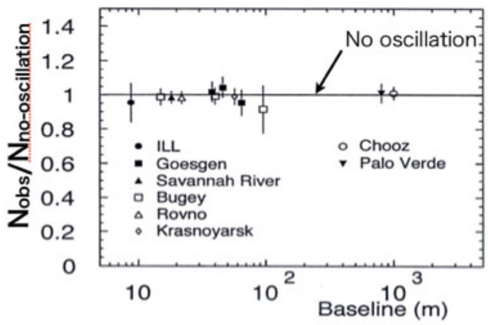

Figure 2: Ratios of the observed numbers of the reactor antineutrino events over the prediction without the neutrino oscillation in experiments before KamLAND as a function of the baseline.

2. KamLAND experiment

The KamLAND detector was constructed at the former Kamiokande cite in Kamioka mine in Gifu prefecture, Japan. Kamiokande was planned for upgrades to be a world largest water Cherenkov detector by Prof. M.Koshiba in Tokyo University with the project leader of Prof. Y.Totsuka in order to further promote the studies of neutrinos. Due to the Super-Kamiokande, the new version of Kamiokande constructed at a new location, Kamiokande became out of use and was transferred to Tohoku University. Prof. A.Suzuki in Tohoku University decided to make use of Kamiokande but not using water but using oil. He proposed a new experiment, KamLAND (Kamioka Liquid scintillator Anti-Neutrino Detector) which is the world's largest LS detector of 1000 ton LS. It would enable a reactor $\overline{\nu}_e$ oscillation search with a baseline of O(100)km and explore $\Delta m^2 \sim$ O(10^{-6})eV^2 which is the two orders higher sensitivity than any other reactor experiments at that time. The proposal was funded by government as a 5 year project, and physicists from Berkeley laboratory and many US institutes represented by Prof. Stuart J. Freedman joined the project. The KamLAND experimental group was formed and the detector construction was started in 1998.

Kamioka is a unique place for a long baseline reactor neutrino experiment. Reactor $\overline{\nu}_e$s come mostly from Kashiwazaki Power Station, world's largest reactor power station, and other power stations in Wakasa Bay area and in Hamaoka, all located at the distance (175$\pm$35) km from Kamioka. The total thermal power reaches 80 GW$_{th}$ which is more than half of all the Japanese power reactors and around 7% of the world's total reactor power.

Figure 3 shows the KamLAND detector. KamLAND was constructed in 1000 m deep underground in Kamioka mine (2700 m.w.e.), and cosmic-ray muon flux is 10^{-5} of the ground level. The center of the detector is the 1000 ton ultrapure LS contained in a transparent balloon of 13 m in diameter and surrounded by transparent buffer oil. The scintillation light emitted by the neutrino interactions in the LS are detected by 1879 large aperture PMTs (1325 newly developed 17-inch and 554 refurbished 20-inch Kamiokande PMTs) mounted in a 18 m-diameter stainless steel spherical tank. The detector (called the inner detector) provides the energy resolution of $6.5\%/\sqrt{E_{[\mathrm{MeV}]}}$ and position resolution of $12\,\mathrm{cm}/\sqrt{E_{[\mathrm{MeV}]}}$. Outside of the spherical tank is the 3200 ton water Cherenkov detector (called the outer detector) equipped with 225 refurbished 20-inch Kamiokande PMTs to detect cosmic-ray muons and also serves as the radiation shield against the surrounding rock.

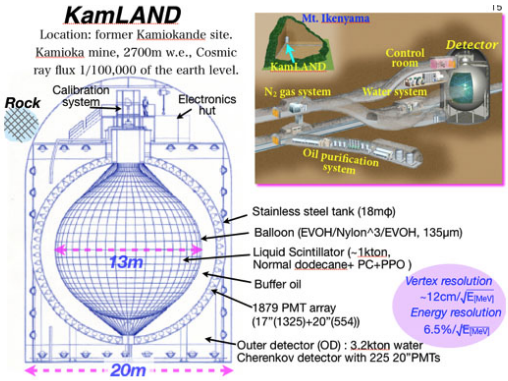

Figure 3: KamLAND detector and the experimental cite.

