Some attempts to explain MINOS anomaly

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Abstract. Some attempts which were made to explain the MINOS anomaly are critically discussed. They include the non-standard neutral current-neutrino interaction and the (3+1)-scheme with sterile neutrino.

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1. Introduction

At the neutrino 2010 conference, the MINOS collaboration reported that the allowed region for the mass squared difference obtained from their anti-neutrino data differed from that for the neutrino data [1]. There have been several attempts to account for this anomaly. They include the non-standard neutral current-neutrino interaction with μ, τ components, and the (3+1)-scheme with sterile neutrino. In this talk I will examine whether they are consistent with other experiments.

2. Non-standard interactions in propagation

One of the ideas to distinguish neutrinos and anti-neutrinos is to use the matter effect. In order to affect ν_μ and $\bar{\nu}_\mu$ at the MINOS energy range, one should introduce the non-standard interaction in propagation of neutrinos so that the matter potential has at least non-zero μ or τ components. Here let us consider a general 3×3 potential matrix:

$$A\left(\begin{array}{ccc} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{\mu e} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{\tau e} & \varepsilon_{\tau\mu} & \varepsilon_{\tau\tau} \end{array}\right), \qquad (1)$$

where $A\equiv\sqrt{2}G_F N_e$ stands for the matter effect. It was pointed out in Ref. [2] that with new physics (1) the disappearance probability in the high-energy atmospheric neutrino oscillations behaves as

$$1-P(\nu_\mu\to\nu_\mu)\simeq c_0+c_1\frac{\Delta m^2_{31}}{AE}+\mathscr{O}\left(\frac{\Delta m^2_{31}}{AE}\right)^2, \qquad (2)$$

where c_0 and c_1 are functions of the parameters $\varepsilon_{\alpha\beta}$ of new physics. On the other hand, in the standard three-flavor scheme, the high-energy behavior of the disappearance oscillation probability is

$$\begin{aligned} & 1-P(\nu_\mu\to\nu_\mu) \\ \simeq\ & \left(\frac{\Delta m^2_{31}}{2AE}\right)^2\left[\sin^2 2\theta_{23}\left(\frac{c^2_{13}AL}{2}\right)^2\right. \\ & \left.+\,s^2_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{AL}{2}\right)\right], \qquad (3)\end{aligned}$$

where the terms of $\mathscr{O}(1)$ and $\mathscr{O}(\Delta m^2_{31}/AE)$ are absent in Eq. (3) which is in perfect agreement with the experimental data. It was shown in Ref. [2] that $|c_0|\ll 1$ and $|c_1|\ll 1$ in Eq. (2) imply

$$|\varepsilon_{e\mu}|^2+|\varepsilon_{\mu\mu}|^2+|\varepsilon_{\mu\tau}|^2\ll 1 \qquad (4)$$

$$\left||\varepsilon_{e\tau}|^2-\varepsilon_{\tau\tau}(1+\varepsilon_{ee})\right|\ll 1, \qquad (5)$$

respectively.[1]

(i) Non-standard interactions in propagation with μ, τ components

The simpler possibility within the ansatz (1) is to assume that all the electron components $\varepsilon_{e\alpha}$ vanish:

$$A\left(\begin{array}{ccc} 1 & 0 & 0 \\ 0 & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ 0 & \varepsilon_{\tau\mu} & \varepsilon_{\tau\tau} \end{array}\right). \qquad (6)$$

In this case, since the contribution from the solar neutrino oscillation is negligible for the range of the energy and the baseline length of MINOS, ν_e decouples from ν_μ and ν_τ. Refs. [4] and [5] performed an analysis with the ansatz (6), where $\varepsilon_{\mu\mu}=\varepsilon_{\tau\tau}=0$ was assumed in the former work. The best fit values for $\varepsilon_{\mu\tau}$ obtained in Refs. [4, 5] do not satisfy the constraint from the atmospheric neutrino data $|\varepsilon_{\mu\tau}|\lesssim 7\times 10^{-2}$ at 90%CL [6, 7, 8], so their solutions are inconsistent with the atmospheric neutrinos.[2]

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[1] Eq. (5) was first found in Ref. [3].

[2] The two flavor ansatz (6) can be regarded as a subset of the three flavor scenario in the limiting case $\varepsilon_{ee}=\varepsilon_{e\mu}=\varepsilon_{e\tau}=\theta_{13}=\Delta m^2_{21}=0$, so the constraint (5) in the two flavor case leads to $|\varepsilon_{\tau\tau}|\simeq 0$. On the other hand, the bound on $|\varepsilon_{\mu\tau}|$ in the three flavor case is independent of other components $\varepsilon_{\alpha\beta}$, so the bound $|\varepsilon_{\mu\tau}|\lesssim\mathscr{O}(10^{-2})$ in Refs. [6, 7, 8] is expected to be valid both in the two and three flavor cases.

