Reactor and geologically-produced antineutrinos

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Abstract. Intense and well-understood neutrino production at nuclear power reactors has been and planned to be used for studying various properties of neutrinos and important physics parameters such as magnetic moment, Weinberg angle, sterile component, $\theta_{12,13}$, $\Delta m^2_{21,31}$ and so on. Highlighted here are the recent precise measurement of $\Delta m^2_{21}$ at about 180km baseline with reactor neutrinos. Studying geophysics with neutrinos is one of applications using neutrinos as a probe for peering astronomical objects. The big and low-background detector dedicated for the long-baseline reactor experiment is also applicable to observe geologically-produced $\bar{\nu}_e$s and the first observational results from the experiment is also reported here.

1. Reactor neutrinos
Since the first discovery of neutrinos, nuclear reactors have been intensively used for studying neutrino properties. Through the development and improvements of various reactor experiments, neutrino production at nuclear reactors and observation of antineutrinos with inverse beta decay reaction on proton have become one of the most established method.

Neutrinos from nuclear power reactors are more than 99.999% pure anti-electron-neutrino at $E_\nu > 1.8$ MeV. Only 4 fissile nuclei ($^{235}$U, $^{238}$U, $^{239}$Pu and $^{241}$Pu) dominate the neutrino production and similar energy release from those fissile nuclei ($^{235}$U:201.7, $^{238}$U:205.0, $^{239}$Pu:210.0, $^{241}$Pu:212.4 MeV [1]) makes strong correlation between thermal power output and neutrino flux. Neutrino spectra from their fission, except $^{238}$U have been experimentally obtained [2] at ILL through a procedure, measurement of beta spectrum with spectrometer, fitting with 30 hypothetical beta spectra and conversion of beta spectra to neutrino spectra. Since $^{238}$U doesn’t go to fission with thermal neutrons, its fission spectra has been theoretically calculated [3] considering 744 traces of fission products. Contribution of 4 fissile nuclei changes in time as fuel burns, but its evolution is traceable from initial composition. Thus, neutrino flux is calculable at a few % level from initial enrichment and history of thermal power output. The uncertainty is usually dominated by an accuracy of cooling-water flow-meters.

A few number of neutrino reactions have been adopted for the observation, inverse beta decay on proton ($\bar{\nu}_e + p \rightarrow e^+ + n$), electron scattering ($\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$) and deuteron disintegration ($\bar{\nu}_e + d \rightarrow \bar{\nu}_e + p + n$ etc), so far. Proton has a big advantage as an anti-electron-neutrino target. In addition to its clear delayed coincidence signature, transparent and bright liquid scintillator is available at low cost. Furthermore, its cross section is calculable with a help of inverse reaction (neutron decay). Recent precise measurement of neutron lifetime with ultra cold neutrons, $\tau_n = 885.7 \pm 0.8$ sec, greatly improved the precision of inverse beta decay cross section to $\sim 0.2%$ [4].
Overall interaction rate and also neutrino spectra models have been experimentally examined at a good accuracy \([5, 6]\). Thanks to thorough previous experiments, current reactor experiments can predict expected spectrum at a few \% level without reference detectors close to reactor cores. The latest long baseline experiment, KamLAND, observes neutrinos from country-wide many reactor cores. Its successful observation without near detectors became possible thanks to the knowledge from previous efforts for understanding reactor neutrinos.

Current challenges to search for finite \(\theta_{13}\) requires sub \% precision of signal rate and reference detectors are necessary for the precision. For such an accuracy, systematic error of experiments are also big issue and various methods to minimize the errors are discussed, such as identical detectors, movable detector and multi references. Another issue to be controlled is effects from long-lived nuclei such as \(^{106}\)Ru \((T_{1/2} = 372\) days\), \(^{144}\)Ce \((285\) days\) and \(^{90}\)Sr \((28.6\) years\) \([7]\). They stagger relation between thermal power and neutrino flux at low energy region. In order to estimate their contribution, histories of fuel and also spent fuel have to be properly traced. Bias effect from spent fuel stored in the onsite pool to the \(\theta_{13}\) experiment is discussed in \([8]\).

