Neutrino Phenomenology of gauged $L_\mu - L_\tau$: MINOS and beyond

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Abstract. If a Z' gauge boson from a gauged $L_\mu - L_\tau$ symmetry is very light, it is associated with a long-range leptonic force. In this case the particles in the Sun create via mixing of the Z' with the Standard Model Z a flavor-dependent potential for muon neutrinos in terrestrial long-baseline experiments. The potential changes sign for anti-neutrinos and hence can lead to apparent differences in neutrino and anti-neutrino oscillations without introducing CP or CPT violation. This could for instance explain the recently found discrepancy in the MINOS experiment. We obtain the associated parameters of gauged $L_\mu - L_\tau$ required to explain this anomaly. The consequences for future long-baseline experiments are also discussed, and we compare the scenario to standard NSIs. When used to explain MINOS, both approaches have severe difficulties with existing limits.

GAUGED $L_\alpha - L_\beta$ AND NEUTRINOS

In the Standard Model one can gauge one of the three lepton numbers $L_e - L_\mu$, $L_e - L_\tau$ or $L_\mu - L_\tau$ without introducing anomalies [1]. The $U(1)$ gauge symmetry associated with $L_\alpha - L_\beta$ goes along with a Z' vector boson, which couples to the current

$$j'^\mu = \bar{\alpha}\,\gamma^\mu\,\alpha + \bar{\nu}_\alpha\,\gamma^\mu\,P_L\,\nu_\alpha - \bar{\beta}\,\gamma^\mu\,\beta - \bar{\nu}_\beta\,\gamma^\mu\,P_L\,\nu_\beta \quad (1)$$

with coupling strength g'. Here α are the charged leptons and ν_α the corresponding neutrino. There is a priori no expectation for the mass of the Z'. Here we will assume that the Z' is ultra-light: $M_{Z'} < 1/R_{\text{A.U.}} \simeq 10^{-18}$ eV, where $R_{\text{A.U.}}$ denotes an astronomical unit. In this case a Coulomb-like potential for leptons, in particular neutrinos, is generated by the particles in the Sun (and Earth). For instance, if we gauge $L_e - L_\beta$ one has [2, 3]

$$V = \alpha_{e\beta}\,\frac{N_e}{R_{\text{A.U.}}} \simeq 1.3 \times 10^{-11}\left(\frac{\alpha_{e\beta}}{10^{-50}}\right)\text{eV}, \quad (2)$$

where $\alpha_{e\beta} = g'^2/(4\pi)$, and N_e is the number of electrons in the Sun. In the 2-neutrino system of ν_e and ν_β we have to add this potential to the usual oscillation Hamiltonian:

$$\mathcal{H}_{e\beta} = \frac{\Delta m^2}{4E}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \begin{pmatrix} V & 0 \\ 0 & -V \end{pmatrix}.$$

The effect of this new neutrino physics looks very much like the usually considered Non-Standard Interactions (NSIs), but does not depend on the matter density and therefore would work even for vacuum oscillations. The effect of V on the mixing observables is

$$\sin^2 2\theta_V = \frac{\sin^2 2\theta}{1 - 4\eta\,\cos 2\theta + 4\eta^2}, \quad (3)$$

$$\Delta m_V^2 = \Delta m^2\sqrt{1 - 4\eta\,\cos 2\theta + 4\eta^2}, \quad (4)$$

where $\eta = 2EV/\Delta m^2$. Note that V changes sign for anti-neutrinos, and hence an apparent difference between neutrino and anti-neutrino parameters will be measured. Note further that neither CP nor CPT violation is required for this effect. From Eqs. (3, 4) it is seen that the mixing angle is required to be non-maximal in order to introduce differences between neutrinos and anti-neutrinos. In the limit of small η we have

$$\Delta m_V^2 - \overline{\Delta m_V^2} \simeq -4\Delta m^2\,\eta\,\cos 2\theta, \quad (5)$$

$$\sin^2 2\theta_V - \sin^2 2\overline{\theta}_V \simeq 8\,\eta\,\cos 2\theta\,\sin^2 2\theta. \quad (6)$$