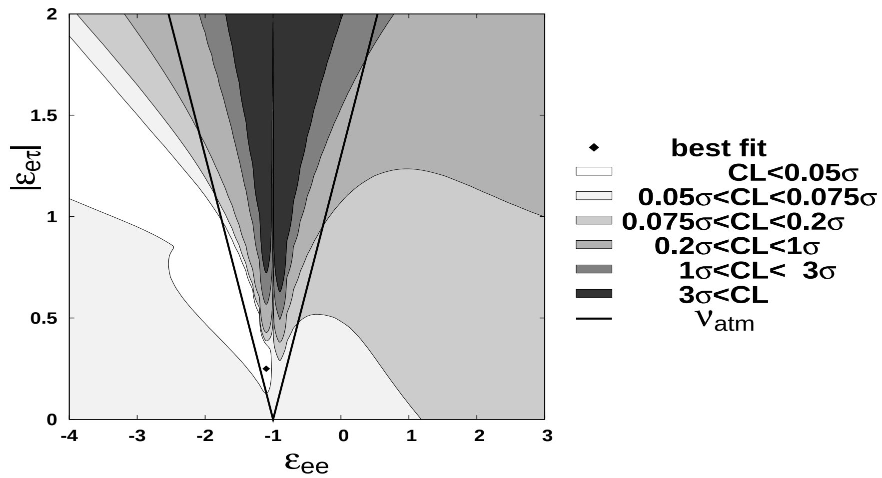

FIGURE 1. The disfavored region [11] obtained from the MINOS data [1]. The region above the diagonal straight lines is excluded because of the atmospheric neutrino data [12]. The contours are drawn to exaggerate its significance.

(ii) A model with gauging $L_\alpha - L_\beta$

Ref. [9] discussed the model with gauging the lepton numbers $L_\alpha - L_\beta$. Such models predict the matter potentials $\mathrm{diag}(V,-V,0)$, $\mathrm{diag}(V,0,-V)$, and $\mathrm{diag}(0,V,-V)$ for $L_e - L_\mu$, $L_e - L_\tau$, $L_\mu - L_\tau$, respectively, where the major contribution to the potential V comes from the Sun instead of the matter in the Earth. In order for this scenario to account for the MINOS anomaly, the matter effect V should be comparable to $|\Delta m^2_{31}|/E_\nu^{\rm MINOS}$ in magnitude. On the other hand, since the matter effect V mainly comes from the Sun, if α or β in $L_\alpha - L_\beta$ is of electron type, then the magnitude of V for the solar neutrino oscillation is expected to be enhanced by the factor (distance between Sun and Earth)/(radius of Sun), and it would destroy the success of the oscillation interpretation of the solar neutrino deficit, because its matter effect would be much larger than the standard one. To avoid its influence on the solar neutrino oscillation, one is forced to work with $L_\mu - L_\tau$. In this case, however, it would contradict with the atmospheric neutrino constraint $|\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}| \ll 1$ [6, 7, 8]. So all the channels have conflict with one experiment or the other.

(iii) Non-standard interactions in propagation with e, τ components

Taking into account the constraint from the atmospheric neutrino data, the only possibility which could potentially produce large difference between neutrinos and anti-neutrinos is the form of the potential:

$$\mathscr{A} = A \begin{pmatrix} 1+\varepsilon_{ee} & 0 & \varepsilon_{e\tau} \\ 0 & 0 & 0 \\ \varepsilon_{e\tau}^* & 0 & |\varepsilon_{e\tau}|^2/(1+\varepsilon_{ee}) \end{pmatrix}, \qquad (7)$$

where $|\varepsilon_{ee}| \lesssim 4$, $\varepsilon_{e\tau} \lesssim 3$ are allowed at 90%CL from all the experimental data (see Ref. [2, 10] and references therein). Although this potential term does not have mixing between ν_μ and ν_e or ν_τ, it can affect ν_μ through the (maximal) mixing between ν_μ and ν_τ in vacuum. The region in which the MINOS anomaly can be accounted for by the ansatz (7) is given in Fig.1 [11]. This result has two undesirable features. Firstly, the best fit point lies in the region which is excluded by the atmospheric neutrino data [12]. Secondly, while the disfavored region at 3σCL almost coincides with the one by the atmospheric neutrino data [12], the significance of the standard case ($\varepsilon_{ee} = \varepsilon_{e\tau} = 0$) compared with the best fit point is only 0.07σCL. Therefore, we conclude that it is not worth introducing this scenario to explain the MINOS anomaly.

