MINOS Anomaly as A Signal of Lorentz Violation postprint

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Abstract

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Full Text

Preamble

MINOS Anomaly as A Signal of Lorentz Violation

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Abstract

Recently, the MINOS collaboration reported an anomaly that the mass-squared difference and mixing angle of $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_\tau$ are both different from that of $\nu_\mu \leftrightarrow \nu_\tau$. In this letter, based on the framework of neutrino oscillations, terms that break the Lorentz symmetry are used as perturbation to explain this anomaly and satisfactory results are obtained. Remarkably, some surprising conclusions are also arrived at, one of which is that in the high energy limit (hundreds of GeV) the neutrino oscillation pattern will be independent of energy.

Introduction

Observations on solar neutrinos [1] and atmospheric neutrinos [2] have provided compelling evidence for neutrino oscillations. Reactor [3] and accelerator [4] neutrino experiments have further confirmed the oscillation paradigm. Nowadays, the fact that neutrinos do oscillate between different flavors has been established. The original idea of neutrino oscillation was proposed by Pontecorvo [5] assuming neutrino-antineutrino oscillation in a pattern similar to that between K^0 and $\bar{K}^0$. This idea was extended to oscillations among different flavors of neutrinos by Maki, Nakagawa and Sakata [6]. One of the key points (MSW effect) in the neutrino oscillation paradigm is due to Wolfenstein [7], Mikheyev and Smirnov [8], who pointed out an effect induced by matter when a neutrino passes through it and interacts with the particles forming the matter.

Now it is well known that massive neutrinos naturally result in neutrino oscillations among different flavors. It is also noteworthy that other mechanisms, like Lorentz symmetry violation [9, 10], can also accommodate neutrino oscillations. There have been many papers discussing neutrino oscillations using Lorentz violation in the literature [11].

Neutrino oscillation data fix the neutrino mass-squared differences and their mixings. According to a global neutrino oscillation data analysis within the three-flavor framework [12], the best-fit values of oscillating parameters are given as follows: $\Delta m^2_{21} = (7.59^{+0.20}_{-0.18}) \times 10^{-5}\,\mathrm{eV}^2$, $\Delta m^2_{32} = (2.45^{+0.09}_{-0.06}) \times 10^{-3}\,\mathrm{eV}^2$, $\sin^2(\theta_{12}) = 0.312^{+0.017}_{-0.006}$, $\sin^2(\theta_{13}) = 0.010^{+0.009}_{-0.015}$, and $\sin^2(\theta_{23}) = 0.51^{+0.06}_{-0.09}$. Within the accuracy of present experiments, the three-flavor oscillations can be reduced to two-flavor oscillations in two sectors, i.e., the 'solar' sector and the 'atmospheric' sector.

In the two-flavor analysis, the oscillation probability can be written as:

$$P = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

For the atmospheric sector, the parameters are approximately $\Delta m^2 \approx 2.45 \times 10^{-3}\,\mathrm{eV}^2$ and $\sin^2(2\theta) \approx 1.0$.

However, recently the MINOS collaboration reported an anomaly in the anti-muon neutrino disappearance experiment: the oscillation parameters are determined to be $\Delta m^2 = (3.36^{+0.45}_{-0.11}) \times 10^{-3}\,\mathrm{eV}^2$ and $\sin^2(2\theta) = 0.86^{+0.11}_{-0.11}$ [13]. This result is still consistent with that of the muon neutrino disappearance experiment within the 3σ level, but if we take the central value seriously it may imply CPT violation, in comparison with the oscillation parameters $\Delta m^2 = (2.35^{+0.11}_{-0.08}) \times 10^{-3}\,\mathrm{eV}^2$ and $\sin^2(2\theta) = 1.00$ ($\sin^2(2\theta) > 0.91$ at 90% CL) [14] determined in the muon neutrino disappearance experiment. There have been some attempts to solve this anomaly either using CPT violation [15, 16] or in terms of non-standard neutrino interaction [17, 18, 19, 20]; for a review about these attempts see [21] and references therein.

In the end of section 3, we will do a detailed comparison between these attempts with ours after having presented our model.

2 Formalism and Model

We consider the MINOS anomaly as a signal of Lorentz and CPT violation. In Refs. [10, 22], the authors point out that observable neutrino oscillations may be a combined result of neutrino masses and Lorentz violation, and results of some neutrino oscillation experiments even can be explained by Lorentz violation without using mass terms. In this letter, we still work in the conventional massive neutrino paradigm which solves the solar neutrino and atmospheric neutrino problems. To explain the MINOS anomaly, a Lorentz and CPT violating term is included as perturbation. We adopt a framework called Standard Model Extension (SME) [9, 22]. It is the general effective theory constructed from the Standard Model and allows any coordinate-independent Lorentz violation, which might arise from Planck scale physics. In the minimal SME Lagrangian, all possible renormalizable terms constructed from Standard Model fields which break the Lorentz symmetry are added to the usual Standard Model Lagrangian.

