Search for sterile neutrinos at reactors

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Abstract

The sensitivity to the sterile neutrino mixing at very short baseline reactor neutrino experiments is investigated. In the case of conventional (thermal neutron) reactors it is found that the sensitivity is lost for $\Delta m^2 \gtrsim 1 \text{ eV}^2$ due to smearing of the reactor core size. On the other hand, in the case of an experimental fast neutron reactor Joyo, because of its small size, sensitivity to $\sin^2 2\theta_{14}$ can be as good as 0.03 for $\Delta m^2 \sim \text{several eV}^2$ with the Bugey-like detector setup.

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I. INTRODUCTION

Since the LSND group announced the anomaly which suggests neutrino oscillations with mass squared difference of $\mathcal{O}(1)\text{ eV}^2$\cite{1–3}, schemes with sterile neutrinos have attracted a lot of attention. This is because the standard three flavor scheme has only two independent mass squared differences, i.e., $\Delta m^2_{21} = \Delta m^2_{\odot} \simeq 8 \times 10^{-5}\text{eV}^2$ for the solar neutrino oscillation, and $|\Delta m^2_{31}| = \Delta m^2_{\text{atm}} \simeq 2.4 \times 10^{-3}\text{eV}^2$ for the atmospheric neutrino oscillation, and it does not have room for the mass squared difference of $\mathcal{O}(1)\text{ eV}^2$. The extra state has to be sterile neutrino, which is singlet with respect to the gauge group of the Standard Model, because the number of weakly interacting light neutrinos has to be three from the LEP data\cite{4}.

The LSND anomaly has been tested by the MiniBooNE experiment. While the MiniBooNE data on the neutrino mode\cite{5} disfavors the region suggested by LSND, their data on the anti-neutrino mode\cite{6} seems to be consistent with the LSND data.

Recently the flux of the reactor neutrino was recalculated in Ref.\cite{7} and it was reported that the normalization is shifted by about $+3\%$ on average.$^1$ Then a re-analysis of 19 reactor neutrino results at short baselines\cite{9} in the light of new reactor neutrino spectra\cite{7} may indicate neutrino oscillation at $\Delta m^2 \gtrsim 1\text{eV}^2$.

Reactor experiments with more than one detector have attracted much attention as a possibility to measure $\theta_{13}$ precisely\cite{10–13}, and three experiments\cite{14–16} are now either running or expected to start soon. In the three flavor case with $|\Delta m^2_{31}| = 2.4 \times 10^{-3}\text{eV}^2$, it was shown assuming infinite statistics that the optimized baseline lengths $L_F$ and $L_N$ for the far and near detectors are $L_F \simeq 1.8\text{km}$ and $L_N \simeq 0\text{km}$ in the rate analysis\cite{17, 18}, while they are $L_F \simeq 10.6\text{km}$ and $L_N \simeq 8.4\text{km}$ in the spectrum analysis\cite{19}. Unfortunately, in order to justify the assumption on negligible statistical errors for $L \sim 10\text{km}$, one would need unrealistically huge detectors, so one is forced to choose the baseline lengths which are optimized for the rate analysis for $\Delta m^2 = 2.4 \times 10^{-3}\text{eV}^2$. On the other hand, if we perform an oscillation experiment to probe $\Delta m^2 \sim \mathcal{O}(1)\text{ eV}^2$, it becomes realistic to place the detectors at the baseline lengths which are optimized for the spectrum analysis (See Sect. 4 in the published version of Ref.\cite{19}).

In this paper we discuss the sensitivity of very short line reactor experiments to the sterile neutrino mixing for $\Delta m^2 \sim \mathcal{O}(1)\text{ eV}^2$ in the so-called (3+1)-scheme.$^2$ Proposals have been made to test the bound of the Bugey reactor experiment\cite{24} on the sterile neutrino mixing angle using a reactor\cite{25}, an accelerator\cite{26, 27}, and a $\beta$-source\cite{28}.

Throughout this paper we discuss the case with a single reactor and two detectors, which have an advantage to cancel the systematic errors that are correlated between detectors. The conditions of the detectors are assumed to be the same as those of the Bugey experiment.

In Sect. 2 we briefly review the four neutrino schemes. In Sect. 3 we evaluate the sensitivity of very short line reactor experiments to the sterile neutrino mixing. In Sect. 4 we summarize our results. In Appendix A we give some details to get an analytical expression

$^1$ The increase in the flux claimed by Ref.\cite{7} was confirmed by an independent calculation in Ref.\cite{8}.

$^2$ According to Ref.\cite{20}, the so-called (3+2)-scheme\cite{21} gives a better fit to the global data than the (3+1)-scheme does. However, we are mainly interested here in the potential sensitivity to the sterile neutrino mixing for $\Delta m^2 \sim \mathcal{O}(1)\text{ eV}^2$, and for simplicity we will discuss the (3+1)-scheme, leaving the analysis of the (3+2)-scheme for the future.

$^3$ See, e.g., Refs.\cite{19} (the published version),\cite{22, 23} for earlier works on search for sterile neutrinos at a reactor.
for $\chi^2$.

