

Bounds on sterile neutrino parameters from reactor experiments¹

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Abstract. In this work, we present a realistic analysis of the potential of the present-day reactor experiments Double Chooz, Daya Bay and RENO for probing the existence of sterile neutrinos. We present exclusion regions for sterile oscillation parameters and find that these experimental set-ups give significant bounds on the parameter Θ_{ee} especially in the low sterile oscillation region $0.01 < \Delta m_{41}^2 < 0.05 \text{ eV}^2$. These bounds can add to our understanding of the sterile neutrino sector since there is still a tension in the allowed regions from different experiments for sterile parameters.

1. Introduction

A few years back, experiments like LSND [1] and MiniBooNE [2] have indicated the presence of a fourth type of neutrino - the sterile neutrino. The LSND result provided evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations from μ^+ decay-at-rest (DAR), and the same oscillation channel was studied in the MiniBooNE experiment. Similar results are also indicated by $\bar{\nu}_e$ and ν_e disappearance channels, by the reactor anomaly [3] and Gallium anomaly [4,5], and from cosmology [6,7]. These results suggest that the deficit of observed neutrino fluxes in the respective channels (ν_e or $\bar{\nu}_e$) may be an indication of the existence of a fourth type of neutrino. The latest global fits of sterile neutrino parameters were presented in [8,9].

A significant amount of work is already available in the literature regarding the search for sterile neutrinos in reactor and atmospheric neutrino oscillation experiments. Recently the possibility of using atmospheric neutrinos as a probe of eV^2 -scale active-sterile oscillations was explored in [10], where bounds on $\sin^2 2\Theta_{\mu\mu}$ and Δm_{41}^2 were presented. The implication of sterile neutrinos on measurements of θ_{13} in a $(3+2)$ scenario in the Double Chooz [11] reactor experiment was studied in [12]. The impact of light sterile neutrinos on θ_{13} measurements in Double Chooz and Daya Bay [13] was studied in [14] in a $(3+1)$ scenario. A study of the effect of sterile neutrinos on θ_{23} and θ_{13} measurements in MINOS, T2K and Double Chooz was performed in [15]. Similar studies for Daya Bay were carried out in [16]. A search for sterile neutrinos using MINOS was done in [17]. A constraint on the mixing angle θ_{14} from a combination of Solar and KamLAND data was given in [18]. An analysis of the results of Double Chooz, Daya Bay and RENO to simultaneously fit θ_{13} and the reactor neutrino anomaly was recently performed in [19].

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In this work, we present exclusion regions in the sterile neutrino parameter space $\sin^2 2\Theta_{ee} - \Delta m_{41}^2$ for the three current reactor experiments, namely Double Chooz, RENO [20] and Daya Bay. A similar study was performed in [14] for Double Chooz and Daya Bay, where a more approximate analysis in the $\sin^2 2\Theta_{ee} - \Delta m_{41}^2$ plane was done assuming an overall systematic error and neglecting detector resolution. In our present work, we have used simulations with reduced values of errors, as quoted in the technical reports of the individual reactor experiments, where the cancellation of correlated reactor-related errors by using both near and far detectors has been taken into account. Also, we have considered realistic detector resolutions, which play an important part in the sensitivity analysis. We also compare our results with those of older reactor experiments like BUGEY [21], GOSGEN [22] and Krasnoyarsk [23].

2. Neutrino mixing-(3 + 1) scenario

In presence of a sterile neutrino, three flavor Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing changes to (3+1) or (2+2) scenario. Here we consider the (3+1) scenario, which is an extension of the three-neutrino scenario with the addition of one massive sterile neutrino. Solar and atmospheric neutrino analyses strongly discourage the (2+2) scenario due to the absence of sterile signals in the atmospheric parameters [24]. The (3+2) scenario is favoured by the tension between appearance and disappearance experiments in the (3+1) case, but disfavoured by cosmology.

