Constraining long-range leptonic forces using iron calorimeter detectors

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Abstract

The leptonic long range forces which distinguish between their flavours have been shown to significantly influence the oscillations of the atmospheric, solar as well as terrestrial neutrinos. The observed oscillations of the atmospheric neutrinos have been used to provide more stringent constraints on the couplings of these forces than the ones obtained in the terrestrial experiments. The potential generated by these forces distinguishes between neutrino and anti neutrino. Thus the magnetic iron calorimeter detectors which can distinguish the muon charges could provide more sensitive test of these forces. We make a detailed analysis in case of the atmospheric neutrinos and conclude that such detectors have the potential to further improve bounds on the long range couplings by an order of magnitude.

Long range forces in the context of particle physics originated with the ideas of Yang and Lee [1] and Okun [2] who proposed that gauging the baryon number or lepton number would give rise to a composition dependent long range force which could be tested in the classic Eotovos type experiments[3]. A special class of long range forces which distinguish between leptonic flavors have far reaching implications for the neutrino oscillations [4, 5] which may be used as a probe of such forces.

The standard model Lagrangian is invariant under four global symmetries corresponding to the Baryon and three lepton numbers $L_\alpha (\alpha = e, \mu, \tau)$. Of these, only three combinations [6] of lepton numbers (i) $L_e - L_\mu$,(ii) $L_e - L_\mu$ or (iii) $L_\mu - L_\tau$, can be gauged in an anomaly free way without extending the matter content. The existence of neutrino oscillations imply that these symmetries have to be broken but the relevant gauge bosons can still be light if the corresponding couplings are very weak. It is possible in this case to obtain light gauge boson induced forces having terrestrial range (e.g. the Sun-Earth distance) without invoking extremely low mass scales [4]. The exchange of such boson would induce matter effects in terrestrial, solar and atmospheric neutrino oscillations. For example, the electrons inside the Sun generate a potential V_{LR} at the earth surface given by

$$V_{LR} = \alpha \frac{N_e}{R_{es}} \approx (1.04 \times 10^{-11} eV) \left(\frac{\alpha}{10^{-50}} \right) \ , \tag{1}$$

where $\alpha \equiv \frac{g^2}{4\pi}$ corresponds to the gauge coupling of the $L_e - L_{\mu,\tau}$ symmetry , N_e is the number of electrons inside the Sun and R_{es} is the Earth-Sun distance $\approx 7.6 \times 10^{26} GeV^{-1}$. The present bound on the Z-dependent force with range $\lambda \sim 10^{13}$ cm is given [3] by $\alpha < 3.3 \times 10^{-50}$. Eq.(1) then shows that the potential V_{LR} can introduce very significant matter-dependent effects in spite of very strong bound on α. One can define a parameter

$$\xi \equiv \frac{2E_\nu V_{LR}}{\Delta m^2}$$

which measures the effect of the long range force in any given neutrino oscillation experiment. Given the terrestrial bound on α, one sees that ξ is given by $\xi_{atm} \sim 8.3$ in atmospheric or typical long baseline experiments while it is given by $\xi_{solar} \sim 2.3$ in case of the solar or KamLand type experiment. In either case, the long range force would change the conventional oscillation analysis. Relatively large value of α suppresses the oscillations of the atmospheric neutrinos. The observed oscillations then can be used to put a stronger constraints on α which were analyzed in [4]. One finds the improved 90% CL bound .

$$\alpha_{e\mu} \leq 5.5 \times 10^{-52} \quad ; \quad \alpha_{e\tau} \leq 6.4 \times 10^{-52} \ , \tag{2}$$

in case of the $L_e - L_{\mu,\tau}$ symmetries respectively.