In SME, the effective Hamiltonian in the neutrino sector takes the following form:

$$(H)_{ab} = \frac{(m^2)_{ab}}{2E} + (a)_{ab} + (cE)_{ab}$$

where $(m^2)_{ab}/(2E)$ is the conventional mass-squared term, the other two terms are Lorentz violating, the term a is CPT-odd and the term cE is CPT-even. The effective Hamiltonian for anti-neutrinos can be gained by reversing the sign of a. Moreover, a does not change with energy while cE is proportional to energy, so that these two terms can complicate the dependence of neutrino oscillations on energies. In the following, we will explain the MINOS anomaly by including the term a in the Hamiltonian. Thus, we would like to discuss the property of the term a in detail before presenting our model.

The term a has something in common with the matter potential induced by the MSW effect: both of them are independent of energy and CPT-odd [22, 23]. However, the term a has differences with the MSW effect in the following two aspects: on the one hand, the MSW effect can appear only when a neutrino passes through matter and is dependent on the density and ingredient of matter [7, 8, 23], while the term a is always constant as a vacuum property [22]; on the other hand, the matter potential only appears diagonally in the flavor basis while the term a may have non-vanishing off-diagonal elements. In addition, the MSW effect does not play any role in the oscillations between ν_μ and ν_τ when considered in the two-flavor analysis, because the matter potential induced by normal matter is proportional to the identity matrix in the (ν_μ, ν_τ) basis. In contrast, we can assume that $a_{\mu\mu}$ differs from $a_{\tau\tau}$.

In the following, we assume that the terms cE and a_{ex} in Eq. (2) are absent or negligible for some reasons. Considering the energy range and the baseline distance in the MINOS experiment, the oscillation between ν_e and ν_μ is negligible, so the two-flavor analysis is still a good approximation. Hence, the effective Hamiltonian in the (ν_μ, ν_τ) basis can be written as:

$$H_\nu = \begin{pmatrix} \frac{m_1^2}{2E} - a_1 & 0 \\ 0 & \frac{m_2^2}{2E} - a_2 \end{pmatrix}$$

The term on the top left corner has been chosen to be zero because the mixing only has to do with the difference of the two terms on the diagonal. Besides, the minus signs before a_1 and a_2 are assigned to ensure that the values of a_1 and a_2 are positive in order to explain the MINOS anomaly as we shall see.

For oscillations between $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$, the effective Hamiltonian will be obtained by reversing the signs before a_1 and a_2:

$$H_{\bar{\nu}} = \begin{pmatrix} \frac{m_1^2}{2E} + a_1 & 0 \\ 0 & \frac{m_2^2}{2E} + a_2 \end{pmatrix}$$

For convenience, we parameterize the Hamiltonians as follows:

$$H' = \begin{pmatrix} 0 & 0 \\ 0 & b \end{pmatrix}$$

where for the neutrino sector $b = \frac{\Delta m^2}{2E} - (a_2 - a_1)$, and for the anti-neutrino sector $b = \frac{\Delta m^2}{2E} + (a_2 - a_1)$. In this case, the oscillation probability can be written as:

$$P = \sin^2(2\theta_{\text{eff}}) \sin^2\left(\frac{\Delta m^2_{\text{eff}} L}{4E}\right)$$

where $\sin^2(2\theta_{\text{eff}}) = \frac{4a^2}{4a^2+b^2}$ and $\Delta m^2_{\text{eff}} = \sqrt{4a^2 + b^2}$ play the role of $\sin^2(2\theta)$ and Δm^2 in Eq. (1) respectively. In our model, the off-diagonal term $a = 0$, so $\sin^2(2\theta_{\text{eff}}) = 1$ and the oscillation is governed by the effective mass splitting b.

We observe that if $\frac{m_2^2}{2E}$ and a_2 cancel at $E \sim$ several GeV, the term on the diagonal will be close to zero in Eq. (3) and the oscillations between ν_μ and ν_τ will be nearly maximal in this energy range. In contrast, a_2 has the opposite sign in Eq. (4), so the mixing between $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ is not maximal anymore. Thus, we can understand why $\sin^2(2\theta) = 0.86^{+0.11}_{-0.11}$ for anti-neutrinos is smaller than that for neutrinos. Furthermore, both values of a and b in the anti-neutrino sector are larger than those in the neutrino sector, resulting in the energy eigenvalue difference in the anti-neutrino sector being larger than that in the neutrino sector. Therefore, the differences between results observed in the neutrino sector and anti-neutrino sector can be well understood.

3 Results and Discussions

In the MINOS experiment, neutrinos whose energy spectrum mainly ranges from 1 to about 10 GeV travel 735 km before being detected. The flux of neutrinos peaks at 3 GeV and has a mean energy of 4 GeV.

