SEARCH FOR STERILE NEUTRINOS AT REACTORS WITH A SMALL CORE*

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The sensitivity to the sterile neutrino mixing at very short baseline reactor neutrino experiments is investigated. If the reactor core is relatively large as in the case of commercial reactors, then the sensitivity is lost for $\Delta m^2 \gtrsim 1$ eV^2 due to smearing of the reactor core size. If the reactor core is small as in the case of the experimental fast neutron reactor Joyo, the ILL research reactor or the Osiris reactor, on the other hand, then sensitivity to $\sin^2 2\theta_{14}$ can be as good as 0.03 for $\Delta m^2 \sim$ several eV^2 because of its small size.

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1. Introduction

Schemes with sterile neutrinos have attracted a lot of attention since the LSND group announced the anomaly [1,2,3] which would imply mass squared difference of $\mathcal{O}(1)$ eV^2 if it is interpreted as a phenomenon due to neutrino oscillation. The standard three-flavor scheme has only two independent mass squared differences, *i.e.*, $\Delta m^2_{21} = \Delta m^2_{\odot} \simeq 8 \times 10^{-5}$ eV^2 for the solar neutrino oscillation, and $|\Delta m^2_{31}| = \Delta m^2_{\rm atm} \simeq 2.4 \times 10^{-3}$ eV^2 for the atmospheric neutrino oscillation. To accommodate a neutrino oscillation scheme to the LSND anomaly, therefore, the extra state should be introduced. This extra state should be sterile neutrino, which is singlet with respect to the gauge group of the Standard Model, because the number of weakly interacting light neutrinos should be three from the LEP data [4].

Recently, sterile neutrino scenarios are becoming popular again because of a few reasons. One is the data of the MiniBooNE experiment which has been performed to test the LSND anomaly. Although their data on the

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neutrino mode [5] disfavor the region suggested by LSND, their data on the anti-neutrino mode [6] seem to be consistent with these of LSND. The second one is the so-called reactor anomaly. The flux of the reactor neutrino was recalculated in Ref. [7] recently and it was claimed that the normalization is shifted by about +3% on average. This claim is qualitatively consistent with an independent calculation in Ref. [8]. If their claim on the reactor neutrino flux is correct, then neutrino oscillation with $\Delta m^2 \gtrsim 1$ eV^2 may be concluded from a re-analysis of 19 reactor neutrino results at short baselines [9]. The third one is the so-called gallium anomaly. The data of the gallium solar neutrino calibration experiments indicate deficit of ν_e and it may imply neutrino oscillation [10].

It has been known that reactor experiments with more than one detector have a possibility to measure θ_{13} precisely because some of the systematic errors can be canceled by the near–far detector complex [11,12,13,14]. Three experiments [15, 16, 17] are now either running or expected to start soon to measure θ_{13}. In the standard three-flavor case with $|\Delta m^2_{31}| = 2.4\times10^{-3}$ eV^2, it was shown assuming infinite statistics that the optimized baseline lengths $L_{\rm F}$ and $L_{\rm N}$ for the far and near detectors are $L_{\rm F} \simeq 1.8$ km and $L_{\rm N} \simeq 0$ km in the rate analysis [18, 19], while they are $L_{\rm F} \simeq 10.6$ km and $L_{\rm N} \simeq 8.4$ km in the spectrum analysis [20]. To justify the assumption on negligible statistical errors for $L \sim 10$ km, unfortunately, one would need unrealistically huge detectors, so one is forced to choose the baseline lengths which are optimized for the rate analysis for $\Delta m^2 = 2.4 \times 10^{-3}$ eV^2. On the other hand, if one performs an oscillation experiment to probe $\Delta m^2 \sim \mathcal{O}(1)$ eV^2, it becomes realistic to place the detectors at the baseline lengths which are optimized for the spectrum analysis (see Sec. 4 in the published version of Ref. [20]).

In this paper, I would like to discuss the sensitivity of very short line reactor experiments to the sterile neutrino mixing for $\Delta m^2 \sim \mathcal{O}(1)$ eV^2 in the so-called (3+1)-scheme [21]. Proposals have been made to test the bound of the Bugey reactor experiment [22] on the sterile neutrino mixing angle using a reactor [23, 24][1], an accelerator [28, 27], and a β-source [29, 30].