In the presence of a sterile neutrino, the standard 3-flavour neutrino oscillation picture changes, and hence the survival probability must be modified due to the effect of (3+1) mixing. The baselines relevant to these experiments are of the order of a few hundred metres, and hence the oscillation would show signatures at the atmospheric scale as well as possible sterile-scale effects. The electron neutrino survival probability expression relevant for our analysis is [14]

$$P_{ee} = 1 - \cos^4 \theta_{14} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{13}^2 L}{4E}\right) - \sin^2 2\theta_{14} \sin^2\left(\frac{\Delta m_{14}^2 L}{4E}\right), \quad (1)$$

where L is the baseline and E is the neutrino energy. Here, P_{ee} is seen to be a function of two mass-squared differences (Δm_{14}^2 and Δm_{13}^2) and two mixing angles θ_{13} and θ_{14} . When $\theta_{14} \rightarrow 0$, we recover the standard three-flavour probability expression in which the solar mass scale is neglected.

3. Technical details of the experiments

In this section, we present some technical details of the three new generation reactor experiments, Double Chooz [11, 20], Daya Bay [13] and RENO [20], for the sake of completeness, collected from [11, 13, 20]. All the information regarding these experiments are given in table 1. The systematic errors associated with each experimental set-up are listed in Table 2.

The details of the three old reactor experiments (BUGEY [21], Gosgen [22] and Krasnoyarsk [23]) with which we compare our exclusion regions for sterile parameters are tabulated in Table 3.

4. Results and analysis

We have generated the 90% c.l. exclusion plots for sterile oscillations for all the three current experiments and compared the results with the old reactor experiments Bugey, Gosgen and Krasnoyarsk. The right side of each contour shows the no-oscillation region while the region left to the contours is the possible oscillation region. The results are found to be very sensitive to the values of systematic errors. In our calculations, we have used GLOBES [25–27] for simulating

Table 1. Details of the three reactor experiments

Name of Exp	Double Chooz	Daya Bay	RENO
Location	France	China	Korea
No of Reactor cores	2	4	6
Total Power(GW _{th})	8.7	11.6	16.4
Baselines- near/Far(m)	410/1067	363(481)/1985(1615)	292/1380
Target mass(tons)	10/10	40 × 2/10	16.1/16.1
No of Detectors	2	2	2
Exposure(years)	3	3	3
Resolution(%)	12	12	12

Table 2. Systematic errors associated with the three experiments

Name of Exp	Double Chooz	Daya Bay	RENO
Reactor correlated error(%)	2.0	2.0	2.0
Detector normalisation error(%)	0.6	0.5	0.5
Scaling or calibration error(%)	0.5	0.5	0.1
Overall normalization error(%)	2.5	2.5	2.0
Isotopic abundance error(%)	2.0	2.0	2.0

Table 3. Details of old reactor experiments

Name of Exp	Bugey	Gosgen	Krasnoyarsk
No of Reactor cores	4	1	3
Total Power(GW _{th})	2.8	2.8	2.8
Baselines(m)	15,40,95	37.9,45.9,64.7	57,57.6,231.4
Target mass(≈tons)	1.67	0.32	0.4
No of Detectors	1	1	1
Exposure(≈ years)	0.2	0.39,0.56,0.98	0.06
Resolution(%)	6	-	-

the experiments. In our calculation we have used the χ^2 function as:

$$\chi^2 = \sum_{i=1}^{\text{\#of bins}} \sum_{d=N,F} \frac{(O_{d,i} - (1 + a_R + a_d)T_{d,i})^2}{O_{d,i}} + \frac{a_R^2}{\sigma_R^2} + \frac{a_N^2}{\sigma_N^2} + \frac{a_F^2}{\sigma_F^2} \quad (2)$$

where $O_{N,i}$, $O_{F,i}$ are the event rates for the i^{th} bin in the near and far detectors, calculated for true values of oscillation parameters; $T_{d,i}$ are the expected event rates for the i^{th} bin in the near and far detector for the test parameter values; a_R , a_F , a_N are the uncertainties associated with the reactor flux and detector mass; and σ_R , σ_F , σ_N are the respective associated standard deviations.