II. FOUR NEUTRINO SCHEMES

Four-neutrino schemes consist of one extra sterile state in addition to the three weakly interacting ones. Depending on whether one or two mass eigenstate(s) are separated from the others by the largest mass-squared gap, the schemes are called (3+1)- and (2+2)-schemes. The (2+2) schemes are excluded by the solar and atmospheric neutrino data [29], so we will not discuss the (2+2) schemes in this paper. In the (3+1) schemes, on the other hand, the phenomenology of solar and atmospheric oscillations is approximately the same as that of the three flavor framework, so as far as the tension between the solar and atmospheric constraints are concerned, the (3+1) schemes do not have any problem. However, if we try to account for LSND and all other negative results of the short baseline experiments, then the (3+1) schemes have a problem. To explain the LSND data while satisfying the constraints from other disappearance experiments, the oscillation probabilities of the appearance and disappearance channels have to satisfy the following relation [30, 31]:

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

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 $\Delta m^2$ in the allowed region for LSND ($\bar{\nu}_\mu \to \bar{\nu}_e$), the CDHSW experiment [32] ($\nu_\mu \to \nu_\mu$), and the Bugey experiment [24] ($\bar{\nu}_e \to \bar{\nu}_e$), respectively. The reason that the (3+1)-scheme to explain LSND has been disfavored until Refs. [7, 9] appeared is because Eq. (1) is not satisfied for any value of $\Delta m^2$, if we adopt the allowed regions in Refs. [32] and [24]. However, if the flux of the reactor neutrino is slightly larger than the one used in the Bugey analysis [24], the allowed region becomes slightly wider and we have more chance to satisfy Eq. (1).

In this paper we will use the following parametrization for the mixing matrix, adopted in Ref. [33]:

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

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

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

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

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{14} \sin^2 \left(\frac{\Delta m^2_{31}L}{4E}\right)$$

(2)

to a good approximation. Eq. (2) is the formula which will be used in the oscillation analysis throughout this paper.
III. SENSITIVITY TO $\sin^2 2\theta_{14}$ BY A SPECTRAL ANALYSIS

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

To evaluate the sensitivity to $\sin^2 2\theta_{14}$, we introduce the following $\chi^2$ which was adopted in Ref. [19]:

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

Here, $m_i^A$ 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$^4$, 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:

$$(t_i^A \sigma_i^A)^2 = t_i^A + (t_i^A \sigma_{db}^A)^2,$$

where $\sigma_{db}^A$ is the uncorrelated bin-to-bin systematic error. For simplicity we assume that sizes of the bin-to-bin uncorrelated systematic errors of the detectors and of the flux are independent of the energy. Also we take the choice of the bins in such a way that the number of events for each bin is equal: $t_i^A = t^A (i = 1, \cdots, n)$. $\alpha$ is a variable which corresponds to a common overall normalization error $\sigma_{DB}$ for the number of events. $\alpha^A (A = N, F)$ is a variable which introduces the detector-specific uncertainties $\sigma_{DB}$ of the near and far detectors. $\alpha_i (i = 1, \cdots, n)$ is a variable for an uncertainty $\sigma_{DB}$ of the theoretical prediction for each energy bin which is uncorrelated between different energy bins.$^5$ $\alpha_{cal}^A (A = N, F)$ is a variable which introduces an energy calibration uncertainty $\sigma_{cal}$ and comes in the theoretical prediction in the form of $(1 + \alpha_{cal}^A)E$ instead of the observed energy $E$. Thus, the deviation $v_i^A$ (divided by the expected number of events) from the theoretical prediction $t_i^A$ due to this

$^4$ As we will see below, in the spectrum analysis, unlike in the rate one, it is not necessary for the near detector to have events without oscillation, since the dominant term in $\chi^2$ looks at the difference between the maximum and minimum of the oscillation pattern. In fact, in Fig. 11 below there are regions in which $L_N \geq L_F$. Therefore, it may be misleading to call the detector at the shorter baseline length the near detector. Nevertheless, we use these words throughout this paper for simplicity.

$^5$ Here we follow the notation for the systematic errors in Ref. [19]. The first suffix of $\sigma$ 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. The correspondence for the notation in Ref. [12] is as follows: $\sigma_{db} = \sigma_{exp}, \sigma_{dB} = \sigma_b, \sigma_{DB} = \sigma_{shape}, \sigma_{DB} = \sigma_a$. 

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uncertainty can be written as

\[
v_i^A = \lim_{\alpha_{\text{cal}} \to 0} \frac{1}{\alpha_{\text{cal}} t_i^A} \left[ \frac{N_p T}{4 \pi L_A^2} \int dE \int_{(1+\alpha_{\text{cal}})E_i}^{(1+\alpha_{\text{cal}})E_i+1} dE' R(E_e, E') \epsilon(E) F(E) \sigma(E) - t_i^A \right],
\]

with

\[
t_i^A = \frac{N_p T}{4 \pi L_A^2} \int dE \int_{E_i}^{E_{i+1}} dE' R(E_e, E') \epsilon(E) F(E) \sigma(E). \tag{5}
\]