The parameter ξ changes the vacuum mixing angle, $(\text{mass})^2$ difference and consequently also the oscillation probabilities. Considering only the $\nu_\mu - \nu_\tau$ oscillations, the survival probability for the atmospheric muon neutrinos can be written as

$$P_{\mu\mu} = 1 - Sin^2 2\tilde{\theta}_{23} \ Sin^2 \frac{\Delta\tilde{m}^2_{23} L}{4E_\nu} \tag{3}$$

The neutrino flight path-length L in (3) is related to the cosine of the zenith angle as

$$L = ((R_e + h)^2 - R_e Sin^2\theta_z)^{1/2} - R_e Cos\theta_z \tag{4}$$

where $R_e = 6374km$ is the mean radius of the earth and $h \simeq 15km$ is the average height in the atmosphere where the neutrinos are produced. The effective mixing angle $\tilde{\theta}_{23}$ and mass squared difference $\Delta\tilde{m}^2_{23}$ are given in terms of the corresponding vacuum quantities by the relations

$$\Delta\tilde{m}^2_{23} = \Delta m^2_{23}((\xi_{e\tau} - Cos2\theta_{23})^2 + Sin^2 2\theta_{23})^{1/2} \tag{5}$$

and

$$Sin^2 2\tilde{\theta}_{23} = \frac{Sin^2 2\theta_{23}}{((\xi_{e\tau} - Cos2\theta_{23})^2 + Sin^2 2\theta_{23})} \tag{6}$$

The $\bar{\nu}_\mu$ survival probability is obtained from the ν_μ survival probability by replacing $\xi \rightarrow -\xi$ in the expressions (5) and (6). We have restricted ourselves to the $L_e - L_\tau$ symmetry for definiteness.

It is clear from the above that the long range forces introduce a (solar) matter dependent term in the oscillations probability even when U_{e3} is zero unlike in the standard case which require participation of the electron neutrino and a non-zero U_{e3} for the matter to influence the atmospheric oscillations. In the following, we neglect the ordinary matter effect assuming a vanishingly small U_{e3}.

The bounds in eq.(2) represent a significant improvement over the terrestrial bound. It is possible to improve them further using future long baseline experiments [7] and using more detailed information from the atmospheric neutrino oscillations. For a range in parameters, the effect of the long range potential is different for neutrinos and anti-neutrinos. The separate determination of neutrino and anti neutrino fluxes can thus help in further probing the long range forces. The iron calorimeter (ICAL) with capabilities of identifying muon charges can provide separate measurement of the neutrino and the anti neutrino fluxes. Such detectors are proposed by the MONOLITH [8],MINOS [9] and ICAL/INO [10] collaboration. As we will see, such detectors provide additional information which can allow detection of the long range forces or improvement on the constraints on the corresponding couplings.

Several features of eqs.(3) allow us to identify proper variable which can lead to significant difference in the neutrino and anti neutrino oscillations.

- It follows from eq.(6) that the oscillations of neutrinos and anti neutrinos are suppressed identically if θ_{23} is maximal and $\xi \geq 1$. The difference in these oscillations can arise only for the non-maximal θ_{23}.

- The down going atmospheric neutrinos which travel average distance of around 15km do not oscillate significantly due to very small path length. The presence of ξ increases the oscillation length compared to the vacuum case (roughly by a factor of 40 for $E_\nu \sim 1$ GeV and α as given by eq.(2)) but it is also accompanied by the suppression in the effective mixing angle. The net result is that the down going neutrinos and anti neutrinos still do not oscillate and $P_{\mu\mu}$ in eq.(3) is practically one both for neutrinos and anti neutrinos. Significant difference between them arise only for the upcoming neutrinos which travel long distances.

Based on the above observations, we identify the following asymmetry[1]:

$$A = \frac{r^\nu - r^{\bar\nu}}{r^\nu + r^{\bar\nu}} \ , \tag{7}$$

where

$$r^{\nu,\bar\nu} \equiv \frac{\int_0^1 d\cos\theta_Z dE_\nu P^{\nu,\bar\nu}_{\mu\mu}(E_\nu,\cos\theta_z)\sigma^{\nu,\bar\nu}(E_\nu)\phi^{\nu,\bar\nu}(E_\nu,\cos\theta_z)}{\int_{-1}^0 d\cos\theta_Z dE_\nu P^{\nu,\bar\nu}_{\mu\mu}(E_\nu,\cos\theta_z)\sigma^{\nu,\bar\nu}(E_\nu)\phi^{\nu,\bar\nu}(E_\nu,\cos\theta_z)} \tag{8}$$

where $P^\nu_{\mu mu}$ is the survival probability given in eq.(3) and the corresponding probability for anti neutrino is obtained with the replacement $\xi \to -\xi$. $\sigma^{\nu,\bar\nu}$ are neutrino cross sections and $\phi^{\nu,\bar\nu}$ are fluxes of the atmospheric $\nu_\mu, \bar{\nu_\mu}$. We use the Fluka-3D flux given in [12]. We consider here only multi GeV neutrinos and carry out energy integral in the range 1-100 GeV. Neutrino cross section in this range are taken proportional to neutrino energy which is a fairly good assumption [13].