2. Four-neutrino schemes

Four-neutrino schemes consist of one extra sterile state and the three weakly interacting ones. The schemes are called (3+1)- and (2+2)-schemes, depending on whether one or two mass eigenstate(s) are separated from the others by the largest mass-squared difference $\sim \mathcal{O}(1)$ eV^2. The (2+2)-scheme is excluded by the solar and atmospheric neutrino data [31], so I will not discuss the (2+2)-schemes here. In the (3+1)-scheme, the phenomenology of

[1] See, *e.g.*, Refs. [20] (the published version), [25, 26] for earlier works on search for sterile neutrinos at a reactor.

solar and atmospheric oscillations is approximately the same as that of the three-flavor framework, so there is no tension between the solar and atmospheric constraints. However, the (3+1)-scheme has a problem in accounting for LSND and all other negative results of the short baseline experiments. To explain the LSND data while satisfying the constraints from other disappearance experiments, the oscillation probabilities of the appearance and disappearance channels should satisfy the following relation [32, 33]

$$\sin^2 2\theta_{\text{LSND}}\left(\Delta m^2\right) < \frac{1}{4}\sin^2 2\theta_{\text{Bugey}}\left(\Delta m^2\right)\sin^2 2\theta_{\text{CDHSW}}\left(\Delta m^2\right)\,, \tag{1}$$

where $\theta_{\text{LSND}}(\Delta m^2)$, $\theta_{\text{CDHSW}}(\Delta m^2)$, $\theta_{\text{Bugey}}(\Delta m^2)$ are the value of the effective two-flavor mixing angle as a function of the mass squared difference Δm^2 in the allowed region for LSND ($\bar{\nu}_\mu \to \bar{\nu}_e$), the CDHSW experiment [34] ($\nu_\mu \to \nu_\mu$), and the Bugey experiment [22] ($\bar{\nu}_e \to \bar{\nu}_e$), respectively. The reason that the (3+1)-scheme to explain LSND has been disfavored is because Eq. (1) is not satisfied for any value of Δm^2, if one adopts the allowed regions in Refs. [34] and [22]. If the flux of the reactor neutrino is slightly larger than the one used in the Bugey analysis [22], however, the allowed region becomes slightly wider and one has more chance to satisfy Eq. (1)[2].

I will use the following parametrization for the mixing matrix [36]

$$U = R_{34}(\theta_{34},0)\,R_{24}(\theta_{24},0)\,R_{23}(\theta_{23},\delta_3)\,R_{14}(\theta_{14},0)\,R_{13}(\theta_{13},\delta_2)\,R_{12}(\theta_{12},\delta_1)\,,$$

where $R_{jk}(\theta_{jk},\ \delta_l)$ are the complex rotation matrices in the jk-plane defined as

$$\begin{aligned}\left[R_{jk}\left(\theta_{jk},\delta_l\right)\right]_{pq} &= \delta_{pq} + \left(\cos\theta_{jk} - 1\right)\left(\delta_{jp}\delta_{jq} + \delta_{kp}\delta_{kq}\right)\\ &\quad + \sin\theta_{jk}\left(e^{-i\delta_l}\delta_{jp}\delta_{kq} - e^{i\delta_l}\delta_{jq}\delta_{kp}\right)\,.\end{aligned}$$

With this parametrization, for the very short baseline reactor experiments, where the average neutrino energy E is approximately 4 MeV and the baseline length is about 10 m, I have $|\Delta m^2_{jk}L/4E| \ll 1$ ($j,k = 1,2,3$), so that the disappearance probability is given by

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{14}\,\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right) \tag{2}$$

to a good approximation. So the analysis of the (3+1)-scheme is reduced to that of a two-flavor framework with the oscillation parameters (Δm^2_{41}, $\sin^2 2\theta_{14}$).

[2] Although the situation of the (3+1)-scheme is improved slightly after Refs. [7, 9], the improvement is not sufficient enough to have a satisfactory fit to all the data, according to Ref. [35].

