Precision measurement of oscillation parameters with reactors

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Abstract. We review the potential of long and intermediate baseline reactor neutrino experiments in measuring the mass and mixing parameters. The KamLAND experiment can measure the solar mass squared difference very precisely. However it is not at the ideal baseline for measuring the solar neutrino mixing angle. If low-LMA is confirmed by the next results from KamLAND, a reactor experiment with a baseline of 70 km should be ideal to measure precisely the solar neutrino mixing angle. If on the contrary KamLAND re-establishes high-LMA as a viable solution, then a 20–30 km intermediate baseline reactor experiment could yield very rich phenomenology.

The first results from the KamLAND experiment in Japan [1] has showed that the electron antineutrinos undergo flavor oscillations on their way from their source to the detector. This result coupled with the assumption of CPT invariance has put to rest all speculations regarding the true solution of the long standing solar neutrino problem, where the electron neutrinos produced inside the Sun apparently disappear as they travel from the Sun to the Earth (see [2] for a recent review of the solar neutrino experiments). This disappearance of the solar neutrinos can now be attributed confidently to neutrino flavor mixing, with the mass squared difference same as that relevant for the KamLAND experiment. Earlier the spectacular evidence that these solar electron neutrinos do not really disappear, but rather appear disguised as a neutrino with a different active flavor, came from the first measurement of the total $^8B$ solar neutrino flux, through the neutral current (NC) reaction on deuterium, at the Sudbury Neutrino Observatory (SNO) [3]. The SNO NC data when combined with the data from all the other solar neutrino experiments picked the so called Large Mixing Angle (LMA) solution to the solar neutrino problem [3, 4]. This remarkable result has very recently been reinforced by the salt phase data from the SNO experiment [5]. Prior to the SNO salt phase results, KamLAND data when combined with the other solar neutrino results, allowed two sub-regions within the LMA allowed region at the 99% C.L.– which we choose to call low-LMA (with best-fit at $\Delta m^2_{21} = 7.2 \times 10^{-5} \text{eV}^2$ and $\sin^2 \theta_{12} = 0.3$) and high-LMA (with best-fit at $\Delta m^2_{21} = 1.5 \times 10^{-4} \text{eV}^2$ and $\sin^2 \theta_{12} = 0.3$) [6]. After the SNO salt phase results, the combined analysis using all available data now allows the high-LMA solution only at the 99.13% C.L. [7]. Thus high-LMA is now further disfavored compared to low-LMA, though still not ruled out comprehensively.

There exists also very strong evidence for $\nu_\mu \leftrightarrow \nu_\tau$ ($\bar{\nu}_\mu \leftrightarrow \bar{\nu}_\tau$) oscillations of the atmospheric $\nu_\mu$ ($\bar{\nu}_\mu$) from the observed Zenith angle dependence of the $\mu$ like events in the Super-Kamiokande (SK) experiment – with maximal mixing and $1 \times 10^{-3} \text{eV}^2 < \Delta m^2_{\Delta} < 3 \times 10^{-3} \text{eV}^2 (90\% \text{ C.L.})$ [8].
Since the solar and the atmospheric neutrino “anomalies” involve two hierarchically different mass scales, simultaneous description of the two requires the existence of three-neutrino mixing. The solar neutrino data constrain the parameters $\Delta m^2_{21}$ and $\theta$ while the atmospheric neutrino data constrain the parameters $\Delta m^2_{\text{ atm}}$ and $\theta_{\text{ atm}}$. The two sectors get connected by the mixing angle $\theta_{13}$ which is at present constrained by the reactor data [9]. After these magnificent results the stage is set for the era of precision measurement of the oscillation parameters. We will discuss here what more can be achieved in this respect in reactor experiments sensitive to the $\Delta m^2$ driven distortions in the $\bar{\nu}_e$ spectrum due to oscillations.

The full expression for the $\bar{\nu}_e$ survival probability in the case of 3 flavor neutrino mixing and neutrino mass spectrum with normal hierarchy (NH) is given by [10]

$$
P_{\text{NH}} = 1 - 2 \sin^2 \theta_{13} \cos^2 \theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4 E_v} - \frac{1}{2} \cos^2 \theta_{13} \sin^2 \theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4 E_v} + 2 \sin^2 \theta_{13} \cos^2 \theta_{13} \sin^2 \theta_{12} \cos \frac{\Delta m^2_{31} L}{2 E_v} \Delta m^2_{21} \cos \frac{\Delta m^2_{21} L}{2 E_v} \cos \frac{\Delta m^2_{31} L}{2 E_v};
$$