We show in Fig.(1) the absolute value of A (in %) as a function of the long range coupling constant α. For definiteness, we have assumed $L_e - L_\tau$ symmetry and assumed normal hierarchy with $\Delta m^2_{23} = 3.0 \times 10^{-3}$ eV^2. A is very small for relatively large or small values of α. For smaller α the long range force is negligible and neutrino and anti neutrinos oscillations are identical giving very small A. For relatively larger α, the $\cos 2\theta_{23}$ term in eq.(5,6) is negligible and the long range force cannot distinguish between neutrino and anti neutrino resulting once again in very small A. The sizable effect of the long range forces on A occur for $\alpha \approx 10^{-51} - 10^{-53}$. In this range,

[1] A similar asymmetry has also been studied in the context of the ordinary matter effects in [11]

A can be quite large, *e.g.* even for an order of magnitude smaller α than the bound in eq.(2), one can get very large asymmetry $A \geq 5\%$. Such a large value indicates that the ICAL detectors have potential to improve the bounds on α obtained without considering the charge separation. Observability of this relatively large asymmetry will depend on the details of the detectors and it would be worthwhile to do this analysis in the context of possible detectors at INO.

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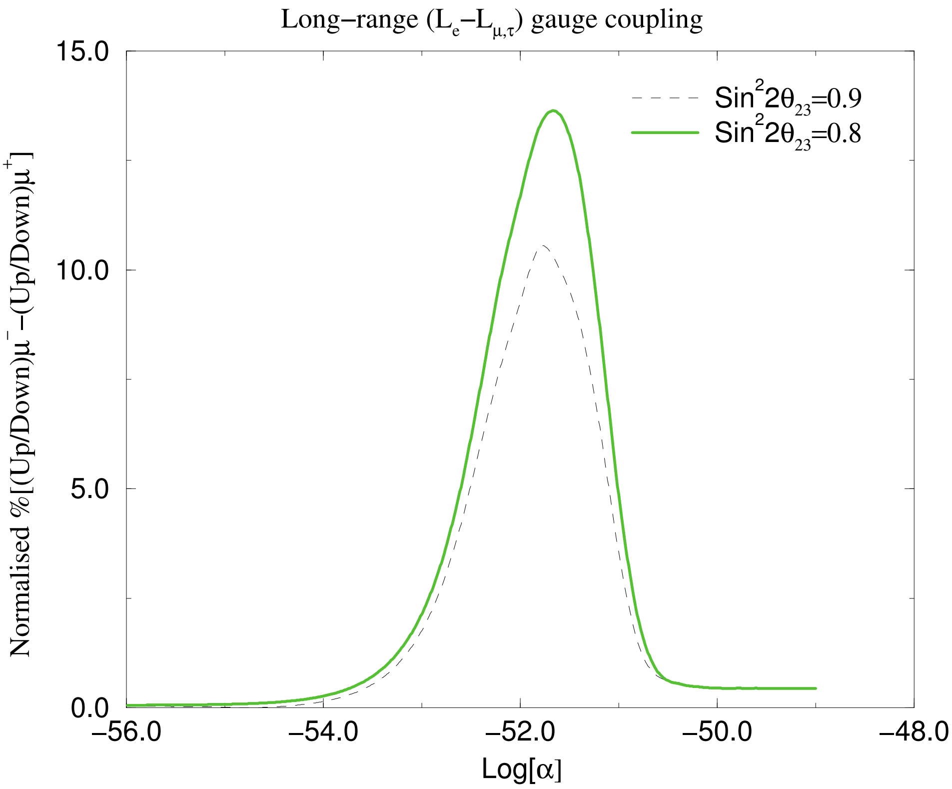

Figure 1: The neutrino-antinutrino asymmetry as defined in eqn (7-8) as a function of the $L_e - L_{\mu,\tau}$ coupling $\alpha \equiv g^2/4\pi$. The plots show the percentage asymmetry for different $Sin^2 2\theta_{23}$ and with $\Delta m^2 = 3 \times 10^{-2} eV^2$.