In Eq. (2) we have given the potential in units of very small $\alpha_{e\beta}$. This is because the potential should be smaller than the energy scale $\Delta m^2/(4E)$, which is about $6 \times 10^{-13}\left(\frac{\text{GeV}}{E}\right)$ eV for atmospheric neutrinos and $2 \times 10^{-11}\left(\frac{\text{MeV}}{E}\right)$ eV for solar neutrinos. With these estimates one can understand the limits of $\alpha_{e\mu}$ $(\alpha_{e\tau}) \leq 5.5$ $(6.4) \times 10^{-52}$ from atmospheric neutrinos [2], and $\alpha_{e\mu}$ $(\alpha_{e\tau}) \leq 3.4$ $(2.5) \times 10^{-53}$ from solar and Kam-LAND neutrinos [3]. These limits are more than one order of magnitude stronger than limits from tests of the equivalence principle.

We note here that in the symmetric limit the neutrino mass matrices for $L_e - L_\mu$ and $L_e - L_\tau$ conservation are

$$m_\nu = \begin{pmatrix} 0 & a & 0 \\ \cdot & 0 & 0 \\ \cdot & \cdot & b \end{pmatrix} \text{ and } \begin{pmatrix} 0 & 0 & a \\ \cdot & b & 0 \\ \cdot & \cdot & 0 \end{pmatrix}, \quad (7)$$

respectively. Rather peculiar breaking patterns are required to achieve successful neutrino mixing phenomenology from these matrices. In contrast, if $L_\mu - L_\tau$
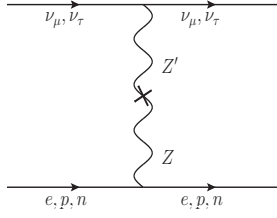
FIGURE 1. Long-range $\nu_{\mu,\tau}-(e,p,n)$ interaction through Z–Z'-mixing.

is conserved one has [4]

$$m_\nu = \begin{pmatrix} a & 0 & 0 \\ \cdot & 0 & b \\ \cdot & \cdot & 0 \end{pmatrix}. \qquad (8)$$

This matrix is automatically μ–τ symmetric ($\theta_{13} = |\theta_{23} - \pi/4| = 0$), hence requires less peculiar breaking, and predicts the presence of neutrino-less double beta decay ($\langle m \rangle = a$). The masses are a and $\pm b$, hence neutrinos will have a mild, if any, hierarchy ($a \sim b$ because both terms are allowed by the symmetry and therefore expected to be of similar magnitude).

The question is now how to apply gauged $L_\mu - L_\tau$ to neutrino oscillations, because the lack of reasonable amounts of muons or tauons in the Universe seems to forbid the generation of a potential in analogy to Eq. (2). The solution [5] lies in Z–Z' mixing, which in turn originates from the last two terms of the general Lagrangian

$$\mathscr{L} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} M_Z'^2 Z'_\mu Z'^\mu - g' j'^\mu Z'_\mu \quad (9)$$

$$-\frac{\sin\chi}{2} Z'^{\mu\nu} B_{\mu\nu} + \delta M^2 Z'_\mu Z^\mu. \quad (10)$$

