Shedding light on LMA-Dark solar neutrino solution by medium baseline reactor experiments: JUNO and RENO-50

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In the presence of Non-Standard neutral current Interactions (NSI) a new solution to solar neutrino anomaly with $\cos 2\theta_{12} < 0$ appears. We show that this solution can be tested by upcoming intermediate baseline reactor experiments, JUNO and RENO-50.

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I. INTRODUCTION

Within the Standard Model (SM) the neutral current interactions are flavor diagonal and universal for all three flavors. However, most beyond SM mechanisms dealing with flavor predict a correction to neutrino interaction terms which violate flavor universality and conservation. Examples of such models include R-parity violating supersymmetry, grand unification, AMEND model [1], extra $U(1)'$ gauge models, left-right symmetric models and various seesaw models (for a review see [2]). The non-standard neutral current interaction of neutrinos can be in general formulated by an effective dimension six operator as

\begin{equation}
\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F \epsilon_{\alpha\beta}^{fP}(\bar{\nu}_\alpha \gamma^\mu L \nu_\beta)(\bar{f} \gamma_\mu P f)
\end{equation}

where $f$ is the matter field ($u$, $d$ or $e$), $P$ is the chirality projection matrix and $\epsilon_{\alpha\beta}^{fP}$ is a dimensionless matrix describing the deviation from the standard model. For neutrino oscillation, only the “vector” part of the interaction operator is relevant so it is convenient to define

\[ \epsilon_{\alpha\beta}^f \equiv \epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR}. \]

Effects of Lagrangian (1) on neutrino oscillation have been extensively studied in the literature. In particular in [3], it is shown that in the presence of a deviation from universality (i.e., $|\epsilon_{\bar{d}e} - \epsilon_{\bar{d}\mu}|$, $|\epsilon_{\bar{d}e} - \epsilon_{\bar{d}\tau}| \neq 0$ with $f = u, d$), another solution with $\cos(2\theta_{12}) < 0$ for solar and KamLAND data exists. This solution is known as LMA-Dark solution. Recent studies show that this new solution survives combining all the available data on oscillation [4]. In fact, in the presence of Non-Standard Interactions (NSI), the fit to solar data is slightly better as in the presence of NSI, the upturn of the spectrum at low energy predicted by the standard LMA solution without NSI can be suppressed, leading to a better agreement with the data [3].

The NSI can also affect other observable quantities such as the invisible decay width of the Z boson (at one-loop) or neutrino scattering off matter. All relevant bounds have extensively been studied [2, 5, 6]. The bound from the CHARM scattering experiment combined with the NuTeV results rule out a NSI violation of flavor universality and conservation. Examples of such models include $\mu \mu$-parity violating supersymmetry, AMEND model [1], extra $U(1)'$, $\mu \mu$-parity violating supersymmetry, AMEND model [1], extra $U(1)'$

II. OSCILLATION PROBABILITY

The energy of the reactor neutrinos are of order of MeV so in the leading order, the matter effects can be neglected in the propagation of these neutrinos in the earth (i.e., $\Delta m^2_{31}/E_\nu \gg \sqrt{2}G_F N_\nu$). As a result, the effect of neutral current NSI in Eq. (1) on neutrino propagation can also be neglected. In fact, Refs. [18, 19] focus on the charged current NSI that affect production and detection [i.e., $(d\gamma^\mu P u)(\bar{e} \gamma_\mu L \nu_\mu(r))]$. Neutral current interaction of type (1) cannot affect the production and detection either. At first sight, it seems counterintuitive that reactor neutrinos help us to probe the impact of neutral current NSI. Notice however that we are proposing to determine $\cos 2\theta_{12}$ rather than constraining the NSI parameters, $\epsilon_{\alpha\beta}^f$. Neglecting the matter effects, one can write

