CONSTRAINTS ON FLAVOR-DEPENDENT LONG RANGE FORCES FROM NEUTRINO EXPERIMENTS

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We study the impact of flavor-dependent long range leptonic forces mediated by the $L_e - L_\mu$ or $L_e - L_\tau$ gauge bosons on the solar neutrino oscillations, when the interaction range $R_{LR}$ is much larger than the Earth-Sun distance. The solar and atmospheric neutrino mass scales do not get trivially decoupled in this situation even if $\theta_{13}$ is vanishingly small. In addition, for $\alpha \gtrsim 10^{-52}$ and normal hierarchy, resonant enhancement of $\theta_{13}$ may give rise to strong energy dependent effects on the $\nu_e$ survival probability. A complete three generation analysis of the solar neutrino and KamLAND data gives the $3\sigma$ limits $\alpha_{e\mu} < 3.4 \times 10^{-53}$ and $\alpha_{e\tau} < 2.5 \times 10^{-53}$ when $R_{LR}$ is much smaller than our distance from the galactic center. With larger $R_{LR}$, the collective LR potential due to all the electrons in the galaxy becomes significant and the constraints on $\alpha$ become stronger by up to two orders of magnitude.

Keywords: Flavor symmetries; Extensions of electroweak gauge sector; Neutrino mass and mixing

1. Introduction

Flavor-dependent long range (LR) leptonic forces, like those mediated by the $L_e - L_\mu$ or $L_e - L_\tau$ gauge bosons,\(^1\) constitute a minimal extension of the standard model that preserves its renormalizability. The extra $U(1)$ gauge boson, albeit nearly massless, would escape direct detection if it couples to the matter very weakly.\(^2\) Since these long range forces violate the equivalence principle, they are strongly constrained by the lunar ranging and Eötvös type gravity experiments.\(^3\)\(^4\) For a range of the Earth-Sun distance or more, these experiments imply the $2\sigma$ bounds $\alpha < 3.4 \times 10^{-49}$, where $\alpha$ denotes the strength of the long range potential.

The coupling of the solar electrons to the $L_e - L_\beta$ gauge bosons generates a long range potential $V_{e\beta}^{\odot}$ for neutrinos, whose value at the Earth is $1.3 \times 10^{-11}$ eV $(\alpha_{e\beta}/10^{-50})$. The typical value of $\Delta m^2/E$ for atmospheric neutrinos is $\sim 10^{-12}$ eV, so even with the strong constraints above, LR forces affect atmospheric neutrino oscillations. This allows one to put stronger constraints\(^2\) on the couplings, $\alpha_{e\mu} < 5.5 \times 10^{-52}$ and $\alpha_{e\tau} < 6.4 \times 10^{-52}$.

2. LR potential due to the Sun, the Earth and the galaxy

The behavior of $V_{e\beta}^{\odot}$ from the solar core all the way to the Earth ($r \approx 215 \ r_\odot$) and beyond is shown in Fig. 1. It is seen that $V_{e\beta}^{\odot}$ dominates over the MSW potential $V_{CC}$ inside the Sun for $\alpha \gtrsim 10^{-53}$. Moreover, it does not abruptly go to zero outside the Sun like $V_{CC}$, but decreases inversely with $r$. Its value at the Earth surface is an order of magnitude larger than the potential there due to the electrons in the Earth, so one can neglect the latter.

When $R_{LR} \gtrsim R_{gal}$, our distance from the galactic center, the collective potential due to all the electrons in the galaxy may become significant. We denote the galactic contribution to the potential $V_{e\beta}$ as

$$V_{e\beta}^{gal} = b \alpha_{e\beta} N_{e,gal}/R_{gal}^0, \quad (1)$$

$$\Delta m^2/E = 1.3 \times 10^{-11} (\alpha_{e\beta}/10^{-50}) \ eV, \quad (2)$$

$$\alpha_{e\mu} < 5.5 \times 10^{-52} \quad (3)$$

$$\alpha_{e\tau} < 6.4 \times 10^{-52} \quad (4)$$

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where \( N_{e,\text{gal}}^0 \equiv 10^{12} N_e^\odot \) and \( R_{\text{gal}}^0 \equiv 10 \) kpc. The parameter \( b \) takes care of our ignorance about the distribution of the baryonic mass in our galaxy. With \( R_{LR} \sim R_{\text{gal}} \), we expect \( 0.05 < b < 1 \). The value of \( b \) may be smaller if \( R_{LR} \) is smaller, \( b = 0 \) is equivalent to \( R_{LR} \ll R_{\text{gal}} \). The screening effects\(^7\) are negligible over the scale of \( R_{\text{gal}} \).