Most of studies are done at the energies above the inverse beta decay threshold, 1.8 MeV. And the spectrum below the threshold is not calibrated very well and the slow glow effect of long-lived nuclei is much serious at the low energy region.

2. Geo-neutrinos

The earth is the most familiar astronomical object. However, its properties are not known very well. One of the most important parameter to understand the earth is the heat generation. It controls earth formation and evolution and is a driving force of mantle and outer core convection. Thus, it is important for understanding the structure of the earth and also various phenomena close to us, such as earthquake, volcano, eruption and terrestrial magnetism.

Total heat released from the surface of the earth was once calculated to be \(44.2 \pm 1\) TW \([9]\). The estimation is based on data from \(\sim 25,000\) bore-holes at more than \(20,000\) locations around the world. Despite the small quoted error, a re-evaluation of the same data provided much smaller value, \(31 \pm 1\) TW \([10]\), telling difficulty of extrapolation of the data to the whole surface. Estimation of the heat sources requires an earth model such as the bulk silicate earth (BSE) model, but the model itself requires heat budget model during the earth formation and evolution. Compromising global knowledge, the BSE model, using analysis of the CI carbonaceous chondrite meteorite as an origin of the earth, predicts radiogenic heat generation of 19 TW (about 8 TW U, 8 TW Th and 3 TW K).

This major heat source may be determined by an observation of anti-neutrinos emitted in their decays. Neutrino emission is directly connected to their heat generation with the formula.

\[
\begin{align*}
^{238}\text{U} & \rightarrow^{206}\text{Pb} + 8^{4}\text{He} + 6e^- + 6\bar{\nu}_e + 51.7\text{MeV} \\
^{232}\text{Th} & \rightarrow^{208}\text{Pb} + 6^{4}\text{He} + 4e^- + 4\bar{\nu}_e + 42.7\text{MeV} \\
^{40}\text{K} & \rightarrow^{40}\text{Ca} + e^- + \bar{\nu}_e + 1.311\text{MeV (89.28\%)} \\
^{40}\text{K} + e^- & \rightarrow^{40}\text{Ar} + \nu_e + 1.505\text{MeV (10.72\%)}
\end{align*}
\]

In 1953, Gamov has already pointed the possibility of these neutrinos as a background of reactor neutrino observation in a letter to Reines. Possibility of using neutrinos to study Earth science was first suggested by Marx \([11]\), Markov \([12]\) and Eder \([13]\) in 1960's, and then revived several times by several authors. Recent low background and large anti-neutrino detector for a long baseline reactor neutrino experiment has an opportunity of the first practical access to the radiogenic heat generation in the earth with neutrinos. Endpoint energies of anti-neutrinos from above decays are 3.27 MeV \((^{238}\text{U})\), 2.25 MeV \((^{232}\text{Th})\) and 1.31 MeV \((^{40}\text{K})\), thus, observation of
anti-neutrinos from U/Th is the current interest for experiments using the inverse beta decay reaction.

Translation of neutrino flux to the heat generation is affected by inhomogeneous distribution of radioactive nuclei. Large nuclei, U/Th, are thought to be deduced from dense material during earth formation and evolution and concentration of them ranges orders of magnitude at various layers of the earth. A model is used for estimating geo-neutrino flux at the experimental site. CC/OC stand for continental and oceanic crust and CS and OS stand for their sediments in Table.1. Roughly, half are in the thin crust and rest are in the mantle. Thorium to uranium ratio is fairly stable as $\sim 3.9$ despite large variation of their absolute concentrations. For a practical estimation, local geology must also be considered [14, 15]. And the most important thing to use neutrinos as a probe for studying interior of the earth is to understand how neutrinos travel. Determination of neutrino oscillation parameters with reactor and solar neutrino experiments is the starting point of the applied neutrino physics.