\begin{equation}
P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = ||U_{e1}\|^2 + ||U_{e2}\|^2 e^{i\Delta_{21}} + ||U_{e3}\|^2 e^{i\Delta_{31}}||^2 = |c_{12}^2 c_{13}^2 + s_{12}^2 c_{13}^2 e^{i\Delta_{21}} + s_{13}^2 e^{i\Delta_{31}}|^2
\end{equation}

\[ c_{13}^4 (1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta_{21}}{2}) + s_{13}^4 + 2s_{13}^2 c_{13}^2 [\cos \Delta_{31} (c_{12}^2 + s_{12}^2 \cos \Delta_{21}) + s_{12}^2 \sin \Delta_{31} \sin \Delta_{21}] \]

where $\Delta_{ij} = \Delta m^2_{ij} L/(2E_\nu)$ in which $L$ is the baseline. For short baseline reactor experiments such as Daya Bay, RENO or (double-)CHOOZ, we can set $\Delta_{21} \approx 0$ so the sensitivity to $\theta_{12}$ is lost altogether. At KamLAND, $\Delta_{21}$ is
sizeable but the oscillatory modes given by $\Delta_{31}$ are averaged out so KamLAND is only sensitive to $\sin^2 2\theta_{12}$ which cannot distinguish between the two solutions with $\theta_{12} > \pi/4$ and $\theta_{12} < \pi/4$. To distinguish between the standard LMA and LMA-dark solutions the experiment should be sensitive to the last terms in Eq. (2) given by $\cos \Delta_{31} \cos \Delta_{21}$ and $\sin \Delta_{31} \sin \Delta_{21}$. The JUNO and RENO-50 experiments are proposed to resolve these terms as the term given by $\sin \Delta_{31} \sin \Delta_{21}$ is the one sensitive to $\text{sgn}(\Delta_{31})$ and hence the mass hierarchy scheme. In principle, by studying the energy spectrum of the events, we can resolve these terms and extract their amplitude and sign. Thus, we can discriminate between the standard LMA and non-standard LMA-Dark solutions. However, it is a non-trivial question to determine whether this can in principle be possible taking into account the realistic uncertainties. In the rest of the paper, we try to address this question. Before proceeding further notice that $P(\bar{\nu}_e \rightarrow \nu_e)$ in Eq. (2) is invariant under

$$s_{12} \leftrightarrow c_{12} \ (i.e., \ \theta_{12} \rightarrow \frac{\pi}{2} - \theta_{12}) \ \text{and} \ \Delta_{31} \rightarrow -\Delta_{31} + \Delta_{21}.$$ 

In other words, as far as we neglect matter effects, there is a degeneracy when we simultaneously flip hierarchy (NH↔IH) and flip between the LMA and LMA-Dark solutions. We will discuss more about this degeneracy in sect. IV.

### III. JUNO AND RENO-50 EXPERIMENTS

The JUNO and RENO-50 experiments with baselines of $L \sim 50$ km are scheduled to become ready for data taking in 2020 [21]. The detectors will use liquid scintillator technique with an energy resolution of

$$\frac{\delta E_\nu}{E_\nu} \simeq 3\% \times \left( \frac{E_\nu}{\text{MeV}} \right)^{1/2}.$$ 

Ref. [10] enumerates the following backgrounds as the dominant ones (i) accidental background; (ii) $^{13}C(\alpha,n)^{16}O$ background and (iii) Geoneutrino background. For the spectrum of these sources of background and their normalization we use values and description respectively in [22] and in [10]. However, as shown in recent paper [23], the background caused by $^9Li$ from cosmic muon interaction will be dominant. We take 10000 and 5000 fake neutrino signals due to $^9Li$ at respectively JUNO and RENO-50 and assume a spectrum of shape given in [24] for them. The reason why the cosmic muon induced $^9Li$ background is substantially less for RENO-50 than that for JUNO is the deeper location of RENO-50 detector and therefore better shielding from cosmic muons. Notice that the normalization we take for $^9Li$ background is relatively conservative. Reconstructing the muon tracks and using a smart veto, the background can be reduced down to half the assumed value [25].