3. Masses, Mixings and Resonances of Solar Neutrinos

The LR potential gives unequal contributions to all three flavors simultaneously unlike in case of the charged current potential. As a result, the inclusion of three generations in the solar analysis becomes necessary.

The appropriate Hamiltonian in the \( L_e - L_\mu \) case describing the neutrino propagation can be written in the flavor basis as

\[
H_f = R H_0 R^T + V ,
\]

(2)

with \( V = \text{Diag}(V_{ee} + V_{e\mu}, -V_{e\mu}, 0) \). Here \( R \equiv R_{23}(\theta_{23})R_{13}(\theta_{13})R_{12}(\theta_{12}) \), we have assumed that no CP violation enters the picture. One can take \( H_0 = \text{Diag}(0, \Delta_{21}, \Delta_{32}) \) with \( \Delta_{ij} \equiv \Delta m^2_{ij}/(2E) \). The antineutrino propagation is obtained by the replacement \( V \rightarrow -V \).

The Hamiltonian (2) can be analytically diagonalized\(^5\) by keeping terms linear in the small parameters \( x \equiv \Delta_{21}/\Delta_{32} \approx 0.03 \) and \( \sin \theta_{13} < 0.2 \), except in a narrow region around \( g_{e\mu} \equiv V_{e\mu}/\Delta_{32} \approx 2/3 \). The exact numerical values for mixing angles and \( m^2_i \) for different values of \( \alpha \) for normal as well as inverted hierarchy are shown in Fig. 2.

fig. 1. Comparison of the MSW potential \( V_{cc} \) and the LR potential \( V_{cc}^0 \) due to the solar electrons. The \((\Delta m^2/2E)\) values corresponding to \( E = 10 \) MeV are also shown.

fig. 2. The angles and \( m^2 \) values in matter for solar neutrinos for \( E = 10 \) MeV, in the case \( R_{LR} \ll R_{\text{gal}} \). The \( m^2 \) values are correct up to an additive constant, so that only their relative values have a physical significance.

3.1. For \( \alpha \lesssim 10^{-52} \)

Both \( \theta_{23} \) as well as \( \theta_{13} \) get only small corrections. In the limit \( \theta_{13} \rightarrow 0 \), the third mass eigenstate decouples and the scenario reduces to 2\( \nu \) mixing. However, the effective matter potential is\(^6\)

\[
V_{12} \approx V_{cc} + V_{e\mu}(1 + \cos^2 \theta_{23m}) ,
\]

(3)

and not \( V_{cc} + 2V_{e\mu} \), as would have been taken in a naive 2-generation analysis.

The MSW resonance takes place with the modified potential \( V_{12} \). For \( \alpha \gtrsim 10^{-53} \), the \( V_{12} \) contribution dominates over \( V_{cc} \) and the resonance is shifted outside the Sun where its behavior is solely determined by the LR potential.
If $P_L(E)$ is the jump probability at the $\nu_{1m}\sim\nu_{2m}$ resonance, the net survival probability of $\nu_e$ is

$$P_{ee}(E) = (1 - P_L) c_{13P}^2 c_{12P}^2 c_{13E}^2 c_{12E}^2 + P_L c_{13P}^2 s_{12P}^2 c_{13E}^2 c_{12E}^2 + (1 - P_L) c_{13P}^2 s_{12P}^2 c_{13E}^2 s_{12E}^2 + P_L c_{13P}^2 s_{12P}^2 c_{13E}^2 s_{12E}^2 + s_{13P}^2 s_{13E}^2.$$

Here $\theta_{ijP}$ and $\theta_{ijE}$ are the values of $\theta_{ijm}$ at the neutrino production point and at the Earth respectively.