### Table 1. A reference model[15].

| layer type | U [ppm] | Th [ppm] | layer type | U [ppm] | Th [ppm] |
|------------|---------|----------|------------|---------|----------|
| upper CC   | 2.8     | 10.7     | OS         | 1.7     | 6.9      |
| middle CC  | 1.5     | 6.1      | OC         | 0.10    | 0.22     |
| lower CC   | 0.2     | 1.2      | mantle     | 0.012   | 0.048    |
| CS         | 2.8     | 10.7     | core       | 0       | 0        |

### 3. Various physics targets

As going farther from reactor cores, various physics targets can be studied. At very close places, neutrino magnetic moment, $\mu_{\nu}$, have been studied using electron scattering. The differential cross section of the scattering is expressed with the following formula,

$$
\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi} \left[ (g_V + g_A)^2 + (g_V - g_A)^2 \left( 1 - \frac{T}{E_{\nu}} \right)^2 - (g_A - g_V) \frac{m_e T}{E_{\nu}^2} \right] + \frac{\pi \alpha^2 \mu_e^2}{m_e^2} \frac{1}{T} - \frac{T}{E_{\nu}}
$$

where the first term is the standard model weak interaction and the second term is the magnetic moment interaction. Increasing contribution of magnetic moment interaction and less accuracy of neutrino spectrum calculation are matter to compromise. TEXONO [16] looked for distortion at lower energy ($\sim 10$ keV threshold) with 1.06 kg HPGe and MUNU studied higher energy region (700 keV threshold) with CF$_4$ TPC. The best limit is so far from MUNU experiment and $\mu_{\nu} < 9 \times 10^{-11} \mu_B$ at 90% C.L.[17].

Weinberg angle, $\sin^2 \theta_W$, is another target at a close site. Inspired by NuTeV result off by $3\sigma$ from the standard model, verification of the Weinberg angle at small $Q^2$ ($\sim 4$ MeV$^2$) and with different systematics become important. A near detector of future $\theta_{13}$ experiment may be adopted [18] for the purpose by measuring $\bar{\nu}e$ scattering with normalization of $\bar{\nu}p$ at a comparable precision with the NuTeV experiment.

At sub km scale, sterile neutrino component may be searched for as a bi-product of $\theta_{13}$ measurement. Unexpected distortion of neutrino spectrum other than $\theta_{13}$ and $\theta_{12}$ oscillations is a possible signature of sterile neutrinos [19].

Survival probability of reactor neutrinos is well approximated by the following formula.

$$
P_{\bar{\nu}e} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E} \right)
$$
Figure 1. The ratio of observed signal rate to no-oscillation expectation is plotted as a function of $L_0/E$. KamLAND data is divided according to observed energies and the constant $L_0$ is chosen at the effective distance, 180 km. Dashed curve shows an ideal oscillation pattern as if one reactor existed and histograms are with real reactor distribution.

At a km scale, exploration of $\theta_{13}$ is the most interesting physics target. It is the last unmeasured mixing angle and it determines the accessibility to the CP phase and the mass hierarchy of lepton sector. Experiment at the proper distance has been already performed at CHOOZ and Palo Verde. Both resulted in consistent neutrino event rate with no oscillation, $R = 1.01 \pm 2.8\% $ (stat.) $\pm 2.7\% $ (syst.) (CHOOZ [20]), and only the upper limit is drawn on $\theta_{13}$-$\Delta m^2_{31}$ space. Improvement of the experiment apparently requires higher statistics and reduction of systematic error. Several experiments [21] using (identical) near detectors, optimized baseline, larger detectors, deeper/better veto and movable feature have been proposed under a compromise among quickness, cost and sensitivity.

Table 2. $\theta_{13}$ proposals.

| project            | planned start | 90% C.L. $\delta (\sin^2 2\theta_{13})$ |
|--------------------|---------------|---------------------------------------|
| CHOOZ              | finished      | 0.15                                  |
| Double CHOOZ, France | 2007/2008    | 0.02-0.03                             |
| Kaska, Japan       | 2008          | 0.02                                  |
| Daya Bay, China    | 2008/2009     | 0.01                                  |
| Braidwood, USA     | 2009          | 0.01                                  |
| Angra, Brazil      | -             | 0.01                                  |

At a distance of several kms, if several phases of 1-3 oscillation can be observed in neutrino spectrum, it will improve the precision of $\Delta m^2_{31}$. The best distance for determination of $\theta_{12}$ with reactor neutrinos is around 50 km and possible sensitivity and site are discussed in [22].