We divide the energy range between 1.8 MeV to 8 MeV to 350 bin of size 17.7 keV in our analysis. We take the energy calibration error equal to 3 %. Let us now describe the features specific for each experiment one by one.

a. The JUNO experiment: JUNO will be located at a distance of 52 km far from Yangjiang and Taishan reactor complexes with a combined power of 36 GW [9]. JUNO will also receive neutrino flux from the existing Daya Bay and planned Huizhou reactors respectively located 215 km and 265 km far from it. We take the flux normalization uncertainty to be 5 %. The scintillator detector will have a fiducial mass of 20 kton. A list of reactor distances and powers can be found in [9]. To simplify computation, in our numerical analysis we combine the reactor cores whose distance to detector are close to each other. Table 1 summarizes the powers and baselines that we take in our analysis.

| reactor core | 1 | 2 | 3 | 4 |
|--------------|---|---|---|---|
| Baseline (km) | 52.17 | 52.38 | 52.80 | 52.80 |
| Power (GW) | 10.4 | 7.5 | 7.5 | 10.4 |

TABLE I. Baselines and powers of reactor cores taken for the JUNO experiment.

b. The RENO-50 experiment The RENO-50 setup is an upgrade of the current RENO experiment using the neutrino flux from the same reactors with a total power of 16.4 GW. The current detector will be used as near detector reducing the flux uncertainty down to 0.3 % [26]. The far detector with a fiducial mass of 18 kton will be located 47 km away.

The potential of reactor neutrino experiments with a baseline of $\sim 50$ km for determining the neutrino mass ordering has been extensively studied in the literature [9, 11–13, 16]. The main goal of JUNO and RENO-50 experiments is determining the sign of $\Delta m^2_{31}$. It is shown that in order to determine $\text{sgn}(\Delta m^2_{31})$, the difference between the distances of different reactor cores contributing to the flux of the detector should be less than $O(500)$ meters [9, 12, 15].
Considering this restriction, the best location for JUNO is found to be at a 52 km distance from Yangjiang and Taishan reactor complexes [8, 9]. Like the case of determining the hierarchy, we expect the distribution of reactor sources to reduce the sensitivity to sign(\cos(2\theta_{12})) because the distribution of the sources lead to average out of the effects of the oscillatory terms given by \Delta_{31}. Although the matter effects are subdominant, in the numerical analysis we take them into account.

From Eq. (2), we observe that the terms sensitive to sign(\cos(2\theta_{12})) are suppressed by \sigma_{13} \sim 2.5\% C.L. Thus, at first glance it seems that an uncertainty of 3\% or larger in the shape of the initial energy spectrum can wash out the sensitivity to sign(\cos(2\theta_{13})) as well as the sensitivity to sign(\Delta m^2_{31}). In fact, the uncertainty in the shape of the initial energy spectrum at source is at the level of O(3\%) [27]. However as we discuss below, the effects of this uncertainty can be safely neglected. Let us denote the uncertainty in the shape of the initial energy spectrum at energy bin “i” by \Delta \alpha_i. We take into account the effect of this uncertainty by pull method, defining

$$
\chi^2 = \text{Min}_{\theta_{\text{pull}}, \alpha_i} \left[ \sum_i \frac{[N_i(\theta_{0}, \theta_{\text{pull}}) - N_i(\theta_{0}, \theta_{\text{pull}})(1 + \alpha_i)]^2}{N_i(\theta_{0}, \theta_{\text{pull}})} + \sum_i \frac{(\alpha_i)^2}{(\Delta \alpha_i)^2} + \frac{(\theta_{\text{pull}} - \bar{\theta}_{\text{pull}})^2}{(\Delta \theta_{\text{pull}})^2} \right],
$$

