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Mass hierarchy sensitivity of medium baseline reactor neutrino experiments with multiple detectors

Hong-Xin Wang [a,*], Liang Zhan [b], Yu-Feng Li [b], Guo-Fu Cao [b], Shen-Jian Chen [a]

[a] *Department of Physics, Nanjing University, Nanjing 210093, China*
[b] *Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*

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Abstract

We report the neutrino mass hierarchy (MH) determination of medium baseline reactor neutrino experiments with multiple detectors, where the sensitivity of measuring the MH can be significantly improved by adding a near detector. Then the impact of the baseline and target mass of the near detector on the combined MH sensitivity has been studied thoroughly. The optimal selections of the baseline and target mass of the near detector are ~12.5 km and ~4 kton respectively for a far detector with the target mass of 20 kton and the baseline of 52.5 km. As typical examples of future medium baseline reactor neutrino experiments, the optimal location and target mass of the near detector are selected for the specific configurations of JUNO and RENO-50. Finally, we discuss distinct effects of the reactor antineutrino energy spectrum uncertainty for setups of a single detector and double detectors, which indicate that the spectrum uncertainty can be well constrained in the presence of the near detector.

1. Introduction

It is reported that the medium baseline reactor neutrino experiment can determine the type of the neutrino mass hierarchy (MH) by precisely measuring the fine structure of the antineutrino

* Corresponding author.
E-mail address: hxwang@iphy.me (H.-X. Wang).

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energy spectrum from reactors [1–5]. Reactor and accelerator neutrino experiments measured an unexpectedly large value of neutrino mixing angle θ_{13} in 2012 [6–10], which implies that the MH determination is feasible in the next one or two decades with neutrino oscillation experiments of the new generation. Consequently, experiments using accelerator neutrinos with a long baseline of $\sim$1000 km [11], atmosphere neutrinos sensitive to the energy range of 1–20 GeV [12,13] and reactor neutrinos at a medium baseline of $\sim$50 km are proposed to determine the neutrino MH [14–17]. Among the above possibilities, medium baseline reactor neutrino experiments, such as JUNO (Jiangmen Underground Neutrino Observatory) [18–20] and RENO-50 [21–24], have the potential to determine the neutrino MH by using the large liquid scintillator detector ($\sim$20 kton) with energy resolution of unprecedented levels.

Key requirements for the MH determination in reactor neutrino experiments are powerful nuclear power plants (NPPs), massive detector and good energy resolution. Sensitivity study about JUNO shows that a 20 kton detector with energy resolution of $3\%/\sqrt{E_{vis}(\text{MeV})}$ is mandatory to achieve significance of better than 3σ after 6 years running [18]. Several interesting ideas are proposed to improve the MH sensitivity of reactor neutrino experiments, including combining the mass splitting measurement from accelerator neutrino experiments [18], synergy of different MH probes in reactor and atmospheric neutrino oscillation experiments [25] and using two identical half-size detectors at near and far sites [26,27].

In this work we shall discuss the MH sensitivity improvement by using the near detector (ND) and far detector (FD) in medium baseline reactor neutrino experiments. For the fixed total mass of the ND and FD, the distribution of target mass between the ND and FD and the baseline of the ND can be optimized. The optimization is also applied to the realistic reactor neutrino experiments: JUNO and RENO-50. Then we discuss distinct effects of the reactor antineutrino energy spectrum uncertainty for the setups of a single detector and double detectors, which indicate that the spectrum uncertainty can be well constrained in the presence of the near detector.

The remaining parts of this work are organized as follows. In Sec. 2 we introduce the analysis method for the MH sensitivity in medium baseline reactor neutrino experiment. Sec. 3 is devoted to the sensitivity improvement in the presence of the ND, and Sec. 4 is devoted to optimize the baseline and target mass of the ND. Finally, we discuss the impact of the energy spectrum shape uncertainty in Sec. 5 and then conclude in Sec. 6.

2. Analysis method

In the quantitative analysis of the neutrino MH sensitivity, the electron antineutrino survival probability in vacuum is adopted as [18,17,28]:

$$\begin{aligned} P_{ee} &= 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ &= 1 - \frac{1}{2}\sin^2 2\theta_{13}\left[1 - \sqrt{1 - \sin^2 2\theta_{12}\sin^2\Delta_{21}}\cos(2|\Delta_{ee}| \pm \phi)\right] \\ &\quad - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}, \end{aligned} \tag{1}$$

where $\Delta_{ij} \equiv 1.267 \cdot \Delta m^2_{ij} L/E$, with $\Delta m^2_{ij} = m^2_i - m^2_j$ (in unit of eV^2) being the neutrino mass-squared difference, L (in unit of meter) being the baseline length and E (in unit of MeV) being the antineutrino energy. In addition,