Detector construction was started in 1998 by dismantling Kamiokande detector with 1000 20-inch PMTs of which 800 were refurbished separately for use in the oil and the water in KamLAND. The access tunnel in the mine was enlarged for heavy trucks to go through the mine. Kamiokande detector was all removed. The bottom of the rock cavern was further dug by 4 m to house the KamLAND spherical tank.

During the construction period check and assembly of the PMTs were quickly made in Sendai and they were sent to KamLAND area and installed in the detector after cleaning. PMTs for the inner detector are made oil proof but not water proof. They were mounted from the top of the spherical tank by using floating boards spread above the water in the tank and the water level was gradually lowered to the bottom.

The balloon which holds 1000 ton LS is made of 3 layers of oriented nylon films sandwiched by EVOH films to make 135 μm thick in total and welded to form spherical shape and suspended by 44 kevlar ropes. More than ten prototype balloons were tested in water, and finally the installation of a real size prototype was rehearsed using the detector tank with the balloon inflated by water. After the rehearsal the real balloon was fabricated.

The purification apparatus consists of water extraction and nitrogen purge towers both for the LS and buffer oil system. Every part of the piping was disassembled and thoroughly washed and cleaned. Radon emanation to the LS from the inner surface of the tanks and piping of the LS purification system was stopped by covering the inner surface of the tanks with the same film as the balloon and by inserting nylon pipes into the piping. Oil filling to the detector was carefully made by monitoring the liquid levels as filling the water in the outer detector in parallel. In November 2001 KamLAND catched a first signal of a cosmic-ray muon traversing the detector as shown in Figure 4.

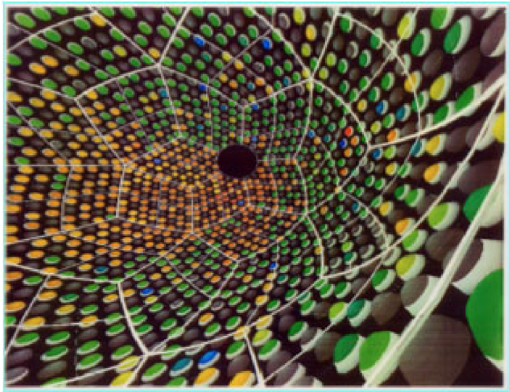

Figure 4: First light of KamLAND in 2001 by a clipping muon signal.

3. Results of KamLAND

In 2002, KamLAND finished the detector tuning and started data taking. Soon after, events were detected which looked like reactor antineutrinos. Analysis results of the data of 145.1 live time days taken from March 4 to October 6 in 2002 [7] are shown in Figure 5 for a scatter plot of delayed vs. prompt energies. Clean signal of the IBD events can be seen, where neutrons are captured on protons to emit 2.2 MeV gamma's. The prompt energy spectrum is shown in Figure 6.

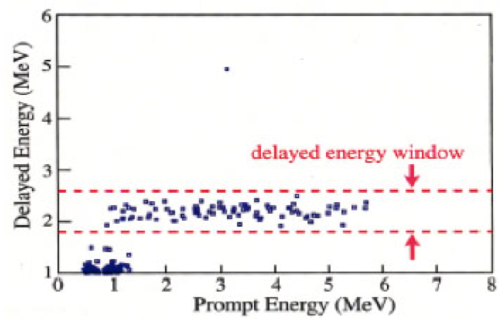

Figure 5: Prompt vs delayed energies for IBD events observed in KamLAND [7].

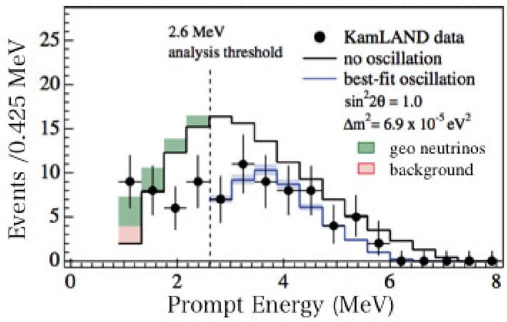

Figure 6: Observed spectrum of the prompt energies of selected IBD events by KamLAND. The expected reactor antineutrino spectrum without oscillation and the best-fit oscillation is shown for energy region above 2.6MeV [7].