In Eqs. (4) and (5), \(N_p\) is the number of target protons in the detector, \(T\) denotes the exposure time, \(L_A\) is the baseline for the detector \(A\), \(F(E)\) is the flux of \(\bar{\nu}_e\), and \(\sigma(E)\) is the cross section of the inverse \(\beta\) decay \(\bar{\nu}_e + p \to n + e^+\). \(E\) is the energy of the incident \(\bar{\nu}_e\) and it is related to the positron energy \(E_e\) and the masses \(m_n\), \(m_p\) of a neutron and a proton by \(E = E_e + m_n - m_p = E_e + 1.3\) MeV. \(E'\) is the measured positron energy and we will assume that the energy resolution is given by \(8/\sqrt{E}\), i.e., \(R(E_e, E') = R(E - m_n + m_p, E')\) is a Gaussian function which describes the energy resolution and is given by \(R(E_e, E') = (1/\sqrt{2\pi\sigma}) \exp[-(E_e - E')^2/2\sigma^2]\), where \(\sigma = 0.08\sqrt{(E_e + m_e)/\text{MeV}} = 0.08\sqrt{(E - 0.8/\text{MeV})/\text{MeV}}\). Our strategy is to assume no oscillation in the theoretical prediction \(t_i^A\), to substitute the number of events with oscillation in \(m_i^A\), and to see the sensitivity by looking at the value of \(\chi^2\). Since \(\chi^2\) is quadratical in the variables \(\alpha, \alpha^A, \alpha_i, \alpha_{\text{cal}},\) we can minimize with respect to these variables in Eq. (3) exactly. \(^6\)

Since we assume no oscillation for the theoretical prediction \(t_i^A\), the quantity \(v_i^A\) in Eq. (4) is independent of \(A (= N, F)\):

\[
v_i^N = v_i^F = v_i. \tag{6}
\]

Here we will take the following assumptions for the systematic errors:

\[
\begin{align*}
\sigma_{\text{db}} &= 0.5\%, \\
\sigma_{\text{dB}} &= 0.5\%, \\
\sigma_{\text{Db}} &= 2\%, \\
\sigma_{\text{DB}} &= 3\%, \\
\sigma_{\text{cal}} &= 0.6\%. \tag{7}
\end{align*}
\]

We will take the number \(n\) of bins \(n=32\) and the energy interval \(2.8\text{MeV} \leq E_{\nu} \leq 7.8\text{MeV}\). The measurement is supposed to continue for \(1,800\) hours, and the total numbers of events is expected to be approximately \(90,000 \times (15m/L_A)^2\) \((A = N, F)\). \(^6\)

\(^6\) In principle we could take a different convention, such as multiplying the measured numbers \(m_i^A\) by the uncertainty \((1 + \alpha + \alpha^A + \alpha_i)\), etc., and in fact it is done in some references. With such a convention, it becomes complicated to work with an analytical approach because \(\chi^2\) is not a Gaussian with respect to \(m_i^A\), which includes oscillation parameters, after the minimizations of \(\alpha\)’s. However, the difference between such a convention and ours affects only the higher orders in \(\sigma^2\)’s. The conclusion on the sensitivity with such a convention should coincide with ours numerically.
A. An analytical expression for $\chi^2$

As was demonstrated in Refs. [18, 19], it is instructive to have an analytic expression for $\chi^2$, since it enables us to see which term becomes dominant in the spectrum analysis. Unfortunately, it is difficult to evaluate $\chi^2$ analytically with non-zero statistical errors and the energy calibration uncertainty $\sigma_{\text{cal}}$. In the limit of infinite statistic, an analytical expression for $\chi^2$ can be obtained (cf. Eq. (10) in Ref. [19]). On the other hand, in the presence of finite statistical errors (with equal numbers of events for each bin, $t_j = t^A$), we can obtain an analytical form in the limit of $\sigma_{\text{cal}} = 0$ and the result is given by Eq. (A7) in Appendix A.

In the present case, under the assumption that the total numbers of events $N^F$ and $N^N$ are of order $10^5$, that the number $n$ of bins is 32, and that the systematic errors are given by Eq. (7), we get

$$\frac{\chi^2}{\sin^4 2\theta_{14}} \approx \frac{\left\{ \vec{u}_1 \cdot (\vec{D}^F + \vec{D}^N) \right\}^2}{4\sigma^2_{\text{DB}}} + \frac{\left\{ \vec{u}_1 \cdot (\vec{D}^N - \vec{D}^F) \right\}^2}{2\sigma^2_{\text{DB}} + 1/N^F + 1/N^N}$$

$$+ \frac{\left\{ \vec{u}_j \cdot (c_2\vec{D}^F + s_2\vec{D}^N) \right\}^2}{n} + \frac{\left\{ \vec{u}_j \cdot (c_2\vec{D}^N - s_2\vec{D}^F) \right\}^2}{n}$$

where we have introduced the variables

$$D_i^A \equiv -\frac{1}{\sin^2 2\theta_{14}} \frac{m^A_i - t_i^A}{t_i^A}$$

$$= \int dE \int_{E_i}^{E_{i+1}} dE' R(E_e, E') \epsilon(E) F(E) \sigma(E) \sin^2 \left( \frac{\Delta m^2_{41} L}{4E} \right),$$

and $\vec{u}_j$ are the orthonormal eigenvectors of some $n \times n$ unitary matrices (see Appendix A). $n$ is the number of bins and $N^A$ ($A = N, F$) stands for the total number of events ($n \times t_i^A = N^A$). $c_2 \equiv \cos \varphi_2$, $s_2 \equiv \sin \varphi_2$, and $\varphi_2$ are angles defined in Eq. (A6) to diagonalize a $2 \times 2$ matrix.

Because $\sigma^2_{\text{DB}}/n \sim 1/(2N^F)$, we have $0 < \varphi_2 \leq \pi/4$. The numerators in all the four terms on RHS in Eq. (8) are divided by the number $n$ of bins, because it is known in the case of infinite statistics [19] that $\{ \vec{u}_1 \cdot (\vec{D}^F \pm \vec{D}^N) \}^2/n$ etc. are almost independent of $n$ for $n \gtrsim 16$.