(1)

where $E_v$ is the $\bar{\nu}_e$ energy. If the neutrino mass spectrum is with inverted hierarchy (IH), the $\bar{\nu}_e$ survival probability can be written in the form [10]

$$
P_{\text{NH}} = 1 - 2 \sin^2 \theta_{13} \cos^2 \theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4 E_v} - \frac{1}{2} \cos^2 \theta_{13} \sin^2 \theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4 E_v} + 2 \sin^2 \theta_{13} \cos^2 \theta_{13} \cos^2 \theta_{12} \cos \frac{\Delta m^2_{31} L}{2 E_v} \Delta m^2_{21} \cos \frac{\Delta m^2_{21} L}{2 E_v} \cos \frac{\Delta m^2_{31} L}{2 E_v};
$$

(2)

Thus the $\bar{\nu}_e$ survival probability depends on the four continuous parameters $\Delta m^2_{21}$, $\sin^2 \theta_{13}$, $\Delta m^2_{31}$, and $\sin^2 \theta_{13}$, and on a single “discrete” parameter — the type of the neutrino mass spectrum — NH or IH. Which of these parameters could be measured in a given reactor experiment depends on which of the terms in Eqs. (1) and Eqs. (2) dominate, which in turn depends crucially on the baseline. For a given $\Delta m^2$, if the baseline is such that $\sin^2 (\Delta m^2 L=4E) \sim 1$, the neutrinos undergo maximum flavor oscillations, we have a trough in the resultant $\bar{\nu}_e$ spectrum and we call this a case of SPMIN (Survival Probability MINimum). If on the other hand the baseline corresponds to $\sin^2 (\Delta m^2 L=4E) \sim 0$, we have a peak in the $\bar{\nu}_e$ spectrum and denote this case as SMAX (Survival Probability MAXimum). Since the shape of the spectrum depends very crucially on the mass squared difference, the value of the relevant $\Delta m^2$ can be expected to be determined very accurately as long as there is an observable distortion, irrespective of whether the distortion corresponds to a SPMIN or SMAX. However since for SMAX, the survival probability can be written approximately as $P_{ee} \sim 1$, there is little sensitivity to $\theta$ if the SMAX appears in the statistically most relevant part of the observed spectrum. On the other hand since for SPMIN the probability is $P_{ee} \sim \sin^2 2\theta$, one can expect maximum sensitivity to the mixing angle if the SPMIN is produced in the spectrum.

The KamLAND experiment in Japan is the world’s first very long baseline reactor experiment which looks for disappearance of $\bar{\nu}_e$ from nuclear reactors all over Japan. The most powerful reactors are at a distance of about 160 km. Thus for $\Delta m^2_{21}$ in the
LMA range, this experiment is expected to put very stringent bounds on the allowed values of the solar neutrino oscillation parameters. In Table 1 we present the 99% C.L. allowed range for the parameters $\Delta m^2_{21}$ and $\sin^2 \theta_{12}$, along with the corresponding % uncertainty ("spread"), obtained by taking various combination of data sets into account. We note that the uncertainty in $\Delta m^2_{21}$ reduces from 68% from only the solar data to 30% by including first KamLAND data. This uncertainty would further go down to 9% (6%) after 1 kTyr (3 kTyr) data from KamLAND. However there seems to be little improvement in the uncertainty on the value of $\sin^2 \theta_{12}$, with increase in the KamLAND statistics.

The reason for this failure of KamLAND to measure $\sin^2 \theta_{12}$ accurately enough can be traced back to the fact that the KamLAND spectrum shows a peak in its survival probability (SPMAX) at around 3.6 MeV. Thus, as discussed before, this sensitivity to the spectral shape gives KamLAND the ability to accurately pin down $\Delta m^2_{21}$. However since the oscillatory term $\sin^2 (\Delta m^2 L/E)$, is close to zero, it smothers any $\sin^2 \theta_{12}$ dependence along with it. Therefore, we conclude that KamLAND probably is not at the ideal baseline for determining the solar neutrino mixing angle.

What is the baseline most suited for measuring $\theta$? For $\Delta m^2_{21}$ in the low-LMA region, we expect to find a minimum in the survival probability (SPMIN) in the statistically most relevant part of the energy spectrum when the baseline $L = 70$ km. It was shown in [11] that for a new experimental set-up with a powerful reactor source, a la Kashiwazaki nuclear reactor in Japan with a maximum power generation of about 24.6 GW, producing a SPMIN in the detected spectrum in a KamLAND like detector at a distance of 70 km, $\sin^2 \theta_{12}$ can be measured to within 10% uncertainty, after 3 kTyr of data.