In Figure 6 it is clear that not only the observed number of events is significantly smaller than the prediction without oscillation, but the spectrum is distorted compared to the no-oscillation spectrum. We set the analysis 2.6 MeV threshold not to be affected by the low energy backgrounds and possible events of geoneutrinos. Observed number of events above the threshold is 54 including 1 background event expected from ^{9}He/^{8}Li, fast neutrons and accidental events. The number of background-subtracted events is compared with the expectation without oscillation (86.8±5.6). The ratio of observed reactor $\overline{\nu}_e$ events to the expectation in the absence of neutrino disappearance is $(N_{obs} - N_{bkg})/N_{no-osc} = 0.611 \pm 0.085(stat) \pm 0.041(syst)$ which clearly shows the deficit. This is the first evidence of the reactor antineutrino deficit. If the deficit is caused by the neutrino oscillation, all the solutions to the solar neutrino problem were rejected except for the large-mixing angle solution under the assumption of the CPT symmetry.

As the data accumulation went on, a wavy behavior appeared in the prompt energy spectrum which is consistent with neutrino oscillation [8]. Figure 7 shows the ratio of the observed $\overline{\nu}_e$ spectrum to the expectation for no-oscillation as the function of the $L_0/E_{\overline{\nu}}$ where L_0 is taken as 180 km, which is the flux-weighted average reactor baseline. The data is inconsistent with assumptions of the neutrino decay and decoherence. Solar neutrino problem was finally resolved under the CPT symmetry, and the oscillation parameters are precisely determined. The vast region formerly allowed in the Δm^2-$\tan^2\theta$ oscillation parameter space is strongly constrained by KamLAND and the parameter values were precisely determined by combining the solar neutrino experiments.

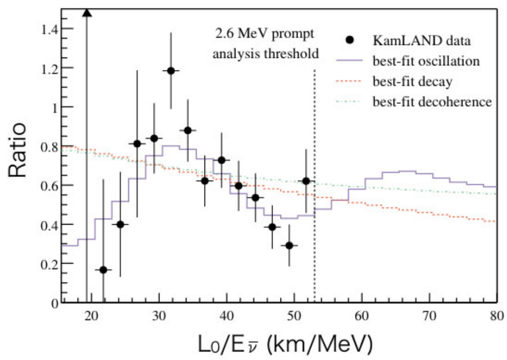

Figure 7: Ratio of the observed $\overline{\nu}_e$ spectrum to the expectation for no-oscillation versus $L_0/E_{\overline{\nu}}$ with L_0=180 km by KamLAND [8]. The data is fitted by oscillation, decay and decoherence of the neutrinos.

KamLAND constructed a distillation plant for LS and conducted purification campaign of the 1000 ton LS in 2007 and 2008. The purpose was to remove low energy backgrounds dominated by (α,n) reaction induced by α particles from ^{210}Po decays in the LS. Figure 8 shows the results of the data taken from 2002 to 2012 for the ratio of the observed spectrum to the no-oscillation expectation and the fit to the survival probability of the reactor antineutrinos as a function of the L_0/E where L_0 is taken as the 180 km. The contribution of geoneutrinos is subtracted. A much clearer oscillation pattern with almost two cycles can be seen. Δm^2 is measured with 2.5% uncertainty as $(7.54 \pm 0.19(\mathrm{stat.}) \pm 0.18(\mathrm{sys.})) \times 10^{-5}\mathrm{eV}^2$ by KamLAND only, which make a great contribution to determine the oscillation parameters with solar neutrino experiments.