The first (last) two terms in Eq. (8) correspond to the rate (spectral) analysis, because $\vec{u}_1 \propto (1, \cdots, 1)^T$, while the other vectors $\vec{u}_j$ ($j = 2, \cdots, n$) are orthogonal to $\vec{u}_1$. The first (second) term looks at the sum (difference) of the total numbers of events at the far and near detectors. The dominant error in the first term is the systematic error $\sigma^2_{\text{DB}}$ which is correlated between the two detectors, while the dominant one in the second is the statistical error $1/N^F + 1/N^N$ plus the systematic one $\sigma^2_{\text{DB}}$ which is uncorrelated between the two detectors. These first two terms are basically what was discussed in the rate analysis to
study the sensitivity to \( \sin^2 2\theta_{13} \) in Ref. [11]. The third (fourth) term examines the sum (difference) of the significance of the spectrum shapes of events at the far and near detectors. As statistic increase, the denominator of the fourth term becomes the smallest, and it is the fourth term which dominates \( \chi^2 \) in the limit of infinite statistics. With the finite numbers of events, however, the last three terms do contribute to \( \chi^2 \).

In the limit of large mass squared difference \( \Delta m^2_{41} \), the vector \( D^A_j \) becomes \( D^A_j \to (1/2)(1, \cdots, 1) \), \( \vec{u}_1 \cdot \vec{D}^A \to \sqrt{n}/2 \) and \( \vec{u}_j \cdot \vec{D}^A \to 0 \) \( (j = 2, \cdots, n) \). So the right hand side of Eq. (8) becomes \( (4\sigma^2_{DB})^{-1} \), and the sensitivity in this limit is given by \( \sin^2 2\theta_{14} \sim \sqrt{4\sigma^2_{DB}2.7} \sim 0.1 \). Note that \( \chi^2 = 2.7 \) gives a 90% CL bound on \( \sin^2 2\theta_{14} \).

**B. Thermal neutron reactors**

A core of conventional (thermal neutron) reactors typically has a diameter of 4m, a height 4m and its thermal power is typically a few GW. As we will see below, when we try to perform an oscillation experiment at very short baseline lengths, smearing of the reactor core size gives a nontrivial contribution to the results because the baseline lengths are comparable to the core size.

We have computed \( \chi^2 \) in Eq. (3) numerically in the case of a thermal neutron reactor. Fig. 1 shows the sensitivity to \( \sin^2 2\theta_{14} \) as a function of the baseline lengths of the near and far detectors for \( \Delta m^2_{41} = 1\text{eV}^2 \), and \( 5\text{eV}^2 \), respectively. We have assumed a thermal power of \( 2.8\text{GW} \), and a diameter of 4m and a height of 4m, and we have varied the baseline lengths in the range \( 14\text{m} \sim L_A \sim 40\text{m} \). Unlike the case of infinite statistics [19], the statistical errors are important in the present setup of the detectors, and longer baseline lengths are disfavored.

For \( \Delta m^2_{41} = 1\text{eV}^2 \) (Fig. 1 upper panel), the set \( (L_N, L_F) \approx (17\text{m}, 23\text{m}) \) gives the optimum. In contrast to the rate analysis, in which the optimized baseline length of the near detector is \( L_N = 0\text{m} \) to avoid oscillations, the spectrum analysis with \( (L_N, L_F) = (17\text{m}, 23\text{m}) \) looks at the difference between the maximum and minimum of the spectrum shape with neutrino oscillations at \( L_N \) and \( L_F \) mainly for the energy region \( E_\nu \sim 4\text{MeV} \) where the number of events are expected to be the largest.

On the other hand, for \( \Delta m^2_{41} = 5\text{eV}^2 \) (Fig. 1 lower panel), the sensitivity to \( \sin^2 2\theta_{14} \) is as low as 0.1 for most of the set of the baseline lengths \( (L_N, L_F) \). This implies that \( \Delta m^2_{41} \) is so large that we have average over rapid oscillations for almost any baseline lengths and the only term which contributes in Eq. (8) is the first term, that corresponds to the rate analysis.

Fig. 2 shows the sensitivity to \( \sin^2 2\theta_{14} \) as a function of \( \Delta m^2_{41} \) in the case of the baseline lengths \( (L_N, L_F) = (17\text{m}, 23\text{m}) \). For \( \Delta m^2_{41} \gtrsim 2\text{eV}^2 \), it indicates that 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. 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 \( \Delta m^2_{41} \gtrsim 2\text{eV}^2 \) because of the smearing effect of the finite core size of the reactor. We have computed the sensitivity also for different numbers of bins \( (n=16, 64) \), and verified explicitly that the result of Fig. 2 is almost independent of \( n \) for \( 16 \leq n \leq 64 \). This is because the statistical errors are dominant in \( \chi^2 \).
FIG. 1: The sensitivity to $\sin^2 2\theta_{14}$ as a function of the two baseline lengths in the case of an ordinary thermal neutron reactor of a diameter 4m, a height 4m, a thermal power 2.8GW. $\Delta m^2_{41} = 1$eV$^2$ (upper panel), 5eV$^2$ (lower) is assumed.
\( \Delta m^2_{41}/\text{eV}^2 \)  

FIG. 2: The sensitivity to \( \sin^2 2\theta_{14} \). The red line stands for the one for a thermal neutron reactor (of a diameter 4m, a height 4m, a thermal power 2.8GW) with two detectors at \( L_F = 23\text{m} \) and \( L_N = 17\text{m} \), while the blue line for the one for a hypothetical reactor with a point-like core.

