Terrestrial matter effects on reactor antineutrino oscillations at JUNO or RENO-50: how small is small? postprint

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Abstract

We have carefully examined, in both analytical and numerical ways, how small the terrestrial matter effects can be in a given medium-baseline reactor antineutrino oscillation experiment like JUNO or RENO-50. Taking the ongoing JUNO experiment for example, we show that the inclusion of terrestrial matter effects may reduce the sensitivity of the neutrino mass ordering measurement by ^2_{MO} 0.6, and a neglect of such effects may shift the best-fit values of the flavor mixing angle *{12} and the neutrino mass-squared difference* {21} by about 1 to 2 in the future data analysis. In addition, a preliminary estimate indicates that a 2 sensitivity of establishing the terrestrial matter effects can be achieved for about 10 years of data taking at JUNO with the help of a proper near detector implementation.

Full Text

Terrestrial Matter Effects on Reactor Antineutrino Oscillations at JUNO or RENO-50: How Small Is Small?

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Abstract

We have carefully examined, through both analytical and numerical approaches, how small the terrestrial matter effects can be in a medium-baseline reactor antineutrino oscillation experiment such as JUNO or RENO-50. Taking the

ongoing JUNO experiment as an example, we demonstrate that including terrestrial matter effects may reduce the sensitivity of the neutrino mass ordering measurement by Δ ^{2} 0.6, and neglecting these effects could shift the best-fit values of the flavor mixing angle and the neutrino mass-squared difference Δ by approximately 1 to 2 in future data analyses. Furthermore, a preliminary estimate indicates that a 2 sensitivity for establishing the terrestrial matter effects can be achieved with about ten years of data taking at JUNO, provided a suitable near detector is implemented.

1. Introduction

The approved JUNO project in China represents a flagship of the new generation of medium-baseline reactor antineutrino oscillation experiments [1, 2], with its primary physics goal being the determination of the intriguing neutrino mass ordering [3, 4] (i.e., whether m $<$ m $<$ m or m $<$ m $<$ m). A similar project in South Korea, the RENO-50 experiment [5], has been proposed for the same purpose. Since the typical energies of electron antineutrinos produced by reactors are around 4 MeV, terrestrial matter effects are expected to be negligibly small in a$^-$ oscillation experiment. However, a careful examination of how the sensitivity to neutrino mass ordering measurement is affected by matter-induced contamination has been lacking, although some preliminary estimates of matter effects on leptonic flavor mixing angles and neutrino mass-squared differences have been made in this context [6, 7, 8].

In the present work, we aim to evaluate how small the terrestrial matter effects are and whether they can significantly impact the precision measurements planned for the JUNO and RENO-50 experiments. Our main results are presented both numerically and through useful, instructive analytical approximations. A remarkable observation is that terrestrial matter contamination may produce a correction close to 1% to the quantity associated with the crucial determination of whether the neutrino mass ordering is normal or inverted. Using the ongoing JUNO experiment as an example, we show that including terrestrial matter effects may reduce the sensitivity of the neutrino mass ordering measurement by Δ ^{2} 0.6, and neglecting these effects may shift the best-fit values of the flavor mixing angle and the neutrino mass-squared difference Δ by about 1 to 2 in future data analyses. Moreover, a preliminary estimate indicates that a 2 sensitivity for establishing the terrestrial matter effects can be achieved with about ten years of data taking at JUNO with the help of a proper near detector implementation.

2. Theoretical Framework

Let us begin with the effective Hamiltonian that governs antineutrino propagation in matter [9, 10]:

$$H = U \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U^\dagger + \begin{pmatrix} -A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} ,$$

where U (or $\tilde{U}$) and m_i (or $\tilde{m}_i$) stand respectively for the effective (or fundamental) lepton flavor mixing matrix and neutrino masses in matter (or in vacuum), and $A = 2\sqrt{2} G_F N_e E$ with G_F being the Fermi constant and N_e being the background electron density. In fact, A itself and the minus sign in front of A denote the charged-current contribution to coherent $^-$ e forward scattering in matter. For a constant matter profile, which is a good approximation for reactor-based antineutrino oscillation experiments, one may establish the exact analytical relations between $\tilde{m}_i^2$ and m_i^2 as follows [11]:

$$\tilde{m}_i^2 = m_i^2 + \frac{A}{3} + \frac{2}{3} \sqrt{A^2 - 3A\Delta_{ee} + 3\Delta_\odot^2} \cos\left[\frac{1}{3} \arccos\left(\frac{2A^3 - 9A^2\Delta_{ee} + 9A(\Delta_{ee}^2 - \Delta_\odot^2) + 27\Delta_\Lambda^3}{2(A^2 - 3A\Delta_{ee} + 3\Delta_\odot^2)^{3/2}}\right) + \frac{2(i-1)\pi}{3}\right]$$

where $\Delta_{ij} \equiv m_i^2 - m_j^2$ and $\Delta'_{ij} \equiv \tilde{m}_i^2 - \tilde{m}_j^2$ (for $i, j = 1, 2, 3$). To reveal the matter effects hidden in Δ'_{ij} as compared with the fundamental neutrino mass-squared differences Δ_{ij}, we consider their approximate expressions expanded in terms of two small parameters $\alpha \equiv \Delta_{21}/\Delta_{31}$ and $\beta \equiv A/\Delta_{31}$ in the normal neutrino mass ordering (i.e., $\Delta_{31} > 0$) case [12]:

$$\Delta'_{21} \approx \Delta_{21} \left(1 - \frac{\beta \cos^2\theta_{13}}{c_{12}^2 - s_{12}^2\alpha - \beta\cos^2\theta_{12}}\right) ,$$

$$\Delta'_{31} \approx \Delta_{31} \left(1 + \frac{\beta \cos^2\theta_{13}}{c_{12}^2 - s_{12}^2\alpha - \beta\cos^2\theta_{12}}\right) ,$$

$$\Delta'_{32} \approx \Delta_{32} \left(1 + \frac{\beta \cos^2\theta_{13}}{c_{12}^2 - s_{12}^2\alpha - \beta\cos^2\theta_{12}}\right) ,$$

where $c_{12}^2 \equiv \cos^2\theta_{12}$ and $s_{12}^2 \equiv \sin^2\theta_{12}$. Note that the smallness of θ_{13} is already implied in making the above approximations.

With the help of these relations, the expressions can be simplified to:

$$\Delta'_{21} \approx \Delta_{21} + A\cos^2\theta_{12}, \quad \Delta'_{31} \approx \Delta_{31} - A\cos^2\theta_{12}, \quad \Delta'_{32} \approx \Delta_{32} - A\cos^2\theta_{12},$$

in the leading-order approximation. Given $A \simeq 10^{-4}\mathrm{eV}^2 \times Y_e(\rho/\mathrm{g/cm}^3)(E/\mathrm{GeV})$ for a realistic oscillation experiment [13], where $Y_e \simeq 0.5$ is the electron fraction and $\rho \simeq 2.6\mathrm{g/cm}^3$ is the typical matter density for an antineutrino trajectory through the Earth' s crust, we find that β is much smaller than α in magnitude: $\beta \sim 10^{-4} \ll \alpha \sim 10^{-2}$. In this case one may simplify the expression further as $\epsilon \equiv A\cos^2\theta_{12}/\Delta_{21}$ plus much smaller terms. Note that these equations are valid for a normal neutrino mass ordering. If an inverted neutrino mass ordering (i.e., $\Delta_{31} < 0$) is considered, the corresponding expressions can be obtained with the straightforward replacement $\epsilon \to -\epsilon$.

In the standard parametrization of U [14], the best-fit values $\theta_{12} \approx 33.5^\circ$ and $\theta_{13} \approx 8.5^\circ$ [15, 16, 17, 18] are insensitive to the neutrino mass ordering. Therefore, $\cos^2\theta_{12} \approx 0.69$ and $\sin^2\theta_{13} \approx 0.022$. Taking the same parametrization for the effective neutrino mixing matrix $\tilde{U}$ in matter, one may link the effective flavor mixing angles $\tilde{\theta}_{12}$ and $\tilde{\theta}_{13}$ with the fundamental angles θ_{12} and θ_{13} via the analytical approximations. Accordingly, we obtain:

$$\sin^2 2\tilde{\theta}_{12} \approx \sin^2 2\theta_{12}\left(1 - \frac{2\beta\cos^2\theta_{12}}{\alpha + \beta\cos 2\theta_{12}}\right), \quad \cos 2\tilde{\theta}_{12} \approx \cos 2\theta_{12} + \frac{\beta\sin^2 2\theta_{12}}{\alpha + \beta\cos 2\theta_{12}},$$

which are associated with the determination of the sign of Δ_{31} and with precision measurement of θ_{12}, respectively. Note that these equations are valid regardless of whether the neutrino mass ordering is normal or inverted. We see that the matter-induced correction is clearly characterized by the ratio $\beta/\alpha \simeq A/\Delta_{21} \sim 10^{-2}$. Therefore, we conclude that precision measurements at JUNO and RENO-50 may suffer from terrestrial matter contamination at the 1% level.

3. Oscillation Probability and Matter Effects

We proceed to calculate the matter-induced correction to the $^{-} \to ^{-}$ survival probability. In vacuum, we have $P_0(\bar{\nu}_e \to \bar{\nu}_e) = 1 - P_{21} - P_{31}$ with [19]:

$$P_{21} = \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2 F_{21}, \quad P_{31} = \sin^2 2\theta_{13}\left(\cos^2 F_{31} + \cos^2\theta_{12}\sin^2 F_{31} - \cos 2\theta_{12}\sin F_{31}\cos F_{31}\right),$$

where $F_{ji} \equiv 1.267\Delta_{ji}L/E$ with Δ_{ji} in units of eV², L in km, and E in MeV (for $ji = 21, 31, 32$), and $F_{31} + F_{32} = 1.267(\Delta_{31} + \Delta_{32})L/E$. The matter-corrected probability can be written in exactly parallel form:

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \tilde{P}_{21} - \tilde{P}_{31},$$

with $\tilde{P}_{21}$ and $\tilde{P}_{31}$ obtained by replacing $\theta_{12} \to \tilde{\theta}_{12}$, $\theta_{13} \to \tilde{\theta}_{13}$, and $\Delta_{ji} \to \Delta'_{ji}$. Using the approximations, we find:

$$\Delta'_{21} \approx \Delta_{21} + A\cos 2\theta_{12}, \quad \Delta'_{31} \approx \Delta_{31} - A\cos^2\theta_{12}, \quad \Delta'_{32} \approx \Delta_{32} - A\cos^2\theta_{12}.$$

The probability difference, which is proportional to A, provides a clear measure of terrestrial matter effects for JUNO or RENO-50.

4. Numerical Analysis

Now we turn to a numerical study of terrestrial matter effects in medium-baseline reactor antineutrino experiments like JUNO or RENO-50. For illustration, we adopt the best-fit values $\Delta_{21} \simeq 7.5 \times 10^{-5}\mathrm{eV}^2$, $\Delta_{31} \simeq 2.5 \times 10^{-3}\mathrm{eV}^2$, $\sin^2\theta_{12} \simeq 0.304$, and $\sin^2\theta_{13} \simeq 0.0218$ from recent global analyses [18]. The terrestrial matter density along the antineutrino trajectory is typically assumed to be $\rho \simeq 2.6\mathrm{g/cm}^3$. We focus on the normal neutrino mass ordering as the true ordering, though our conclusions remain valid for the inverted case.

Our exact numerical calculations, shown in Fig. 1 [Figure 1: see original paper], display the absolute and relative differences between the matter-corrected probability and its vacuum counterpart for a medium-baseline experiment with $L = 52.5$ km. The solid curves show the true antineutrino energy, while dashed curves include a Gaussian energy resolution of $3\%/\sqrt{E(\mathrm{MeV})}$. The absolute difference reaches about 0.7% near the first oscillation peak, corresponding to a relative matter-induced correction of about 4%. The main profile is attributed to the Δ -triggered oscillation, where matter-induced suppression of sin²2 provides a positive correction in the Δ -dominated range. Small wiggles arise from Δ*-triggered oscillations, with amplitudes modulated by the energy-dependent correction of cos2˜ .

Fig. 2 [Figure 2: see original paper] compares exact numerical results with our analytical approximation. The absolute errors of our analytical approximations are below 3×10 across most of the energy range, confirming that the analytical expressions can be safely used in sensitivity studies.