Fig.1 shows the variation of the average bound on $\sin^2 2\theta_{ee}$ from each of the three experiments Double Chooz, Daya Bay and RENO as a function of the bin-to-bin systematic error for a

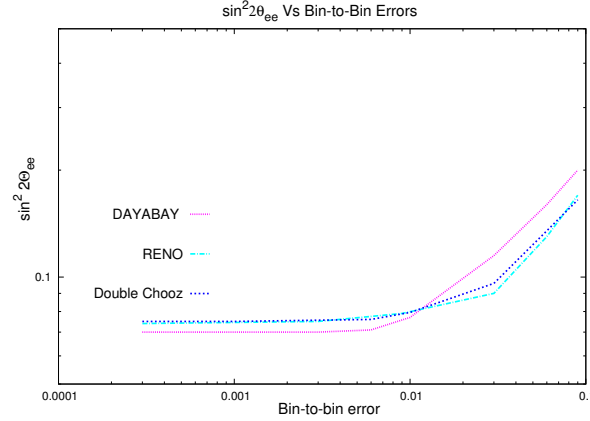


Figure 1. Dependence of the average $\sin^2 2\theta_{ee}$ bound on the correlated bin-to-bin error for Double Chooz, Daya Bay and RENO.

Table 4. Set of reduced errors used in our calculation

Name of Exp	Double Chooz	Day Bay	RENO
Reactor correlated error(%)	0.06	0.087	0.5
Detector normalisation error(%)	0.06	0.12	0.5
Scaling or calibration error(%)	0.5	0.5	0.1
Overall normalization error(%)	0.5	0.5	0.5
Isotopic abundance error(%)	0.06	0.087	0.5

constant overall normalisation. We depict the behaviour with respect to the correlated bin-to-bin error since this is found to have the most significant effect on parameter sensitivities. The figure shows that the dependence of the sensitivity in the case of Daya Bay is slightly steeper, even for low values of the bin-to-bin systematics, than for the other two experiments.

In our further analysis, we have used a reduced set of systematic errors as listed in Table 4, taking into account the partial cancellation of errors due to the presence of both near and far detectors, as documented in the experiment literature.

We have included the changed flux normalisation given by the reactor flux anomaly [3] in our sensitivity analysis. We are performing a simulation and not a data analysis, and hence varying the flux normalisation has minimal effect on our results, since the relative normalisation simultaneously affect both the true and test spectra in the simulation and lead to a cancellation of their effect in the parameter sensitivity. For the same reason, leaving the flux normalisation as a freely varying parameter does not have a major influence on our results, and therefore they may be taken to be indicative of the effect of spectral information only.

In Fig.2, we show the comparison of the exclusion plots for Double Chooz, RENO and daya Bay experiments with existing reactor experiments using modified errors. Our results for all the three experiments show better exclusion regions for sterile neutrino oscillation parameters than Gosgen and Krasnoyarsk in the range $\Delta m_{41}^2 = 0.01$ to 1 eV^2 . Our bounds are an improvement over Bugey in the range $\Delta m_{41}^2 = 0.01$ to 0.05 eV^2 but in the Δm_{41}^2 region above this, Bugey gives better bounds. From these curves, we see that $\sin^2 2\theta_{ee} > 0.1$ and $\sin^2 2\theta_{ee} > 0.08$ is excluded for sterile oscillation in the $\Delta m_{41}^2 = 0.01$ to 1 eV^2 region for Double Chooz and RENO respectively. The Daya Bay exclusion bound in the region $\Delta m_{41}^2 = 0.1$ to 1 eV^2 is found to be