C. Experimental fast neutron 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. Fast neutron reactors are known to have a high power density, and an oscillation experiments using them might be more advantageous than those with thermal neutron reactors. While experimental fast neutron reactors have a small power, it may allow experimentalists to put the detectors at a nearer location because of their experimental nature.

Here we will discuss the concrete example of Joyo [34] with MK-III upgrade [35], which
FIG. 3: The sensitivity to $\sin^2 2\theta_{14}$ as a function of the two baseline lengths in the case of Joyo \cite{3} with MK-III upgrade \cite{35} which is an experimental fast reactor (of a diameter 0.8m, a height 0.5m, a thermal power 0.14GW). $\Delta m^2_{41} = 1eV^2$ (upper panel), $5eV^2$ (lower) is assumed.
FIG. 4: The sensitivity to $\sin^2 2\theta_{14}$ of the Joyo reactor with two detectors. The Blue line stands for the one in the case with two detectors at $L_F = 4m$ and $L_N = 3m$, while the red line for the one for in the case with two detectors at $L_F = 8m$ and $L_N = 4m$. The sensitivity in the case of a conventional thermal neutron reactor (the green line) is also given for comparison.

is an experimental fast breeder reactor. It has a relatively small size (a diameter of 0.8m, a height of 0.5m), and a relatively large thermal power 0.14GW. Its power density is approximately 500 kW/ℓ, whereas a typical power density of thermal neutron reactors is approximately 50 kW/ℓ.

Again we have computed $\chi^2$ in Eq. (3) numerically in the case of Joyo with MK-III upgrade. Fig. 3 shows the sensitivity to $\sin^2 2\theta_{14}$ as a function of the baseline lengths of the near and far detectors for $\Delta m_{41}^2 = 1eV^2$, and $5eV^2$, respectively. We have assumed the

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7 An experiment [36] was performed to detect neutrinos from a fast neutron reactor at Joyo, although they did not get sufficient statistical significance.
same conditions for the detectors (the size, the efficiency, the exposure time etc.) as those assumed in Fig. 1. From Fig. 3 we see that the set \((L_N, L_F) \simeq (4m, 8m)\) gives the optimum for \(\Delta m^2_{41} = 1\text{eV}^2\) (Fig. 3 upper panel).

Fig. 4 shows the sensitivity to \(\sin^2 2\theta_{14}\) as a function of \(\Delta m^2_{41}\) in the case of the sets of the baseline lengths \((L_N, L_F) = (4m, 8m)\) and \((L_N, L_F) = (3m, 4m)\). The set of the baseline lengths \((L_N, L_F) = (3m, 4m)\) has a peak for \(\sin^2 2\theta_{14} \simeq 4\text{eV}^2\), while the other set \((L_N, L_F) = (4m, 8m)\) has sensitivity to \(\sin^2 2\theta_{14}\) for a wider range of \(\Delta m^2_{41}\). The sensitivity in the case of a conventional thermal neutron reactor is also given in Fig. 2 for comparison, and the advantage of the case with Joyo is clear. Also in this case the statistical errors are dominant in \(\chi^2\), and the result of Fig. 4 is almost independent of the number \(n\) of bins for \(16 \leq n \leq 64\).

IV. DISCUSSION AND CONCLUSION

In the framework of the \((3+1)\)-scheme, we studied the sensitivity to \(\sin^2 2\theta_{14}\) of very short baseline reactor oscillation experiments by a spectrum analysis. The assumptions are that we have two detectors whose size and efficiency are exactly the same as those used at the Bugey experiment [24].

In the case of a conventional thermal neutron reactor, which has a core of a diameter 4m, a height 4m and a thermal power 2.8GW, by putting the detectors at \(L_N = 17m\) and \(L_F = 23m\), we obtain the sensitivity as good as several \(\times 10^{-2}\) for \(\Delta m^2_{31} \lesssim 1\text{eV}^2\), but we lose the sensitivity above \(1\text{eV}^2\) due to the smearing of the finite core size.

In the case of an experimental fast neutron reactor with a core of a diameter of 0.8m, a height of 0.5m and a thermal power 0.14GW, on the other hand, we obtain the sensitivity as good as a several \(\times 10^{-2}\) for \(1\text{eV}^2 \lesssim \Delta m^2_{41} \lesssim 10\text{eV}^2\) if we put the detectors at \(L_N = 4m\) and \(L_F = 8m\).

In both types of reactors with the Bugey-like detector setup, the statistical errors are dominant, and the sensitivity is almost independent of the number \(n\) of bins of the spectral analysis. The reason that the case of the experimental fast neutron reactor 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 the thermal neutron reactor at \(L \sim\) a few \(\times 10\) meters.

Since the best fit value obtained in Ref. [9] is \(\Delta m^2_{41} \sim 2\text{eV}^2\), an experiment using an experimental fast neutron reactor offers a promising possibility.

It should be emphasized that the flux uncertainty by 3% which was pointed out in Ref. [7] does not cause a problem in our discussion. The reason is because the main contribution to \(\chi^2\) comes from the spectrum analysis, which looks at the difference of the maximum and the minimum of the energy spectrum and the effect of the overall normalization of the flux (the first term of the RHS in Eq. (8)) gives little contribution to \(\chi^2\) in the region of \(\Delta m^2_{41}\) in which the sensitivity to \(\sin^2 2\theta_{14}\) is better than 0.1.