Here $Z'_{\mu\nu}$ and $B_{\mu\nu}$ are the field strength tensors of the new $U(1)$ and the Standard Model hypercharge. Diagonalizing the kinetic and mass terms to obtain the physical particles $Z_{1,2}$ introduces Z–Z' mixing:

$$\mathscr{L}_{Z_1} = -\left(\frac{e}{s_W c_W} \left((j_3)_\mu - s_W^2 (j_{EM})_\mu \right) + g' \xi (j')_\mu \right) Z_1^\mu,$$

$$\mathscr{L}_{Z_2} = -\left(g'(j')_\mu - \frac{e}{s_W c_W} (\xi - s_W \chi) \left((j_3)_\mu \right. \right.$$
$$\left. \left. -s_W^2 (j_{EM})_\mu \right) - e c_W \chi (j_{EM})_\mu \right) Z_2^\mu,$$

where ξ is a small mixing angle depending on χ and δM^2. The Z' couples weakly with the electromagnetic and isospin currents j_{EM} and j_3, and mixes with the (mainly) Standard Model Z. One can now obtain [5] the following potential for ν_μ and ν_τ (see Fig. 1):

$$V = \alpha \frac{e}{4 s_W c_W} \frac{N_n}{4\pi R_{A.U.}} = 3.60 \times 10^{-14} \mathrm{eV} \left(\frac{\alpha}{10^{-50}} \right), \quad (11)$$
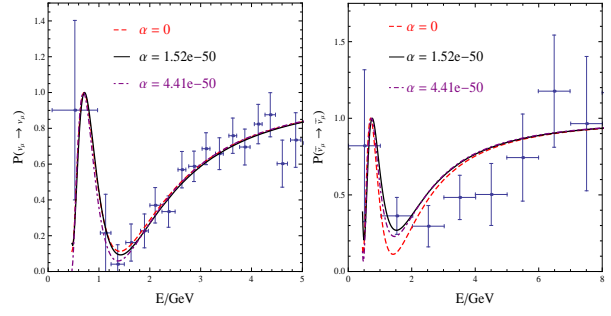
FIGURE 2. The oscillation probabilities for the best-fit values from Eq. (12) for neutrinos and anti-neutrinos superimposed on the MINOS data. Also plotted are the cases $\alpha = 0$ and the value for a second, local χ^2-minimum. Taken from [5].

where we have defined $\alpha = g'(\xi - s_W \chi)$ and included the Earth's contribution to the solar one. For neutral objects like the Sun or Earth the electron and proton numbers cancel and only the neutron number N_n is of interest. The above potential acts on the μ–τ neutrino sector and introduces different oscillation probabilities for neutrinos and anti-neutrinos. Consequently it is a good candidate for an explanation of the MINOS results, which seemingly give different mixing parameters in the muon neutrino and anti-neutrino survival probabilities.

APPLICATION TO MINOS AND OTHER EXPERIMENTS

The MINOS long-baseline experiment reported on individual measurements of ν_μ and $\bar{\nu}_\mu$ survival probabilities, and gave the following results [6]

$$\Delta m^2 = \left(2.35^{+0.11}_{-0.08}\right) \times 10^{-3} \mathrm{eV}^2, \quad \sin^2 2\theta > 0.91,$$
$$\overline{\Delta m^2} = \left(3.36^{+0.45}_{-0.40}\right) \times 10^{-3} \mathrm{eV}^2, \quad \sin^2 2\overline{\theta} = 0.86 \pm 0.11.$$

The apparent difference of the neutrino and anti-neutrino parameters has motivated several explanation attempts, in the form of CPT violation [8], NSIs [9, 10, 11], sterile neutrinos plus gauged $B - L$ [12], and gauged $L_\mu - L_\tau$ [5]. As became clear during this meeting [13], none of the explanations put forward so far works[1]: the standard three-neutrino picture is remarkably stable and robust.