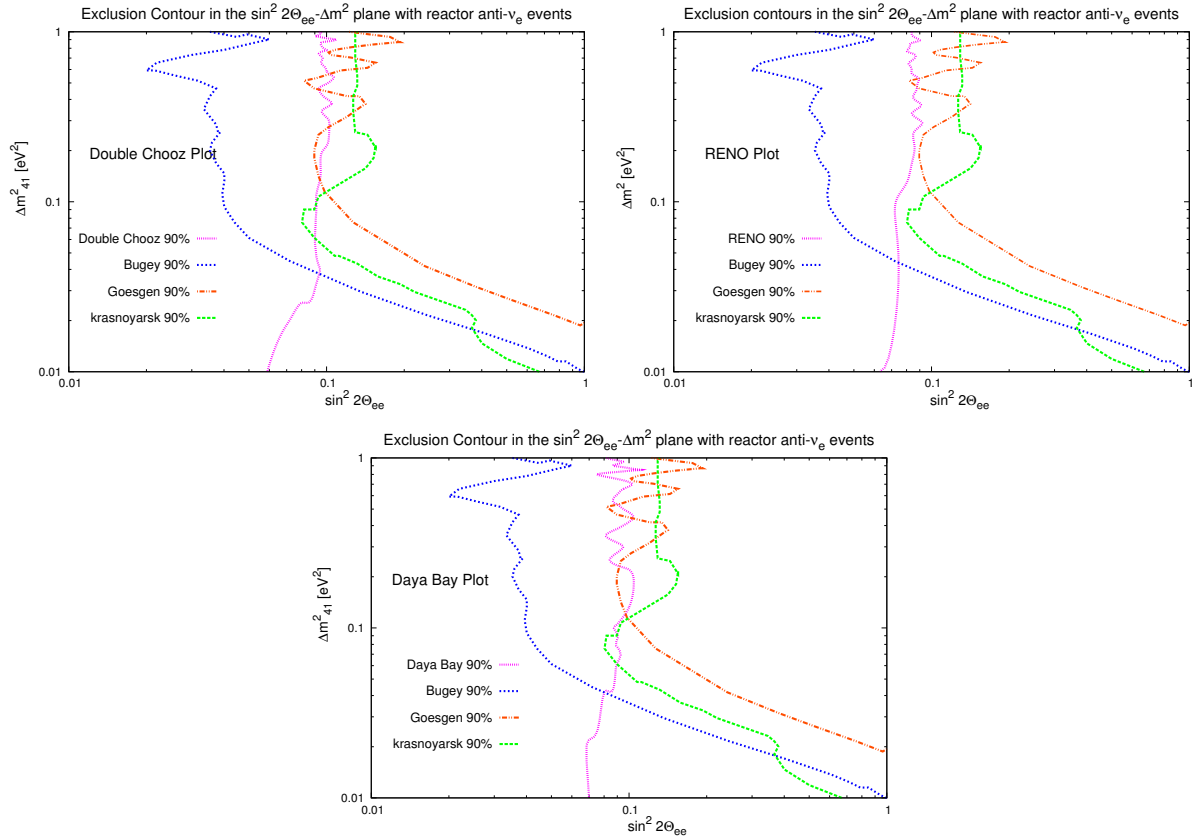


Figure 2. Comparison of Double Chooz, RENO and Daya Bay exclusion plot with other reactor experiments at 12% resolution using modified errors.

nearly $\sin^2 2\theta_{ee} > 0.07$.

5. Conclusions

From the above results, we can draw the following conclusions:

- The sensitivity of reactor experiments like Double Chooz, Daya Bay and RENO to sterile oscillation parameters is significantly dependent on the systematic errors, detector resolutions and uncertainties of each experiment. The dependence is especially strong on the correlated reactor-related errors and the normalisation uncertainty.
- Because of the multiple detectors and baselines in each of these experimental set-ups, it is possible to have partial cancellations of the experimental errors, especially of the correlated errors, which is beneficial in giving us better parameter sensitivities.
- In an analysis with duly reduced values of errors, it is possible to obtain better bounds with these set-ups than those from many of the older reactor experiments, in spite of the fact that the relatively higher baselines in this case are less suited for a determination of oscillations in the $\Delta m_{14}^2 = 1 \text{ eV}^2$ range. For the latter reason, we find that we obtain better bounds in the low region $0.01 < \Delta m_{14}^2 < 0.05 \text{ eV}^2$.

The appearance and disappearance experiments indicates that there is still significant uncertainty on the favoured region for sterile oscillation. In view of this, these results are significant.

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