Although we may not be able to put the detectors at such a close location, we could increase the detector volume and/or the measurement period, so that the data size is the same as those described in this paper. While the experimental feasibility of the idea of putting detectors at a location very near to an experimental fast reactor is yet to be seen, it is worth investigating whether this method is technically possible.
Appendix A: Derivation of the covariance matrix

By choosing the bins in such a way that $t_i^A = t_i^A$, Eq. (3) becomes

$$
\chi^2 = \min_{\alpha's} \left\{ \sum_{A=N,F}^{n} \sum_{i=1}^{n} \frac{(m_i^A/t_i^A - 1 - \alpha - \alpha^A - \alpha_i - \alpha_{cal}^A v_i^A)^2}{1/t_i^A + (\sigma_{db}^A)^2} \right. \\
+ \left. \sum_{A=N,F}^{n} \left[ \left( \frac{\alpha^A}{\sigma_{db}} \right)^2 + \left( \frac{\alpha_{cal}^A}{\sigma_{cal}} \right)^2 \right] \right. \\
+ \left. \sum_{i=1}^{n} \frac{\alpha_i}{\sigma_{DB}} + \left( \frac{\alpha}{\sigma_{DB}} \right)^2 \right\}
$$

$$
\equiv \min_{\alpha's} \chi^2_{\alpha}.
$$

Let us redefine the variables

$$
y_i^A \equiv \frac{m_i^A - t_i^A}{t_i^A} = -\sin^2 2\theta_{14} D_i^A
$$

and let us introduce a vector notation

$$
\vec{y}^N \equiv \begin{pmatrix} y_1^N \\ \vdots \\ y_n^N \end{pmatrix}, \quad \vec{y}^F \equiv \begin{pmatrix} y_1^F \\ \vdots \\ y_n^F \end{pmatrix}.
$$

Following the discussions in the Appendix A in [18], the matrix element of the covariance matrix can be obtained as the expectation value of $y_i^A y_j^B$:

$$
(\rho)^{AB}_{ij} = \langle y_i^A y_j^B \rangle \\
\equiv N \int d\alpha_i \prod_{A=N,F} \int d\vec{y}^A \int d\alpha^A \prod_{i=1}^{n} \int d\alpha_i \ y_i^A y_j^B \exp \left( -\frac{\chi^2_{\alpha}}{2} \right),
$$

where the normalization $N$ is defined in such a way that $\langle 1 \rangle = 1$. From a straightforward calculation, we have

$$
\langle y_i^A y_j^B \rangle = \delta^{AB} \delta_{ij} 1/t^A + \delta^{AB} \delta_{ij} \sigma_{db}^2 + \sigma_{DB}^2 + \delta^{AB} \sigma_{db}^2 + \delta_{ij} \sigma_{DB}^2 + \delta^{AB} v_i^A v_j^A \sigma_{cal}^2.
$$

Thus we have

$$
\chi^2 = (\vec{y}^N \ T, \vec{y}^F \ T) \rho^{-1} \left( \begin{pmatrix} \vec{y}^N \\ \vec{y}^F \end{pmatrix} \right) = \sin^4 2\theta_{14} \begin{pmatrix} \vec{D}^N \ T, \vec{D}^F \ T \end{pmatrix} \rho^{-1} \begin{pmatrix} \vec{D}^N \\ \vec{D}^F \end{pmatrix},
$$

where the covariance matrix $\rho$ is defined by

$$
\rho = \begin{pmatrix} M + 1/t^N I_n & N \\ N & M + 1/t^F I_n \end{pmatrix},
$$

with

$$
M \equiv (\sigma_{db}^2 + \sigma_{db}^2) I_n + (\sigma_{DB}^2 + \sigma_{DB}^2) H_n + \sigma_{cal}^2 G_n; \\
N \equiv \sigma_{DB}^2 I_n + \sigma_{DB}^2 H_n.
$$

(A1)

(A2)
Here $I_n$ is an $n \times n$ unit matrix, $H_n$ and $G_n$ are $n \times n$ matrices defined by

\[
H_n \equiv \begin{pmatrix}
1 & \cdots & 1 \\
\vdots & \ddots & \vdots \\
1 & \cdots & 1
\end{pmatrix}, \tag{A3}
\]

\[
G_n \equiv \begin{pmatrix}
v_1^2 & v_1v_2 & \cdots & v_1v_n \\
v_1v_2 & v_2^2 & \cdots & v_2v_n \\
\vdots & \vdots & \ddots & \vdots \\
v_1v_n & v_2v_n & \cdots & v_n^2
\end{pmatrix}, \tag{A4}
\]

where $v_j$ ($j = 1, \cdots, n$) is defined by Eqs. (4), and (6). Note that the covariance matrix does not include oscillation parameters but only errors. Diagonalization of the covariance matrix is useful to see which errors dominate $\chi^2$.

Unlike in Ref. [19], the presence of the statistical errors $1/t^4$ and the matrix $G_n$ makes it difficult to evaluate the eigenvalues analytically, so only in this appendix, we will take the limit $\sigma_{\text{cal}}^2 \to 0$ which may be justified in the present setup with the total numbers of events $\sim 10,000 \times (15m/L_A)^2$.