4. Challenge to geoneutrino detection

KamLAND is the first experiment to challenge the detection of geoneutrinos, which are the geologically produced electron antineutrinos. The Earth is a quite active planet whose inside is known to be very hot. The thermal energy causes various phenomena such as volcanic activity, earthquake activity, mountain-building activity, and large-scale movements like continental drifts, mantle convection and generation of the geomagnetic field. The origin and the amount of the heat for these activities is of fundamental importance to be understood for studying the internal structure and evolution of the Earth. The Earth's surface heat outflow is estimated by geothermal measurements to be around 47±2 TW [10]. A large contribution is considered to come from

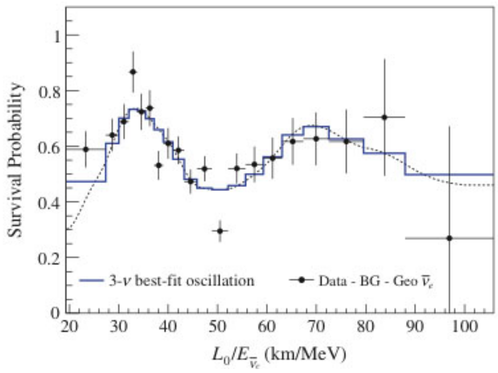

Figure 8: Ratio of the observed $\overline{\nu}_e$ spectrum to the expectation for no-oscillation as a function of $L_0/E_{\overline{\nu}}$ for the KamLAND data with L_0=180 km. The solid histogram is the best fit survival probability from the 3-ν flavor analysis using only the KamLAND data [9].

radiogenic heat generated by decays of radioactive elements mainly of ^{238}U, ^{232}Th and ^{40}K. Direct measurement of these elements by taking the samples from deep inside the Earth is impractical. Detection of electron aintineutrinos from the Earth would make the studies possible, because they are produced by the beta decays of these elements and they directly go out through the Earth without interactions. However, the energies of the geoneutrinos are very low and the detection is quite difficult. Therefore, geoneutrino detection seemed almost a dream for geoscientists.

Among the geoneutrinos a part of them from ^{238}U and ^{232}Th have energies above the threshold of the IBD reaction (1.8MeV) and could be detected. KamLAND made a first challenge to the geoneutrino detection in 2005. Figure 9 shows the results [11]. In the figure a black solid line is the summed spectrum of the reactor antineutrinos, (α,n) reaction and accidental backgrounds. The measured spectrum shows an enhancement of 25^{+19}_{-18} events over the background. Although it is statistically weak, the results shows that a direct method to explore the Earth interior is obtained for the first time. This means the opening of a new research field of “Neutrino Geoscience” as the “Neutrino Astrophysics” which was opened by the first detection of the supernova neutrinos by Kamiokande experiment. It is quite interesting that KamLAND rebuilt of the Kamiokande detector made another pioneering work.

KamLAND continues the measurement of the geoneutrinos. Figure 10 shows the preliminary results from the data collected in 3901 live-time days. The left panel shows the time variation of the low energy event rate with prompt energies of 0.9-2.6 MeV and the expected rates of reactor antineutrinos and background events. Purification campaign of the 1000 ton LS was made twice in 2007 and 2008 as shown by vertical bands. It reduced significantly the ^{210}Pb nuclei in the LS which cause the IBD-mimicking reaction of ^{13}C$(\alpha,n)^{16}$O through α-decay of the daughter nuclei of ^{210}Po. By shutdown of all Japanese reactors due to the great east Japan earthquake on March 11, 2011, major contribution of reactor $\overline{\nu}_e$ events has gone. Therefore, high quality geoneutrino data has been collected. The right panel of Figure 10 shows a comparison of the observed event rates with expected background rates of reactor neutrinos and other backgrounds. Contribution of geoneutrinos can be seen clearly as an upward shift of the observed rate above the expected rate of reactor $\overline{\nu}_e$ plus known backgrounds.