Let us illustrate the problems of the solutions: Fig. 2 shows our fit to the MINOS data with the potential from Eq. (11). The best-fit values and 1σ ranges are [5]

$$\sin^2 2\theta = 0.83 \pm 0.08, \quad \alpha = \left(1.52^{+1.17}_{-1.14}\right) \times 10^{-50},$$
$$\Delta m^2 = (-2.48 \pm 0.19) \times 10^{-3} \mathrm{eV}^2, \quad (12)$$

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[1] An exception is probably CPT violation, if one is willing to abandon such an important cornerstone of modern physics.

with $\chi^2_{\mathrm{min}}/N_{\mathrm{dof}} = 47.77/50 \simeq 0.96$, to be compared with the fit without new physics, which has $\chi^2_{\mathrm{min}}/N_{\mathrm{dof}} = 49.43/51 \simeq 0.97$. Recall now that the total Hamiltonian including V looks like a typical NSI Hamiltonian, for which limits have of course been derived already [14]. Values of $\alpha = 10^{-50}$ correspond to Earth matter NSIs of $|\varepsilon^{\oplus}_{\mu\mu}| \simeq 0.25$. The current limit on this parameter is $|\varepsilon^{\oplus}_{\mu\mu}| \lesssim 0.068$, corresponding to $\alpha \lesssim 10^{-51}$, too small to have an effect of necessary size for MINOS.

However, there is one important difference to NSIs: in a gauge invariant framework the ε parameters of the neutrino NSIs are responsible also for charged lepton decays, which are subject to stringent constraints and improve the bounds by typically one or two orders of magnitude. Of course, there might be an additional symmetry protecting the charged leptons, or highly fine-tuned cancellations of different higher order terms may take place [15]. For instance, consider the Lagrangian[2] $\mathscr{L}^{\mathrm{NSI}}_{\mathrm{CC}} \supset -2\sqrt{2}\, G_F\, \varepsilon^d_{\tau\mu}\, V_{ud}\, [\bar{u}\, \gamma^{\mu}\, d]\, [\bar{\mu}\, \gamma_{\mu}\, P_L\, \nu_{\tau}]$, which leads to interference between ν_{μ} CC events and events in which ν_{μ} oscillate into ν_{τ}, subsequently creating muons via $\varepsilon^d_{\tau\mu}$. For anti-neutrinos, $\varepsilon^d_{\tau\mu} \to (\varepsilon^d_{\tau\mu})^*$, and hence different neutrino and anti-neutrino parameters arise. Values of $|\varepsilon^d_{\tau\mu}|$ around 0.1 are enough to explain the MINOS results. However, the Lagrangian written in a gauge invariant way induces the tree-level decay $\tau \to \mu\, \pi^0$, from which a limit of $|\varepsilon^d_{\tau\mu}| \lesssim 10^{-4}$ is derived [16]. We note here that the scenario of gauged $L_{\mu} - L_{\tau}$ discussed here does not suffer from such problems (the reason being diagonal and small couplings to leptons), and does not require strong and fine-tuned cancellations or extra symmetries protecting charged leptons.

Returning to neutrinos, a GLoBES [17] analysis of future prospects for constraints on gauged $L_{\mu} - L_{\tau}$ has been performed in [5]. Modifying the program with the (now 3-flavor) Hamiltonian including V from Eq. (11) and using the standard "AEDL-files" provided with the software, we find future limits on α listed in Table 1.

In Ref. [5] a variety of experimental observables which could be modified by the parameters of gauged $L_{\mu} - L_{\tau}$ is checked for consistency. These include the magnetic moment of the muon, Big Bang Nucleosynthesis, charge difference of electron and muon, electroweak precision data, and tests of the equivalence principle. The strongest constraints are and will be provided by neutrino oscillation experiments, which shows the remarkable sensitivity of neutrinos to new and interesting physics.

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[2] This is a charged current (CC) NSI, because neutral current NSIs required to explain the MINOS data are at least of order 0.1 and hence in conflict with bounds obtained from neutrino data alone [9, 10, 11].

TABLE 1. Sensitivity to α from future experiments using GLoBES.

Experiment	Sensitivity to $\alpha/10^{-50}$ at 99.73% C.L.
T2K (ν-run)	11.8
T2K	4.3
T2HK	1.7
SPL	7.5
NOνA	1.9
Combined Superbeams	1.4
Nufact	0.53

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