To diagonalize the matrix (A1) with $\sigma_{\text{cal}}^2 = 0$, we first note that the matrix $H_n$ can be diagonalized as

\[
H_n = U_n D_n U_n^{-1},
\]

where

\[
D_n = \text{diag}(n, 0, \cdots, 0)
\]

is a diagonal matrix and

\[
U_n = (\vec{u}_1, \cdots, \vec{u}_n),
\]

\[
\vec{u}_1 \equiv \frac{1}{\sqrt{n}} (1, \cdots, 1)^T
\]

\[
\vec{u}_2 \equiv \frac{1}{\sqrt{2}} (1, -1, 0, \cdots, 0)^T
\]

\[
\vec{u}_3 \equiv \frac{1}{\sqrt{6}} (1, 1, -2, 0, \cdots, 0)^T
\]

\[
\vdots
\]

\[
\vec{u}_n \equiv \frac{1}{\sqrt{n(n-1)}} (1, \cdots, 1, -(n-1))^T
\]

is a $n \times n$ unitary matrix. Thus $M$ and $N$ can be diagonalized as

\[
M = U_n \left\{ (\sigma_{Db}^2 + \sigma_{db}^2) I_n + (\sigma_{DB}^2 + \sigma_{dB}^2) D_n \right\} U_n^{-1}
= U_n \text{diag}(p_1, p_2, \cdots, p_2) U_n^{-1},
\]

\[
N = U_n \left( \sigma_{Db}^2 I_n + \sigma_{DB}^2 D_n \right) U_n^{-1}
= U_n \text{diag}(q_1, q_2, \cdots, q_2) U_n^{-1},
\]
where
\[p_1 \equiv \sigma^2_{Db} + \sigma^2_{db} + n(\sigma_{DB}^2 + \sigma_{dB}^2)\]
\[p_2 \equiv \sigma^2_{Db} + \sigma^2_{db}\]
\[q_1 \equiv \sigma^2_{Db} + n\sigma^2_{DB}\]
\[q_2 \equiv \sigma^2_{Db}.\]  \hspace{1cm} (A5)

Now (A1) can be cast into a block diagonal by
\[
\begin{align*}
\begin{pmatrix}
U^{-1} & 0 \\
0 & U^{-1}
\end{pmatrix}
\begin{pmatrix}
M + 1/t^N I_n & N \\
N & M + 1/t^F I_n
\end{pmatrix}
\begin{pmatrix}
U & 0 \\
0 & U
\end{pmatrix}
&=
\begin{pmatrix}
\sigma^2_{Db} + \sigma^2_{db} + 1/t^N I_n + (\sigma^2_{DB} + \sigma^2_{dB}) D_n \\
\sigma^2_{Db} I_n + \sigma^2_{dB} D_n & \sigma^2_{Db} I_n + (\sigma^2_{DB} + \sigma^2_{dB}) D_n
\end{pmatrix} \\
\begin{pmatrix}
B_1 & 0 & \cdots & 0 \\
0 & B_2 & \ddots & \vdots \\
& & \ddots & 0 \\
0 & \cdots & 0 & B_2
\end{pmatrix}
\begin{pmatrix}
U & 0 \\
0 & U
\end{pmatrix}
\end{align*}
\]

where \(U\) is a \(2n \times 2n\) unitary matrix whose matrix elements are given by
\[U_{pq} \equiv \sum_{j=1}^{n} \left( \delta_{p,2j-1} \delta_{q,j} + \delta_{p,2j} \delta_{q,n+j} \right).\]

\(B_1, B_2\) are \(2 \times 2\) matrices defined as follows and are diagonalized as
\[B_1 \equiv \begin{pmatrix} p_1 + 1/t^N & q_1/p_1 + 1/t^F \\ q_1 & p_1 + 1/t^F \end{pmatrix} = e^{i\varphi_1\sigma_2} \text{diag}(\lambda_1^{(-)}, \lambda_1^{(+)}) e^{-i\varphi_1\sigma_2}\]
\[B_2 \equiv \begin{pmatrix} p_2 + 1/t^N & q_2/p_2 + 1/t^F \\ q_2 & p_2 + 1/t^F \end{pmatrix} = e^{i\varphi_2\sigma_2} \text{diag}(\lambda_2^{(-)}, \lambda_2^{(+)}) e^{-i\varphi_2\sigma_2},\]

where
\[\sigma_2 \equiv \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}\]
is the Pauli matrix, \(\varphi_1\) and \(\varphi_2\) are introduced to diagonalize each matrix and are given by
\[\tan 2\varphi_1 = \frac{2q_1}{1/t^F - 1/t^N}, \quad \frac{2(\sigma^2_{Db} + n\sigma^2_{DB})}{1/t^F - 1/t^N}\]
\[\tan 2\varphi_2 = \frac{2q_2}{1/t^F - 1/t^N}, \quad \frac{2\sigma^2_{Db}}{1/t^F - 1/t^N},\]  \hspace{1cm} (A6)
and $\lambda_j^{(\pm)}$ ($j = 1, 2$) are the eigenvalues given by

$$
\lambda_1^{(\pm)} \equiv n \left[ \frac{\sigma_{db}^2}{n} + \sigma_{db}^2 + \frac{1}{2} \left( \frac{1}{N^F} + \frac{1}{N^N} \right) \right] \\
\pm \left\{ \frac{1}{4} \left( \frac{1}{N^F} - \frac{1}{N^N} \right)^2 + \left( \frac{\sigma_{db}^2}{n} + \sigma_{db}^2 \right)^2 \right\} \\
\lambda_2^{(\pm)} \equiv n \left[ \frac{\sigma_{db}^2}{n} + \frac{1}{2} \left( \frac{1}{N^F} + \frac{1}{N^N} \right) \right] \\
\pm \left\{ \frac{1}{4} \left( \frac{1}{N^F} - \frac{1}{N^N} \right)^2 + \left( \frac{\sigma_{db}^2}{n} + \sigma_{db}^2 \right)^2 \right\} .
$$

In the last expression, we have factored out $n$ from the eigenvalues for later convenience, and we have introduced the total numbers of events $N^A \equiv n \times t^A$ ($A = N, F$).