In Figure 11 the bottom panel shows preliminary results of the observed prompt energy spec-

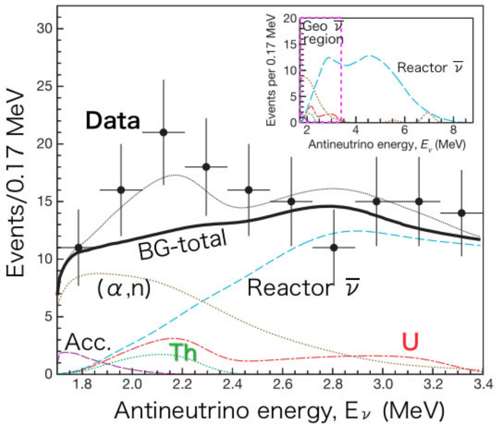

Figure 9: Observed energy spectrum of the electron antineutrino candidates by KamLAND [11]. Thick solid line shows the sum of the expected components of reactor $\overline{\nu}_e$ and other backgrounds excluding the geoneutrino signal. The inset shows the expected spectra extended to the higher energy. Geo $\overline{\nu}_e$ components of ^{238}U and ^{232}Th are prediction of the reference model assuming 16TW radiogenic heat.

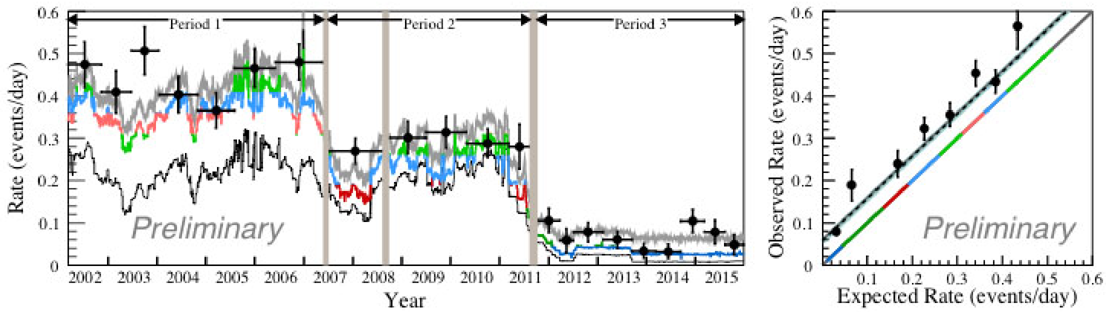

Figure 10: Preliminary results on the time variation of the event rates of the low energy antineutrino candidates with prompt energies of 0.9-2.6 MeV for the data of 3901 livetime days taken by KamLAND. Left panel: Variation of the observed event rates and the expectation of the reactor $\overline{\nu}_e$'s (black line) and reactor $\overline{\nu}_e$'s+backgrounds (colored line). The analysis does not include the periods in the vertical bands which correspond to the purification campaign in 2007 and 2008, and the installation of a balloon of the KamLAND-Zen in 2011. Right panel: Observed vs. expected rates from reactor $\overline{\nu}_e$'s + backgrounds.

trum of the antineutrino candidates with the best-fit spectra of the reactor $\overline{\nu}_e$, (α,n) and accidental backgrounds. The background-subtracted spectrum with expectations for geoneutrino contributions from ^{238}U and ^{232}Th based on a reference model [12] is shown in the upper panel. The best fit and contours of confidence levels of the numbers of ^{238}U vs. ^{232}Th geoneutrino events is presented in Figure 12.

The obtained geoneutrino flux from ^{238}U and ^{232}Th decays is $3.9^{+0.7}_{-0.6} \times 10^6$ cm^{-2}s^{-1}. Increased statistics and a remarkable decrease of the reactor $\overline{\nu}_e$s after 2011 stimulated more precise discussion about the ^{238}U and ^{232}Th amount in the Earth. For example, the hatched area in Figure 12 is the prediction of the geological reference model [12] based on the BSE (Bulk Silicate Earth) model. The KamLAND results is consistent with the prediction. The KamLAND data is getting a sensitivity to check the Th/U mass ratio of the whole Earth which is known as around 3.9