5. Sensitivity Studies

Using JUNO' s nominal setup [1, 20], we consider a 20 kt liquid scintillator detector with 3%/√E(MeV) energy resolution. We incorporate the real reactor powers and baseline distributions from the Yangjiang and Taishan nuclear plants (total thermal power 36 GWth, power-weighted baseline 52.5 km), assuming 80% detection efficiency and six years of operation at 300 effective days per year.

We construct the standard ² function:

$$\chi^2 = \sum_i \frac{\left[M_i(p_M, \eta) - T_i(p_T, \eta)\left(1 + \sum_k \alpha_{ik}\epsilon_k\right)\right]^2}{M_i(p_M, \eta)} + \sum_k \frac{\epsilon_k^2}{\sigma_k^2},$$

where M_i and T_i are measured and predicted events in the i-th energy bin; σ_k and ϵ_k are systematic uncertainties and pull parameters. Nominal systematic uncertainties include: correlated reactor rate uncertainty (2%), uncorrelated reactor rate uncertainty (0.8%), energy-uncorrelated bin-to-bin flux spectrum uncertainty (1%), and detector-related uncertainty (1%). In the equation, p represents oscillation parameters, and $\eta \equiv A(\rho)/A(\rho = 2.6\text{g/cm}^3)$ is the effective matter potential index.

Fig. 3 [Figure 3: see original paper] compares mass ordering sensitivities with and without matter effects. The vertical distance between minima of the normal mass ordering (NMO) and inverted mass ordering (IMO) curves defines the sensitivity Δ ^{2}_MO. Including matter effects reduces Δ ^{2}_MO from 10.28 to 9.64, comparable to other important systematic uncertainties and thus non-negligible. For a medium-baseline experiment, the$^-$ trajectory includes a large proportion of sedimentary layer, suggesting a somewhat smaller density 2.0 g/cm^3 may be appropriate. Fig. 4 [Figure 4: see original paper] shows Δ ^{2}_MO as a function of , demonstrating linear dependence. With = 2.0 g/cm^3, the sensitivity reduction is from 10.28 to 9.79.

Fig. 5 [Figure 5: see original paper] shows the allowed regions of Δ and . When matter effects are included in predictions (left panel), best-fit points return to true values with 1 precisions of 0.23% for Δ and 0.58% for sin^2 . When matter effects are neglected (right panel), allowed regions shift to higher Δ and lower , with best-fit values deviating by ~0.8 and ~2.4 from true values, respectively.

Fig. 6 [Figure 6: see original paper] illustrates the sensitivity to establish terrestrial matter effects. With fixed oscillation parameters, Δ ^{2}(=0) 11 (>3 significance). After marginalizing over oscillation parameters, significance drops to 1.3 . Including additional systematic uncertainties (background, flux spectrum, energy scale, non-linearity) reduces projected precisions to 0.72% for sin^2 and 0.60% for Δ , making the sensitivity <1 .

Fig. 7 [Figure 7: see original paper] shows the sensitivity to rule out vacuum oscillations (=0) as a function of running time with near detectors. Assuming absolute errors are cancelled and relative errors reach Daya Bay levels [26, 27, 28, 29], a 2 sensitivity can be achieved in ~10 years with one or two appropriate near detectors.

6. Conclusion

We have examined how small terrestrial matter effects can be in medium-baseline reactor antineutrino experiments like JUNO or RENO-50, which aim for precision measurements of neutrino mass ordering and flavor parameters. By expanding the $^-$ → $^-$ survival probability in terms of the small matter parameter, we derived simple yet accurate analytical approximations. Using JUNO as an example, we showed that matter effects reduce mass ordering sensitivity by Δ ^{2} 0.6 and may shift best-fit values of and Δ by 1-2 if ignored.

We conclude that terrestrial matter effects must be carefully accounted for as they are non-negligible in reactor-based measurements. However, establishing these effects at high significance remains difficult without near detectors. Our preliminary estimate indicates that with proper near detector implementation, JUNO could achieve 2 sensitivity to terrestrial matter effects in ~10 years of data taking.

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Note: Figure translations are in progress. See original paper for figures.