3. Sensitivity to $\sin^2 2\theta_{14}$ by a spectral analysis

Throughout my paper I discuss the case with a single reactor and two detectors. I assume here that the near and far detectors are identical and they have the same sizes of systematic errors. The conditions of the detectors are assumed to be the same as those of the Bugey experiment, *i.e.*, liquid scintillation detector of volume 600 liters with the detection efficiency which yields about 90,000 events at $L = 15$ m from a reactor of a power 2.8 GW after running for 1800 hours.

To evaluate the sensitivity to $\sin^2 2\theta_{14}$, let us introduce the following χ^2 which was adopted in Ref. [20] (see Ref. [21] for details)

$$\chi^2 = \min_{\alpha' s}\left\{\sum_{A=N,F}\sum_{i=1}^{n}\frac{1}{(t_i^A\sigma_i^A)^2}\left[m_i^A - t_i^A\left(1+\alpha+\alpha^A+\alpha_i\right) - \alpha^A_{\rm cal}t_i^A v_i^A\right]^2 \right.$$
$$\left. + \sum_{A=N,F}\left[\left(\frac{\alpha^A}{\sigma_{\rm dB}}\right)^2 + \left(\frac{\alpha^A_{\rm cal}}{\sigma_{\rm cal}}\right)^2\right] + \sum_{i=1}^{n}\left(\frac{\alpha_i}{\sigma_{\rm Db}}\right)^2 + \left(\frac{\alpha}{\sigma_{\rm DB}}\right)^2\right\}. \qquad (3)$$

χ^2 stands for a quantity which expresses how much deviation we have between the numbers of events with and without oscillations, compared with the experimental errors. In Eq. (3), m_i^A is the number of events to be measured at the near ($A = N$) and far ($A = F$) for the i-th energy bin with the neutrino oscillation, and t_i^A is the theoretical prediction without the oscillation. $(\sigma_i^A)^2$ is the uncorrelated error which consists of the statistical plus uncorrelated bin-to-bin systematic error: $(t_i^A\sigma_i^A)^2 = t_i^A + \left(t_i^A\sigma_{\rm db}^A\right)^2$, where $\sigma_{\rm db}^A$ is the uncorrelated bin-to-bin systematic error. α^A ($A = N, F$) is a variable which introduces the detector-specific uncertainties $\sigma_{\rm dB}$ of the near and far detectors. α_i ($i = 1, \cdots, n$) is a variable for an uncertainty $\sigma_{\rm Db}$ of the theoretical prediction for each energy bin which is uncorrelated between different energy bins[3]. $\alpha^A_{\rm cal}$ ($A = N, F$) is a variable which introduces an energy calibration uncertainty $\sigma_{\rm cal}$ and comes in the theoretical prediction in the form of $(1+\alpha^A_{\rm cal})E$ instead of the observed energy E. v_i^A is the deviation divided by the expected number of events from the theoretical prediction t_i^A due to the energy calibration uncertainty. Here, I take the following reference values for the systematic errors: $\sigma_{\rm db} = 0.5\%$, $\sigma_{\rm dB} = 0.5\%$, $\sigma_{\rm Db} = 2\%$, $\sigma_{\rm DB} = 3\%$, $\sigma_{\rm cal} = 0.6\%$.

[3] The first suffix of σ stands for the property for the systematic error with respect to the detectors while the second is with respect to bins, and capital (small) letter stands for a correlated (uncorrelated) systematic error.

3.1. Commercial reactors

First of all, I will consider a commercial reactor whose thermal power is 2.8 GW and I will assume that the dimension of its core is 4 m in diameter and 4 m in height.