Going farther, KamLAND is located at about 180 km distance, effectively. The distance is about optimal to determine $\Delta m^2_{12}$ with an observation of spectrum distortion. However, in order to acquire sufficient statistics, very big detector (kton class) and intense neutrino sources are necessary. In KamLAND case, 7% of world total reactors (70 GW$_{\text{thermal}}$) are located at 130-220 km distance. As reactor neutrino signal becomes weaker, geologically-produced neutrino becomes a major signal. If detectors are clean enough ($\sim 10^{-15}$ g/g U and Th level) and large enough (more than several hundred tons), geo-neutrino observation will be possible. KamLAND meets both requirements and is the first practical candidate pioneering “neutrino geophysics.”
4. KamLAND results
KamLAND[23] contains 1,200 m$^3$ liquid scintillator (1,2,4-trimethylbenzene 20%, dodecane 80% and PPO 1.52g/l as a fluor) and is covered by 2,700 m.w.e. mountain rock under Mt. Ikenoyama. Photons from a positron emitted by the inverse beta decay reaction and a 2.2 MeV gamma ray from the neutron capture on a proton are monitored by 1879 PMTs with 34% photo-coverage. The liquid scintillator was purified by the water extraction technique and the achieved impurity level is $3.5 \pm 0.5 \times 10^{-18}$ g/g for Uranium and $5.2 \pm 0.8 \times 10^{-17}$ g/g for Thorium, low enough to observe reactor and geologically-produced anti-neutrinos. $^{210}$Pb, a daughter nucleus of $^{222}$Rn, is about 50 mBq/m$^3$. It is a major background below 1.5 MeV ($^{210}$Bi) as singles and alpha decay of $^{210}$Po is the main source of $^{13}$C($\alpha$, n) background. Reactor neutrino analysis uses events with visible energies more than 2.6 MeV ($E_{\text{vis}} \simeq E_{\bar{\nu}_e} - 0.8$ MeV) for avoiding uncertainty of geo-neutrino contribution ($E_{\bar{\nu}_e} < 3.27$ MeV).

The first results [24] were deduced from 162 ton-year exposure from March 4th to October 6th of 2002. Observed number of events was 54 where expected signal is 86.8 ± 5.6 and expected background is 2.8 ± 1.7, resulting 99.95% C.L. significance of neutrino disappearance. This evidence of reactor neutrino disappearance has solved the long-standing “solar neutrino problem” in a process of elimination, combining with the solar neutrino data. Since then, KamLAND has improved analysis tools, fiducial volume enlargement by factor 1.33 (5.5 m radius) with more uniform energy scale and less vertex bias, relaxed coincidence criteria gaining factor 1.15 better detection efficiency (89.8%), factor 3.55 longer run-time (515.1 days). Considering factor 0.77 lower reactor operation, total statistical improvement is factor 4.2. So far achieved systematic errors and background summary for the improved analysis [25] are shown in Table 3 and 4.

**Table 3.** Estimated systematic errors (%).

| Source                  | Error (%) |
|------------------------|-----------|
| Fiducial volume        | 4.7       |
| Reactor power          | 2.1       |
| Energy threshold       | 2.3       |
| Fuel composition       | 1.0       |
| Cut efficiency $\bar{\nu}_e$ | 1.6       |
| $E_{\text{vis}}$ spectra | 2.5       |
| Live time              | 0.06      |
| Cross-section          | 0.2       |
| **Total**              | **6.5**   |

**Table 4.** Background summary (events).

| Source                      | Events (%) |
|-----------------------------|------------|
| Accidental                  | 2.69 ± 0.02|
| Spallation                  | 4.8 ± 0.9  |
| Fast neutron                | < 0.9      |
| $^{13}$C($\alpha$, n)       | 10.3 ± 7.1 |
| **Total**                   | **17.8 ± 7.3**|

The 2nd results with 766.3 ton-year exposure accumulated 258 events where 365.2 ± 23.7 signals and 17.8±7.3 backgrounds are expected. Improved statistics strengthened the significance...
of neutrino disappearance to 99.9998% C.L. and made the spectral distortion analysis more powerful. Observed spectrum doesn’t agree with a scaled no-oscillation spectrum and the obtained significance of the spectrum distortion is more than 99.6% ($\chi^2$/dof = 37.3/19 for arbitrarily chosen 20 equal expected-rate bins). Combining the rate and shape information, no-oscillation is excluded at 99.99995% C.L. Survival probability of neutrino is expressed with $L/E$ in models, neutrino oscillation, decay and decoherence. To illustrate relation between survival probability and distance, $L_0/E_\nu$ distribution is plotted in Fig.1 together with the best-fit models. Here, different distances to various reactors are represented by effective distance, $L_0 = 180$ km. KamLAND data show clear oscillatory behavior and matches with neutrino oscillation, but monotonically decreasing decay and decoherence models can not explain the behavior.