(4)

where \alpha_i is the pull parameter taking care of the uncertainty in the initial spectrum at bin i. \theta_{\text{pull}} collectively denotes pull parameters other than \alpha_i which have true values collectively denoted by \bar{\theta}_{\text{pull}} and uncertainties collectively denoted by \Delta \theta_{\text{pull}}. \theta_0 and \theta_0 are respectively the fit parameter and its true value. N_i is the number of events at bin i. To calculate the deviation, we minimize over each \alpha_i as well as over all \theta_{\text{pull}}. It is straightforward to show that as long as

$$
N_i(\Delta \alpha_i)^2 \ll 1,
$$

(5)

we can neglect the effects of \Delta \alpha_i in evaluating \chi^2. Considering Fig (13) of Ref. [28] and uncertainties found in [27], we observe that even with spectrum divided into bins of size 17.7 keV, the condition in (5) is fulfilled so the uncertainty in the shape of the spectrum will not be a major limitation for extracting sign(\cos(2\theta_{12})) and/or sign(\Delta m^2_{31}).

To carry out our analysis, we employ the GLoBES software [20]. We use the reactor neutrino energy spectrum and neutrino cross section that are respectively given in [24, 30] and [31]. For neutrino mass and mixing parameters, we take the best fit values listed in [32]. We assume an uncertainty of 6% both in \theta_{13} and in \Delta m^2_{21}. We use the pull-method to treat the uncertainties.

IV. NUMERICAL RESULTS

Figs (12) show the potential of JUNO and RENO-50 experiments in determining both hierarchy and sign(\cos(2\theta_{12})) after five years of data taking. We have assumed normal hierarchy and have taken the true value of \theta_{12} to be equal to \theta_{12} = 33.57\% in Fig. (1) and equal to \theta_{12} = 56.43\% in Fig. (2). Contours show the 3\% C.L. solutions. Notice that the determination of |\Delta m^2_{31}| by either of these experiments will be far more precise than what is obtained by global analysis of the present data both in the absence of NSI [23] and in its presence [4]. They can also remarkably improve the precision on \theta_{12}. After five years of data taking, the precision of \theta_{12} will reach a remarkable value of \Delta \theta_{12} = \pm 0.4\% or better at 3\% C.L. For ruling out the wrong hierarchy, we have checked our result against that in Ref. [11] and it seems our results are in agreement.

From Fig (1a) and Fig. (2b), we observe that JUNO can determine these parameters more precisely than RENO-50 would. This is mainly due to the fact that the reactor power and therefore neutrino flux are higher at JUNO. As seen from Figs. (2a and -d), while at 3\% RENO-50 finds solutions with wrong sign(\Delta m^2_{31}) or wrong sign(\cos(2\theta_{12}), JUNO rules out these wrong solutions. We have found that when LMA-Dark is taken as the true solution, RENO-50, JUNO and their combined results rule out the wrong LMA solution with \chi^2 = 5.5 (i.e., > 90\% C.L.), \chi^2 = 12.9 (i.e., \sim 3\% C.L.) and \chi^2 = 19.94 (i.e., \sim 4\% C.L.), respectively. Similarly for standard LMA solution with cos(2\theta_{12}) > 0, RENO-50, JUNO and their combined results rule out the wrong LMA-Dark solution with \chi^2 = 4.95 (i.e., > 90\% C.L.), \chi^2 = 11.4 (i.e., slightly less than 3\% C.L.) and \chi^2 = 18.34 (i.e., slightly less than 4\% C.L.), respectively. Turning off the background, JUNO can also rule out the wrong LMA-Dark solution at more than 3\% C.L. From Figs. (1) and (2), we also see that the precision by JUNO is overall better. Remember that we had assumed similar calibration uncertainty, energy resolution and background for these two experiments. By varying the calibration error by a factor of two we have found that the results from these two setup do not change much. However, as expected, similarly to the case of hierarchy determination [12, 13] the results are very sensitive to the energy resolution. For example, if we change the energy resolution from 3\% (E_{\nu}/MeV)^{1/2} to 3.5\% (E_{\nu}/MeV)^{1/2}, the wrong solution becomes acceptable at 3\% C.L. by combined five years data of JUNO and RENO-50.
FIG. 1. Allowed region at 3 σ C.L. after 5 years of data taking by RENO-50 and JUNO. The true values of the neutrino parameters, marked with a star in Fig. (a), are taken to be $\Delta m^2_{21} = 2.417 \times 10^{-3} \text{ eV}^2$, $\theta_{12} = 33.57^\circ$, $\Delta m^2_{31} = (7.45 \pm 0.45) \times 10^{-5} \text{ eV}^2$ and $\theta_{13} = (8.75 \pm 0.5)^\circ$. The upper (lower) panels show the allowed region for normal (inverted) hierarchy and left (right) panels show LMA (LMA-Dark) solution for $\theta_{12}$.