χ^2 in Eq. (3) is computed numerically in the case of $\Delta m^2_{41} = 1$ eV^2 as a function of the baseline lengths $L_{\rm N}$ and $L_{\rm F}$ of the two detectors, and the baseline lengths $L_{\rm N}$ and $L_{\rm F}$ are varied to optimize the sensitivity to $\sin^2 2\theta_{14}$. It is found that the set $(L_{\rm N}, L_{\rm F}) \simeq$ (17 m, 23 m) gives the optimum. In contrast to the rate analysis, in which the optimized baseline length of the near detector is $L_{\rm N} = 0$ m to avoid oscillations, the spectrum analysis with $(L_{\rm N}, L_{\rm F}) =$ (17 m, 23 m) looks at the difference between the maximum and minimum of the spectrum shape with neutrino oscillations at $L_{\rm N}$ and $L_{\rm F}$ mainly for the energy region $E_\nu \sim 4$ MeV, where the number of events are expected to be the largest (see left panel in Fig. 1). Unlike the case of infinite statistics [20], the statistical errors are important in the present setup of the detectors, and longer baseline lengths are disfavored.

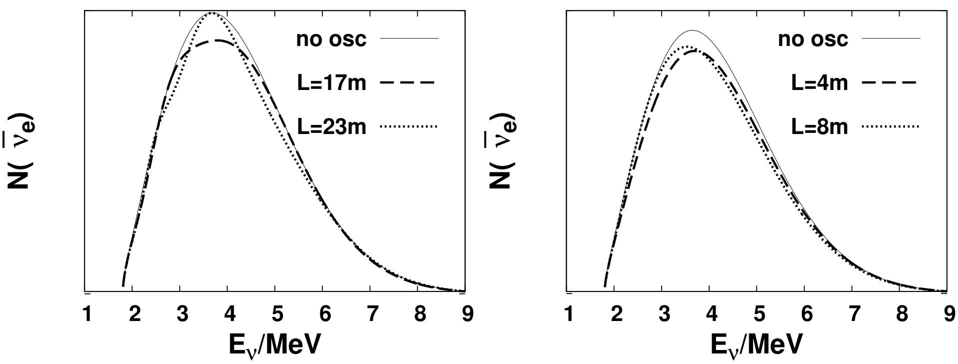

Fig. 1. The energy spectrum with neutrino oscillations at the two different detectors and the one without oscillations. The optimized baseline lengths give maximum difference in the distortions in the energy spectrum. Left panel: the case of a commercial reactor. Right panel: the case of a research reactor.

The sensitivity to $\sin^2 2\theta_{14}$ in the case of the baseline lengths $(L_{\rm N}, L_{\rm F}) =$ (17 m, 23 m) is shown in Fig. 2 as a function of Δm^2_{41} (the line referred to as "Commercial"). The region suggested by combination of the reactor and gallium anomalies and the MiniBooNE data is also given in Fig. 2 for comparison. For $\Delta m^2_{41} \gtrsim 2$ eV^2, the sensitivity is no better than 0.1, which is basically the result of the rate analysis. The sensitivity in the case of a hypothetical point-like reactor, where all the conditions for the detectors are the same, is also given in Fig. 2 for comparison (the line referred to as "Point-like"). Fig. 2 indicates that the sensitivity would be as good as several

$\times 10^{-2}$ for a few eV^2, if the core were point-like. So we can conclude that we have poor sensitivity for $\Delta m_{41}^2 \gtrsim 2\ \text{eV}^2$ because of the smearing effect of the finite core size of the reactor.

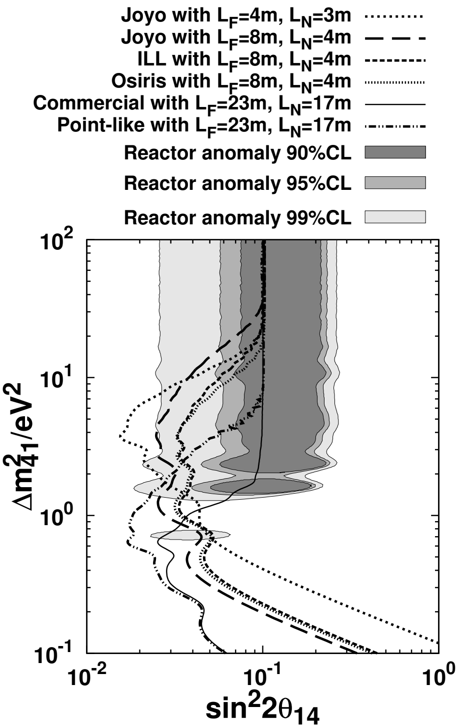

Fig. 2. The sensitivity to $\sin^2 2\theta_{14}$ of each reactor with the two detectors at its optimum baseline lengths. Also shown as a shaded area is the region given in Ref. [9] from the combination of the reactor neutrino experiments, Gallex and Sage calibration sources experiments, the MiniBooNE reanalysis of Ref. [10], and the ILL-energy spectrum distortion.