On the other hand, if contrary to the trend emerging in the solar neutrino experiments, the next KamLAND spectral data conforms to a point in the high-LMA region, then we would need an intermediate baseline reactor experiment with $L = 20$–30 km to get a SPMIN in the resultant spectrum. We have shown in [12] that an experimental set-up with an intermediate baseline of 20–30 km, a reactor with power of 5 GW and with 3 kTyr of statistics, we can measure both $\Delta m^2_{21}$ and $\sin^2 \theta_{12}$ down to the few percent level. The impact of systematic uncertainties, baseline, statistics and energy threshold of the detector was studied [12]. It was concluded that as long as the baseline and the energy threshold allowed the experiment to observe the SPMIN, $\theta_{12}$ could be measured very accurately irrespective of the other conditions.

If in addition, the energy resolution of the detector is good enough to collect data in bins of 0.1 MeV width, then the intermediate baseline reactor experiment can observe

| Data set used | 99% CL range of $\Delta m^2_{21}$ ($10^{-5}$eV$^2$) | 99% CL spread of $\Delta m^2_{21}$ | 99% CL range of $\sin^2 \theta_{12}$ | 99% CL spread in $\sin^2 \theta_{12}$ |
|---------------|--------------------------|----------------|--------------------------|--------------------------|
| only sol     | 3.2 - 17.0               | 68%           | 0.22                    | 0 ± 0.04                 | 29%                  |
| sol+162 Ty   | 5.3 - 9.8                | 30%           | 0.22                    | 0 ± 0.04                 | 29%                  |
| sol+1 kTy    | 6.7 - 8.0                | 9%            | 0.23                    | 0 ± 0.04                 | 27%                  |
| sol+3 kTy    | 6.8 - 7.6                | 6%            | 0.24                    | 0.37                     | 21%                  |
the $\Delta m^2_{31}$ driven subdominant oscillations – given by the second and the last terms in Eqs. (1) and (2). Thus, this experiment can also be used very effectively to extract information on $\Delta m^2_{31}$, $\sin^2 \theta_{13}$ and even the neutrino mass hierarchy. We have checked that an energy resolution of $\sigma(E) = E = 5\%E$, with $E$ in MeV, should be good enough for this purpose. For $L = 20$ km, bin width $0.1$ MeV, systematic uncertainty of $2\%$ and 15 GWkTy statistic, one can put an upper bound of $\sin^2 \theta_{13} < 0.021 (0.012)$ at $3\sigma (90\%)$ C.L.[12]. If on the other hand the true value of $\sin^2 \theta_{13}$ turns out to be large to produce observable effects in this experiment, then $\Delta m^2_{31}$ can be measured to the percent level.

For the measurement of $\sin^2 \theta_{13}$ and $\Delta m^2_{31}$, we do not necessarily need the $\Delta m^2_{21}$ to be in the high-LMA region. But if the condition for $\Delta m^2_{21}$ to be in high-LMA is satisfied, then the difference between the solar and atmospheric neutrino mass scales is not too severe and the last terms in Eqs. (1) and (2) are non-zero. Since they are different for normal (NH) and inverted (IH) hierarchies for $\sin^2 \theta_{12}$ not maximal, we can gain some information on the neutrino mass spectrum. If the next KamLAND spectral data does bring back high-LMA as a viable solution, then if statistics are very high and the real value of $\sin^2 \theta_{13}$ ($\Delta m^2_{31}$) are high (low) enough, one can get some information on the neutrino mass hierarchy. For $\Delta m^2_{21} = 1.5 \times 10^{-4}$ eV$^2$, and statistics of 75 (125) GWkTy, one could distinguish the NH from the IH spectrum at $99.73\%$ C.L. in the region of $\Delta m^2_{31} < 2.5 \times 10^{-3}$ eV$^2$ if $\sin^2 \theta > 0.038 (0.03)$ [12].

In conclusion, reactor neutrino experiments have great potential for precision measurement of the oscillation parameters. The KamLAND experiment can measure the solar mass squared difference very precisely. However it is not at the ideal baseline for measuring the solar neutrino mixing angle. If low-LMA is confirmed by the next results from KamLAND, a reactor experiment with a baseline of 70 km should be ideal to measure the solar neutrino mixing angle. If on the contrary KamLAND re-establishes high-LMA as a viable solution, a 20–30 km, intermediate baseline experiment could yield very rich phenomenology.

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