3. A (3+1)-scheme with one sterile neutrino (ν_s)

The other scenario I would like to discuss is the (3+1)-scheme with one sterile neutrino. Here let us take the parametrization [13]

$$\begin{aligned} U &= R_{34}(\theta_{34},0)\, R_{24}(\theta_{24},0)\, R_{23}(\theta_{23},\delta_3) \\ &\quad \times R_{14}(\theta_{14},0)\, R_{13}(\theta_{13},\delta_2)\, R_{12}(\theta_{12},\delta_1), \end{aligned} \qquad (8)$$

where $[R_{ij}(\theta,\delta)]_{pq} \equiv \delta_{pq} + (\cos\theta - 1)(\delta_{pi}\delta_{qi} + \delta_{pj}\delta_{qj}) + \sin\theta(e^{-i\delta}\delta_{pi}\delta_{qj} - e^{i\delta}\delta_{pj}\delta_{qi})$ is a 4×4 rotational matrix which mixes i and j components with a mixing angle θ and a CP phase δ. It is known that $\sin^2 2\theta_{13} \ll 1$, $\sin^2 2\theta_{14} \ll 1$ should follow from the constraints of the reactor experiments [14, 15], and, if $0.7\mathrm{eV}^2 \lesssim \Delta m^2_{41} \lesssim 10\mathrm{eV}^2$, $\sin^2 2\theta_{24} \lesssim 0.2$ should hold to satisfy the constraint of the CDHSW experiment [16]. Furthermore, one can show that the coefficient

c_0 in the high energy behavior (2) is proportional to $\sin^2 2\theta_{24}$, so θ_{24} should be small also from the atmospheric neutrino constraint.[3] Here for simplicity I assume $\theta_{13} = \theta_{14} = \theta_{24} = 0$ to be consistent with the constraints from the reactor, CDHSW and atmospheric neutrino data. In this case, ν_e decouples from ν_μ, ν_τ and ν_s, and the situation becomes similar to that of the solar neutrino oscillations in the standard case. The disappearance probability in this case is given by

$$\begin{aligned}
&\left\{ \begin{array}{l} 1 - P(\nu_\mu \to \nu_\mu) \\ 1 - P(\bar{\nu}_\mu \to \bar{\nu}_\mu) \end{array} \right\} \\
&\sim \left(\frac{\Delta E_{32}}{\Delta \tilde{E}_{32}^{(\pm)}} \right)^2 \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta \tilde{E}_{32}^{(\pm)} L}{2} \right) \qquad (9) \\
&\Delta \tilde{E}_{32}^{(\pm)} \equiv \left[(\Delta E_{32} \cos 2\theta_{23} \pm \sin \theta_{34}^2 A/2)^2 \right. \\
&\qquad\qquad \left. + (\Delta E_{32} \sin 2\theta_{23})^2 \right]^{1/2},
\end{aligned}$$

where $\Delta E_{32} \equiv \Delta m^2_{32}/2E$ and small quantities such as $\Delta m^2_{32}/\Delta m^2_{42}$ have been ignored. θ_{34} stands for the mixing angle which represents the ratio of $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_s$ oscillations, and deviation of Eq. (9) from the oscillation probability in vacuum becomes larger as θ_{34} increases. The matter effect becomes important for the energy range $E \gtrsim 10$GeV, so the zenith angle dependence of the high-energy atmospheric data gives a constraint on θ_{34}. The analysis in Ref. [13] tells us that the allowed region at 90%CL by the atmospheric neutrino data is $0 \leq \theta_{34} \lesssim \pi/6$. Eq. (9) is potentially interesting because non-zero θ_{34} distinguishes the effective mixing angles and the effective mass squared differences of neutrinos and anti-neutrinos. However, because the atmospheric mixing angle θ_{23} is nearly maximal ($|\cos 2\theta_{23}| \ll 1$), it is difficult in practice to distinguish neutrinos and anti-neutrinos from Eq. (9). In fact, according to the numerical analysis [11], the best fit point with the present (3+1)-scheme is the same as that for the standard case.[4] Also in this case, therefore, it is difficult to explain the MINOS anomaly.[5]

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[3] According to the analysis in Ref. [13], the allowed region for θ_{24} at 90%CL is $0 \leq \theta_{24} \lesssim \pi/15$.

[4] Ref. [17] performed a similar analysis using the old MINOS data, but they obtained a result different from ours.

[5] The situation of the interpretation as sterile neutrino oscillations to account for the LSND anomaly is still confusing because of the MiniBooNE anti-neutrino data [18]. The (3+1)-scheme which I discussed here predict null results for the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ channels at the L/E range of the LSND and MiniBooNE experiments, because $P(\nu_\mu \to \nu_e) = P(\bar{\nu}_\mu \to \bar{\nu}_e) = \sin^2\theta_{24} \sin^2 2\theta_{14} \sin^2(\Delta m^2_{41} L/4E) = 0$ in the present assumption. If the LSND anomaly is real, we can take small mixing angles θ_{14} and θ_{24} into account within the framework of the present (3+1)-scheme. Even in that case, however, the effect of these mixing angles on the disappearance channels $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ is small and the present conclusion does not change.

4. Conclusion

Unfortunately, none of the scenarios, which have been proposed so far to explain the MINOS anomaly, seem to work. They either give little contribution to distinguish neutrinos and anti-neutrinos, or excluded by the constraints of other experiments. Since the MINOS anomaly is only a 2σ effect, probably we should wait until we have more statistics.

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