3.2. Research reactors

In the previous subsection, we have seen that the sensitivity to $\sin^2 2\theta_{14}$ is lost because of the smearing effect of finite core size. Next, I would like to discuss three research reactors, Joyo [37] with MK-III upgrade [38], the ILL research reactor [39], and the Osiris research reactor [40]. They all have a relatively small size and a relatively large thermal power.

Joyo is an experimental fast breeder reactor and the dimension of its core is 0.8 m in diameter and 0.5 m in height, and its thermal power is 140 MW. The ILL (Osiris) research reactor is a thermal neutron reactor with high enrichment of uranium ^{235}U, and the dimension of its core is 0.4 m in diameter and 0.8 m in height (0.57 m × 0.57 m × 0.6 m) and its thermal power is 58 MW (70 MW), respectively.

Again, χ^2 in Eq. (3) is computed numerically in each case, and it is optimized with respect to $L_{\rm N}$ and $L_{\rm F}$. The optimum set of the baseline lengths turns out to be $(L_{\rm N}, L_{\rm F}) \simeq$ (4 m, 8 m) for $\Delta m^2_{41} = 1$ eV^2 for all the three cases. Left panel in Fig. 1 shows the spectrum distortion in the case of $L = 4$ m, 8 m.

The sensitivity to $\sin^2 2\theta_{14}$ is shown in Fig. 2 as a function of Δm^2_{41} in the case of the sets of the baseline lengths $(L_{\rm N}, L_{\rm F}) =$ (4 m, 8 m) for the three cases and $(L_{\rm N}, L_{\rm F}) =$ (3 m, 4 m) for Joyo. From Fig. 2 it is clear that the sensitivity of an experiment with a small core reactor is better than that with a commercial reactor for 2 eV$^2 \lesssim \Delta m^2_{41} \lesssim 10$ eV^2.

4. Discussion and conclusion

In the framework of the (3+1)-scheme, the sensitivity to $\sin^2 2\theta_{14}$ of very short baseline reactor oscillation experiments was studied by a spectrum analysis. The assumptions are that one has two detectors whose size and efficiency are exactly the same as those used at the Bugey experiment and χ^2 is optimized with respect to the positions of the two detectors.

In the case of a commercial reactor, by putting the detectors at $L_{\rm N} =$ 17 m and $L_{\rm F} = 23$ m, one obtains the sensitivity as good as several $\times 10^{-2}$ for $\Delta m^2_{41} \lesssim 1$ eV^2, but the sensitivity is lost above 1 eV^2 due to the smearing of the finite core size.

In the case of a research reactor with a small core (such as Joyo, ILL, Osiris), on the other hand, one obtains the sensitivity as good as a several $\times 10^{-2}$ for 1 eV$^2 \lesssim \Delta m^2_{41} \lesssim 10$ eV^2 if the detectors are located at $L_{\rm N} = 4$ m and $L_{\rm F} = 8$ m.

In all the cases discussed above with the Bugey-like detector setup, the statistical errors are dominant. The reason that the case of the research reactors (Joyo, ILL, Osiris) is competitive despite its small power is because the total numbers of events at $L \sim$ several meters are comparable to those of the case with a commercial reactor at $L \sim$ a few × 10 meters.

To turn this idea into reality, there are two experimental challenges. One is to put detectors at a location very near to a research reactor. The other one is to avoid potentially huge backgrounds from the reactor[4].

Nevertheless, since the best fit point $(\Delta m^2_{41},\ \sin^2 2\theta_{14}) \sim$ (2 eV^2, 0.1) obtained in Ref. [9] lies within the excluded region in Fig. 2, the experiment at these research reactors offers a promising possibility.

[4] An experiment [41] was performed to detect neutrinos from a fast neutron reactor at Joyo, but unfortunately they did not get sufficient statistical significance.

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