Clear oscillation pattern also provides better determination of oscillation parameters, especially $\Delta m^2_{21}$. Combining with solar neutrino data, allowed region of oscillation parameters is obtained as shown in Fig.2. Mass difference is mainly determined by KamLAND as $\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}$ eV$^2$ and mixing angle is by solar data, $\tan^2 \theta = 0.40^{+0.10}_{-0.07}$. KamLAND has a plan to improve fiducial volume estimation by deploying an all-volume calibration device, by enlarging fiducial volume and by eliminating $^{13}$C($\alpha$, n) background with further purification of the liquid scintillator. Assuming 3% rate error and 1% scale error with these improvements and 3 kton-year data accumulation, one can draw a sensitivity plot of KamLAND alone as solid (black) lines in Fig.2. Future KamLAND has capability to reject full mixing, to improve $\Delta m^2$ by factor $\sim 2$ and to determine mixing angle at comparable precision with current solar data.

Precise determination of neutrino oscillation parameter with reactor and solar neutrinos made possible to use neutrinos as a probe to investigate astronomical objects. The largest anti-neutrino detector, KamLAND, has made the first experimental investigation of geologically-produced antineutrinos [26] with data acquired from March 9th, 2002 through October 30th, 2004, total exposure of $(4.87 \pm 0.24) \times 10^{31}$ target proton years. Energy window for the geo-neutrino analysis is 0.9 to 2.6 MeV in visible energy. In order to improve more difficult background situation at lower energy, tighter selection criteria are used and overall efficiency is reduced from 0.898 (reactor analysis) to 0.687 $\pm$ 0.007 (geo-neutrino analysis). Background estimation for geo-neutrino analysis is summarized in Table.5.

By subtracting estimated background from total observed number of events, 152, we obtain an excess of $25^{+19}_{-18}$ events consistent with the prediction of 19 events from a reference geological model [15]. The excess corresponds to interaction rate of $5.1^{+3.9}_{-3.6} \times 10^{-31}$ $\bar{\nu}_e$/target-proton/year.

Uranium and Thorium contribution can be individually determined using spectrum information in an ideal case. But with the limited statistics shown in Fig.3, there is a sensitivity
Table 5. Background summary for geo-neutrino analysis.

| Source          | Rate (events/hr) |
|-----------------|------------------|
| Reactor neutrino| $80.4 \pm 7.2$   |
| $^{13}$C$(\alpha, n)$ | $42 \pm 11$   |
| Accidental      | $2.38 \pm 0.01$  |
| Spallation      | $0.30 \pm 0.05$  |
| Reactor long-lived | $1.9 \pm 0.2$ |
| Total background| $127 \pm 13$     |

only on the total number of U/Th events. By fixing Th/U ratio to 3.9 from geophysics knowledge and performing likelihood rate+shape analysis, the best-fit number of observed geo-neutrino events was obtained as 28 events and 90% confidence interval was obtained as 4.5-54.2 events. Since the significance of the geo-neutrino detection is still only about 95% level, 99% C.L. upper limit of geo-neutrino flux was calculated ($\phi < 1.62 \times 10^7 \bar{\nu}_e$/cm$^2$/sec). This flux upper limit is still 3.8 times larger than the model expectation and statistics is yet poor to discriminate geophysical models. But this is the first step on "Neutrino geophysics" and KamLAND first established the method to observe geo-neutrinos.

Future purification of liquid scintillator will improve statistical significance a lot at KamLAND. And proposed experiments far from any nuclear reactors and on the oceanic plate will have statistical advantages. Adding such experiments and performing global measurement, substantial improvements on geophysics will be brought by neutrino experiments.

5. Closing remark
Rosy and fruitful future will be waiting along anti-neutrino studies.

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