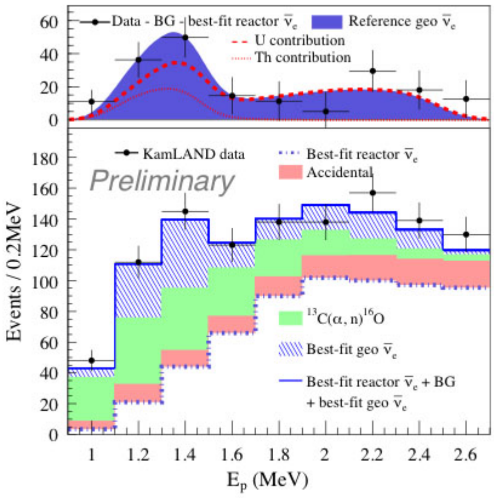

Figure 11: Bottom panel: Prompt energy spectrum observed by KamLAND (dots with error bars), and the fits by reactor $\overline{\nu}_e$'s, backgrounds and ^{238}U+^{232}Th geoneutrinos. Top panel: The observed spectrum after subtraction of reactor $\overline{\nu}_e$'s and the background. Dotted lines are ^{238}U and ^{232}Th geoneutrino contributions. Blue-shaded spectrum is the expectation of the geological reference model [12].

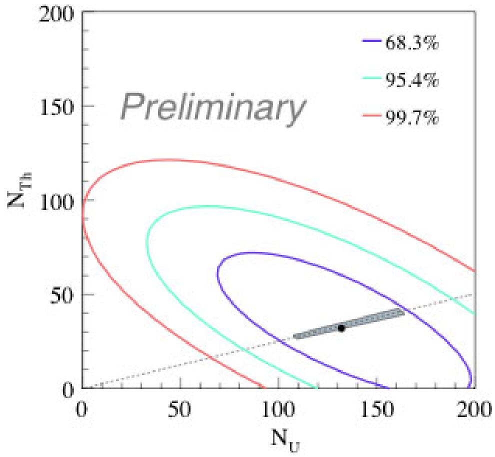

Figure 12: The best fit and the contours of the confidence levels to the number of geoneutrinos from ^{238}U vs ^{232}Th observed by KamLAND. A prediction of the Earth model[12] is shown by a small hatched area and the dashed line shows the Th/U mass ratio of 3.9 derived from chondritic meteorites.

from the geological studies on the abundances in chondritic meteorites. Moreover, the U and Th amount subtracted by the contribution from the crust provides the U and Th amounts in the mantle. As sown in Figure 13 KamLAND is starting to discriminate the different types of the BSE models for the mantle.

Observation of geoneutrinos has been making a great impact on the field of geophysics. The new research field of Neutrino Geoscience is now promoted worldwide. In fact, geoneutrino measurement is now included as one of the main physics items in many ongoing and planned large-scale neutrino experiments like Borexino, SNO+, JUNO, Hanohano, OBK, and Jinping Neutrino Experiment.

5. Prospect of KamLAND

KamLAND has made big contributions to the neutrino physics by the observation of reactor $\overline{\nu}_e$ oscillation and geoneutrino measurements. Since the start of KamLAND the high quality of the data have been further improved by the construction of the LS-distillation plant and introduction of the new electronics system (Mogura). Challenges have been made also to the ^{8}B and ^{7}Be solar neutrino detection. From 2011 new experiment of KamLAND-Zen searching for $0\nu\beta\beta$ decay of ^{136}Xe nucleus has been carried out to test the Majorana nature of neutrinos using the ultra-low radioactive environment of KamLAND. Moreover, other physics programs have been started in KamLAND in the astrophysics field by the detection of supernova and GRB-associated neutrinos.