We have performed a chi-squared analysis of the data [13] and the best-fit values of the parameters are determined to be as follows:

$$a_1 = 3.8 \times 10^{-14}\,\text{eV}, \quad a_2 = 2.2 \times 10^{-13}\,\text{eV},$$

$$\Delta m_1^2 = 1.4 \times 10^{-3}\,\text{eV}^2, \quad \Delta m_2^2 = 7.9 \times 10^{-4}\,\text{eV}^2.$$

Using these values, we compare the expectation of events with the data in $\bar{\nu}_\mu$ and ν_μ disappearance experiments in Fig. 1 [Figure 1: see original paper] and Fig. 2 [Figure 2: see original paper], respectively.

Fig.1: Comparison of the measured Far Detector $\bar{\nu}_\mu$ energy spectrum to the expectation in two cases: in the absence of oscillation; using the oscillation parameters given in Eqs. (7-10).

Fig.2: Comparison of the measured Far Detector ν_μ energy spectrum to the expectation in two cases: in the absence of oscillation; using the oscillation parameters given in Eqs. (7-10).

In the energy range of the MINOS experiment, it is difficult to distinguish the model in the present letter from models where the mass matrices in the neutrino sector and anti-neutrino sector are different. However, as energy rises, the mass term contribution will decrease while a_1 and a_2 do not change; therefore, the two scenarios will show different properties in the high energy limit. When the energy of neutrinos reaches several hundred GeV, the mixing induced completely by mass terms will become very small as shown in Eq. (1) for a fixed distance L, while the mixing induced by mass terms plus the Lorentz violation effect will become independent of energy as shown in Fig. 3 [Figure 3: see original paper] and Fig. 4 [Figure 4: see original paper] below.

Fig.3: ΔE due to Eq. (3) (dashed line) and Eq. (4) (solid line) as a function of energy.

Fig.4: $\sin^2(2\theta)$ due to Eq. (3) (dashed line) and Eq. (4) (solid line) as a function of energy.

Fig. 3 shows ΔE as a function of energy in the neutrino sector and anti-neutrino sector; Fig. 4 shows $\sin^2(2\theta)$ as a function of energy in the neutrino sector and anti-neutrino sector. As shown in these two figures, in the high energy limit where $\frac{m^2}{2E} \ll a_1$ and a_2, there is almost no difference between $\nu_\mu \leftrightarrow \nu_\tau$ and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_\tau$ and these two oscillation patterns will be independent of energy. There is a distinct character in the neutrino sector: when the energy of neutrinos is around 20 GeV, $\sin^2(2\theta)$ has a vanishing point, so the oscillations between ν_μ and ν_τ are highly suppressed in this small energy range.

It should be mentioned that in the energy range of solar neutrinos (a few MeV), $\frac{m^2}{2E} \gg a_1$ and a_2, so a_1 and a_2 will not affect the explanation of the solar neutrino problem. However, this model will be constrained by the atmospheric neutrino oscillation data. In the Super-K experiment, events generated by neutrinos and anti-neutrinos cannot be distinguished, so the results cannot supply strong constraints. In the future, long baseline experiments for the oscillations $\nu_\mu \leftrightarrow \nu_\tau$ and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_\tau$ at high energy (several tens of GeV) with high precision can confirm or exclude this model.

Finally, we would like to do a comparison between other attempts to solve the MINOS anomaly and ours. In [15, 16], the authors use CPT violation to solve the MINOS anomaly and consider that neutrinos and anti-neutrinos do have unequal mass differences at least in the atmospheric neutrino sector. However, in our model, mass differences in the neutrino sector and those in the anti-neutrino sector are equal. Because the mass term and the term a have different dependence on energy, the models in [15, 16] which only contain the mass term will show different properties in energy from our model which includes the term a. Consequently, experiments in different energy ranges can distinguish these two kinds of models. In the low energy range where the mass term is much larger than the term a in our model, there is no CPT violation observable in neutrino oscillation experiments, while there is always CPT violation irrespective of the energy of neutrinos in the models of [15, 16]. Only when the energy of neutrinos reaches the order of GeV can the CPT-violating effect emerge in our model.

When it comes to [17, 18, 19, 20], we have given the comparison between the term a and the potential induced by neutrino interaction in section 2. They share some similarities, but the essential difference between them is that the CPT-violating term a is a property of vacuum, while the matter potential is dependent on the concrete circumstances the neutrinos experience during their flight. Experiments can distinguish these two mechanisms too.

4 Summary

In conclusion, the MINOS anomaly, if it really exists, can be successfully explained by using a CPT-violating term in the formalism of SME as perturbation to the conventional mass-induced oscillation paradigm. Meanwhile, some odd conclusions are arrived at: in the energy range around 20 GeV, oscillations between ν_μ and ν_τ will be highly suppressed due to the very small mixing; in the high energy limit where the mass term is small enough compared to the terms from SME, $\nu_\mu \leftrightarrow \nu_\tau$ and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_\tau$ will have the same oscillating pattern which is independent of energy. Considering the data are statistically limited, the quantitative results are inconclusive. However, if the MINOS anomaly persists, it may become the first evidence of Lorentz violation which has a significant meaning.

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