### 3.2. For $\alpha \gtrsim 10^{-52}$

In this range of $\alpha$, the $\nu_{1m}\sim\nu_{2m}$ resonance is always outside the Sun and adiabatic. In addition the angle $\theta_{13m}$ gets resonantly enhanced when $y_{ee} \approx 2/3$ (normal hierarchy). The $\theta_{13m}$ enhancement corresponds to the $\nu_{2m}\sim\nu_{3m}$ level crossing, with an effective potential

$$V_{23} = V_{cc} + V_{cp} (1 + \sin^2 \theta_{23m}).$$

The net survival probability of $\nu_e$ is

$$P_{ee}(E) = c_{13P}^2 c_{12P}^2 c_{13E}^2 c_{12E}^2 + (1 - P_H) c_{13P}^2 s_{12P}^2 c_{13E}^2 s_{12E}^2 + P_H s_{13P}^2 c_{13E}^2 s_{12E}^2 + (1 - P_H) s_{13P}^2 c_{13E}^2 s_{12E}^2 + P_H s_{13P}^2 s_{12P}^2 c_{13E}^2 s_{12E}^2,$$

where $P_H(E)$ is the probability that $\nu_{2m}$ and $\nu_{3m}$ convert into each other after traversing through this resonance.

In general $P_H \approx 0$ at high values of $\theta_{13}$. For $\theta_{13} \lesssim 0.1^\circ$, the value of $P_H$ becomes significant. In the range where $0.1 < P_H < 0.9$ (the semi-adiabatic range), $P_H$ is also highly energy dependent.

### 4. Constraints from solar neutrinos and KamLAND

We perform a global fit to the data from solar experiments and KamLAND, using the $\chi^2$ minimization technique with covariance approach for the errors. For $\alpha < 10^{-52}$, the value of $\chi^2$ is minimum for $\theta_{13} = 0^\circ$. When $\alpha > 10^{-52}$, a strong energy dependence in the survival probability is introduced for $\theta < 0.1^\circ$ through $P_H(E)$, so that the $\chi^2$ values for extremely low $\theta_{13}$ values become large. However, the region $\alpha > 10^{-52}$ turns out to be excluded to more than $3\sigma$. Therefore we quote the most conservative upper bounds on $\alpha$, by taking $\theta_{13} = 0^\circ$. These limits are shown in Fig. 3: the $3\sigma$ limit corresponding to the one-parameter fit in the $L_e - L_\mu$ case is $\alpha_{ee} < 3.4 \times 10^{-53}$. The corresponding $L_e - L_\tau$ limit is $\alpha_{et} < 2.5 \times 10^{-53}$. The bounds are independent of the neutrino mass hierarchy.

### 5. LR potential from the galaxy

When $R_{LR} \gg R_{gal}$, the net potential $V_{\nu} \equiv V_{\nu}^{gal} + V_{\nu}^{gal}$ is shown in Fig. 4. For $V_{\nu}^{gal} \gg \Delta m_{\odot}^2/(2E)$, there is no MSW resonance that is essential for a good fit to the solar neutrino data. Even for lower values of $b$ and $\alpha$, if $V_{\nu}^{gal}$ dominates over $V_{CC}$ at the MSW resonance,
the resonance tends to be adiabatic even for low energies, so the radiochemical data disfavors the solution.

Fig. 4. The net potential $V_{e\mu} = V_{e\mu}^{\odot} + V_{e\mu}^{gal}$ for various values of $b$ and $\alpha$.

The $\Delta \chi^2$ values as a function of $\alpha$ for different $b$ values are shown in Fig. 3. The 3σ constraints for the $L_e - L_{\mu}$ case are $\alpha_{e\mu} < 2.9 \times 10^{-54}$ (b = 0.1) and $\alpha_{e\mu} < 2.6 \times 10^{-55}$ (b = 1). For $L_e - L_{\tau}$, the constraints are $\alpha_{e\tau} < 2.3 \times 10^{-54}$ (b = 0.1) and $\alpha_{e\tau} < 2.1 \times 10^{-55}$ (b = 1). We expect $b < 1$ even with generous estimates. The most conservative constraints are clearly with $b = 0$, as calculated in Sec. 4.

6. Concluding remarks

The long range forces mediated by $L_e - L_{\mu, \tau}$ vector gauge bosons can give rise to non-trivial 3-ν mixing effects inside the Sun, and affect the MSW resonance picture. The angle $\theta_{13}$ may even get resonantly amplified if $\alpha \gtrsim 10^{-52}$ for normal hierarchy. These effects allow one to put constraints on the coupling of the LR forces from the solar and KamLAND data. The bounds obtained are orders of magnitude better than those obtained earlier from the gravity experiments and atmospheric neutrino data. If the range of the forces is larger than $R_{gal}$, the bounds become still stronger by upto two orders of magnitude.

A recent paper$^9$ also has given comparable bounds on the LR couplings. However, they assume one mass scale dominance, neglecting the effect of the third neutrino altogether. Moreover, they have not taken the galactic contribution into account even when the range of the force is more than $R_{gal}$.

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