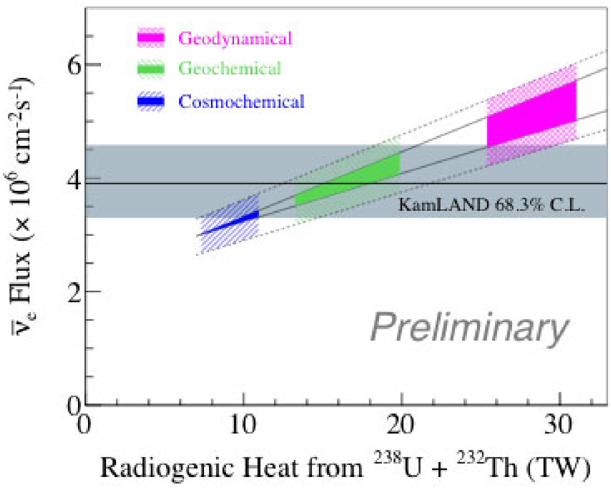

Figure 13: Preliminary results of the ^{238}U plus ^{232}Th geoneutrino flux measured by KamLAND. Prediction of the $\overline{\nu}_e$ flux by different mantle models is shown by sloped bands started at 7 TW. Solid lines show the homogeneous and sunken-layer hypotheses for ^{238}U and ^{232}Th distribution. Dashed lines show the uncertainty of the crustal contribution.

Many R&Ds are going on in parallel for the higher sensitivities. KamLAND continues to make further contributions to the neutrino physics.

6. Summary

- KamLAND is the first O(100)km long baseline reactor antineutrino experiment using a 1000ton LS detector to challenge the SNP.
- KamLAND made the first observation of the reactor $\overline{\nu}_e$ disappearance and the oscillatory pattern in the spectrum showing the clear evidence of the neutrino oscillation.
- KamLAND has solved the solar neutrino problem and determined the oscillation parameter with great precision.
- KamLAND made the first challenge to the geoneutrino detection which opened the new research field of Neutrino Geoscience.
- KamLAND continues measurement of geo-neutrinos and astronomical neutrinos, and promotes KamLAND-Zen project for $0\nu\beta\beta$ search using the ultra-low background facility.

Acknowledgments

We would like to express our great appreciation to Kamiokande and Super-Kamiokande people and also to the local people in Kamioka for providing continuously warm support and encouragement to KamLAND. The author gives a special thank to the organizing committee for providing an opportunity to attend the workshop and excellent hospitality throughout the workshop. The

KamLAND experiment is supported by the Grant-in-Aid for Speccially Promoted Research under Grant No.21000001 of the Japanese Ministry of Education, Culture, Sport, Science and Technology; the World Premier International Research Center Initiative (WPI Initiative), MEXT, Japan; Stichting FOM in the Netherlands; and under US Department of Energy (DOE) Grant No. DE-AC02-05CH11231, as well as other DOE grants to individual institutions. The Kamioka Mining and Smelting Company has provided service for activities in the mine.

References

[1] B.Aharmin *et al.*, (SNO Collaboration), *Phys. Rev.* **C72**, 055502 (2005).

[2] B.Aharmin *et al.*, (SNO Collaboration), *Phys. Rev.Lett.* **87**, 071301 (2001).

[3] Y.Fukuda *et al.*, (Super-Kamiokande Collaboration), *Phys. Rev.Lett.* **86**, 5651 (2001).

[4] C.Bemporad, G.Gratta, and P.Vogel, *Rev. Mod. Phys.* **74**, 297 (2002).

[5] M.Appolonio *et al., Phys. Lett.* **B466**, 415 (1999).

[6] F.Boehm *et al., Phys. Rev.* **D62**, 072002 (2000).

[7] K.Eguchi *et al.,* (KamLAND Collaboration), *Phys. Rev. Lett.* **90**, 021802 (2003).

[8] T.Araki *et al.,* (KamLAND Collaboration), *Phys. Rev. Lett.* **94**, 081801 (2005).

[9] A.Gando *et al.,* (KamLAND Collaboration), *Phys. Rev. D* **88**, 033001 (2013).

[10] J.H.Davies and D.R.davies, *Solid Earth* **1** (1), 5-24 (2010).

[11] T.Araki *et al.,* (KamLAND Collaboration), *Nature(London)* **436**, 499 (2005).

[12] S.Enomoto, E.Ohtani, K.Inoe and A.Suzuki, *Earth Planet. Sci. Lett.* **258**, 147 (2007).