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Search for sub-eV sterile neutrinos in the precision multiple baselines reactor antineutrino oscillation experiments

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Abstract

According to different effects on neutrino oscillations, the unitarity violation in the MNSP matrix can be classified into the *direct* unitarity violation and the *indirect* unitarity violation which are induced by the existence of the light and the heavy sterile neutrinos respectively. Of which sub-eV sterile neutrinos are of most interesting. We study in this paper the possibility of searching for sub-eV sterile neutrinos in the precision reactor antineutrino oscillation experiments with three different baselines at around 500 m, 2 km and 60 km. We find that the antineutrino survival probabilities obtained in the reactor experiments are sensitive only to the direct unitarity violation and offer very concentrated sensitivity to the two parameters θ_{14} and Δm^2_{41}. If such light sterile neutrinos do exist, the active–sterile mixing angle θ_{14} could be acquired by the combined rate analysis at all the three baselines and the mass-squared difference Δm^2_{41} could be obtained by taking the Fourier transformation to the L/E spectrum. Of course, for such measurements to succeed, both high energy resolution and large statistics are essentially important.

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1. Direct and indirect unitarity violation in the lepton flavor mixing matrix

Besides the three known active neutrinos ν_e, ν_μ and ν_τ, there may exist additional sterile neutrinos which do not directly take part in the weak interactions except those induced by the mixing with active neutrinos [1]. In the presence of n generations of sterile neutrinos, the 3×3 Maki–Nakagawa–Sakata–Pontecorvo (MNSP) matrix [2] is the submatrix of the full $(3+n) \times (3+n)$ unitary mixing matrix. If there is small mixing between the active and the sterile neutrinos, the MNSP matrix must be slightly non-unitary. According to the different effects on neutrino oscillations, the unitarity violation in the MNSP matrix can be classified into two categories: *direct* unitarity violation and *indirect* unitarity violation [3].

- The indirect unitarity violation is brought by the existence of heavy sterile neutrinos, which themselves are too massive to be kinematically produced in the neutrino oscillation experiments. The heavy right-handed sterile neutrinos are natural ingredients of the canonical type-I seesaw mechanism [4] and some other seesaw models [5].
- The direct unitarity violation is caused by the existence of light sterile neutrinos which are able to participate in neutrino oscillations as their active partners. The sterile neutrinos with masses $m \sim \mathcal{O}(1)$ eV are proposed to explain the LSND [6], MiniBooNE [7], reactor antineutrino [8] and Gallium [9] anomalies. Furthermore, current cosmological observations [10] still allow the existence of sub-eV sterile neutrinos.

To study their different effects on neutrino oscillations, we consider in a special $(3 + \mathbb{1} + \mathbf{1})$ framework where $\mathbb{1}$ light sterile neutrino ν_s and $\mathbf{1}$ heavy right-handed neutrino ν_N are added to the standard 3 active neutrinos framework.[1] In the $(3 + \mathbb{1} + \mathbf{1})$ scenario, the full picture of the neutrino mixing should be described by a 5×5 unitary matrix V

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_N \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} & V_{e4} & V_{e5} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} & V_{\mu 4} & V_{\mu 5} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} & V_{\tau 4} & V_{\tau 5} \\ V_{s1} & V_{s2} & V_{s3} & V_{s4} & V_{s5} \\ V_{N1} & V_{N2} & V_{N3} & V_{N4} & V_{N5} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \end{pmatrix}, \quad (1)$$

where ν_4 and ν_5 are corresponding mass eigenstates of the light and the heavy sterile neutrinos. Here we restrict us to the typical neutrino oscillation process $\nu_\alpha \to \nu_\beta$ where both the production of ν_α and the detection of ν_β are via the charged-current interaction. Then the neutrino oscillation probability in vacuum can be written as [12]

$$P\,(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = \frac{1}{\left(\sum_{i=1,2,3,4} |V_{\alpha i}|^2\right)\left(\sum_{i=1,2,3,4} |V_{\beta i}|^2\right)} \left\{ \left| \sum_{i=1,2,3,4} V^*_{\alpha i} V_{\beta i} \right|^2 \right.$$

[1] The reason why we consider the $(3+\mathbb{1}+\mathbf{1})$ scenario is that current cosmological observations favored the existence of at most one species of light sterile neutrino, and for simplicity, we also introduce only one species of heavy sterile neutrino to illustrate the indirect unitarity violation effects. However, it is worth to mention that just one heavy right-handed neutrino is not enough to generate the neutrino masses. To accommodate the neutrino masses with the seesaw mechanism, one need to further introduce the Higgs triplet [11] or another generation(s) of heavy right-handed neutrino(s). A more general $(3 + \mathbb{1} + \mathbf{N})$ scenario is briefly discussed in Appendix A.