To evaluate $\chi^2$, we need to calculate the following factor:

$$
\begin{pmatrix}
  e^{-i\varphi_1\sigma_2} & 0 & \cdots & 0 \\
  0 & e^{-i\varphi_2\sigma_2} & \cdots & 0 \\
  \vdots & \vdots & \ddots & \vdots \\
  0 & \cdots & e^{-i\varphi_2\sigma_2} & 0
\end{pmatrix} U \begin{pmatrix}
  U_n^{-1} & 0 & 0 \\
  0 & U_n^{-1} & 0
\end{pmatrix} \begin{pmatrix}
  \bar{D}^N \\
  \bar{D}^F
\end{pmatrix}
$$

$$
= \begin{pmatrix}
  e^{-i\varphi_1\sigma_2} \left( \bar{u}_1 \cdot \bar{D}^N \right) \\
  e^{-i\varphi_2\sigma_2} \left( \bar{u}_2 \cdot \bar{D}^N \right) \\
  \vdots \\
  e^{-i\varphi_2\sigma_2} \left( \bar{u}_n \cdot \bar{D}^N \right)
\end{pmatrix} \begin{pmatrix}
  c_1 \bar{u}_1 \cdot \bar{D}^N - s_1 \bar{u}_1 \cdot \bar{D}^F \\
  c_1 \bar{u}_1 \cdot \bar{D}^F + s_1 \bar{u}_1 \cdot \bar{D}^N \\
  c_2 \bar{u}_2 \cdot \bar{D}^N - s_2 \bar{u}_2 \cdot \bar{D}^F \\
  c_2 \bar{u}_2 \cdot \bar{D}^F + s_2 \bar{u}_2 \cdot \bar{D}^N
\end{pmatrix},
$$

where $c_j \equiv \cos \varphi_j$, $s_j \equiv \sin \varphi_j$ ($j = 1, 2$).
Putting everything together, we obtain

\[
\frac{\chi^2}{\sin^4 2\theta_{14}} = \left( \frac{c_1 u_1 \cdot \vec{D}^F + s_1 u_1 \cdot \vec{D}^N}{\sigma_{DB}^2 + \sigma_{db}^2 + (\sigma_{Db}^2 + \sigma_{db}^2)/n + (1/N^F + 1/N^N)/2 + \{(1/N^F - 1/N^N)^2/4 + (\sigma_{DB}^2 + \sigma_{Db}^2/n)^2\}^{1/2}} \right) \\
+ \left( \frac{c_1 u_1 \cdot \vec{D}^N - s_1 u_1 \cdot \vec{D}^F}{\sigma_{DB}^2 + \sigma_{db}^2 + (\sigma_{Db}^2 + \sigma_{db}^2)/n + (1/N^F + 1/N^N)/2 - \{(1/N^F - 1/N^N)^2/4 + (\sigma_{DB}^2 + \sigma_{Db}^2/n)^2\}^{1/2}} \right) \\
+ \sum_{j=2}^{n} \left[ \left( \frac{c_2 u_j \cdot \vec{D}^F + s_2 u_j \cdot \vec{D}^N}{\sigma_{DB}^2 + \sigma_{db}^2 + (\sigma_{Db}^2 + \sigma_{db}^2)/n + (1/N^F + 1/N^N)/2 + \{(1/N^F - 1/N^N)^2/4 + (\sigma_{DB}^2 + \sigma_{Db}^2/n)^2\}^{1/2}} \right) \right] \\
+ \sum_{j=2}^{n} \left[ \left( \frac{c_2 u_j \cdot \vec{D}^N - s_2 u_j \cdot \vec{D}^F}{\sigma_{DB}^2 + \sigma_{db}^2 + (\sigma_{Db}^2 + \sigma_{db}^2)/n + (1/N^F + 1/N^N)/2 - \{(1/N^F - 1/N^N)^2/4 + (\sigma_{DB}^2 + \sigma_{Db}^2/n)^2\}^{1/2}} \right) \right]
\]

(A7)

where both the numerators and denominators are divided by the number \( n \) of bins, because the numerators are almost independent of \( n \) after being divided by \( n \) in the limit of infinite statistics \([19]\).

In the present case, assuming that the total numbers of events \( N^F \) and \( N^N \) are of order \( 10^5 \) and that the number \( n \) of bins is 32, our reference values (7) satisfy \( \sigma_{DB}^2 \simeq 9 \times 10^{-4} \gg 1/N^A \sim 10^{-5} (A = N, F) \), \( \sigma_{dB}^2 \simeq 3 \times 10^{-5} \gg \sigma_{db}/n \simeq 1 \times 10^{-6} \), \( \sigma_{DB}/n \simeq 1 \times 10^{-5} \sim 1/N^A \sim 10^{-5} (A = N, F) \). Hence we obtain Eq. (8).

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