As seen from the Figs. (a), the reactor experiments cannot distinguish between the solution with $\cos 2\theta_{12} > 0$ and $\Delta m^2_{31} > 0$ and the one with $\cos 2\theta_{12} < 0$ and $\Delta m^2_{31} < 0$. This degeneracy is the result of the symmetry under transformations in (3) when matter effects are neglected. The subdominant matter effects slightly lift this degeneracy but not enough to render them distinguishable. Alternative methods to determine $\text{sign}(\Delta m^2_{31})$ based on matter effects by long baseline experiments or atmospheric neutrino experiments can lift this degeneracy. Moreover the LMA-Dark solution can be tested by neutrino scattering experiments sensitive to NSI effect. Similar discussion can be repeated for Fig. (b) where the LMA-Dark solution is taken as the true solution.

A similar discussion also applies for inverted hierarchy: Contours for inverted hierarchy with $\cos(2\theta_{12}) > 0$ and $\cos(2\theta_{12}) < 0$ are very similar respectively to Fig. (b) and Fig. (a).
FIG. 2. The same as Fig. 1 except that we have taken the true values to be $\Delta m^2_{31} = 2.417 \times 10^{-3}$ eV$^2$ and $\theta_{12} = 56.43^\circ$. That is we have taken the LMA-dark solution instead of the standard LMA solution.

V. CONCLUSIONS

We have examined the potential of the intermediate baseline reactor experiments in discriminating between LMA and LMA-Dark solutions. This method is based on determining $\text{sign}(\cos 2\theta_{12})$ rather than probing the NSI. Sensitivity to $\text{sign}(\cos 2\theta_{12})$ (i.e., LMA versus LMA-Dark solutions) as well as to $\text{sign}(\Delta m^2_{31})$ (i.e., normal versus inverted mass ordering) both appear in oscillatory terms in the survival probability, $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ that are given by $\Delta m^2_{31}$ and are suppressed by $s^2_{13}$. Thus, to disentangle their effects, the following challenges have to be overcome: (1) the statistics should be high enough; (2) the energy resolution, $\delta E_{\nu}/E_{\nu}$, should be small enough to resolve the oscillatory terms given by $\Delta m^2_{31}L/E_{\nu}$ and (3) the effects of oscillatory terms given by $\Delta m^2_{31}$ should not be washed out by averaging over baselines of various reactor cores contributing to the flux. These conditions will be fulfilled at the JUNO and RENO-50 experiments. We have found that RENO-50, JUNO and combined RENO-50 and JUNO results can discriminate between LMA and LMA-Dark solution, respectively, at $> 90 \%$ C.L., $\sim 3\sigma$ C.L. and $\sim 4\sigma$ C.L. after five years.
We have demonstrated that neglecting the matter effects, $P(\bar{\nu}_e \to \nu_e)$ becomes symmetric under transformation in Eq. (3). This means there is a degeneracy between solutions for which both the mass hierarchy and the sign of $\cos 2\theta_{12}$ are simultaneously flipped. Matter effects can to some extent lift this degeneracy but not enough in order for JUNO and RENO-50 to resolve this degeneracy. Setups employing matter effects to determine hierarchy (like PINGU or INO investigating the atmospheric neutrinos) can break the degeneracy. Moreover experiments probing neutral current NSI such as neutrino scattering experiments can test LMA-Dark solution and hence break this degeneracy.

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