Status of the solutions to neutrino anomalies based on non-standard neutrino interactions

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We review the status of the solutions to neutrino anomalies by flavor-changing as well as flavor-diagonal neutrino interactions. While it is difficult to explain the atmospheric neutrino data the solar neutrino data can be well accounted for by the massless neutrino oscillation induced by such non-standard neutrino interactions. We also discuss the possibility to test such kind of interactions by the future neutrino oscillation experiments at neutrino factories.

1. Introduction

In this talk we review the present status of the solutions to the solar neutrino problem and atmospheric neutrino observations by the oscillation of neutrinos which are massless (or degenerate in mass) induced by flavor-changing (FC) as well as flavor-diagonal (FD) interactions [1–8] in matter. (The possibility to explain LSND signal by flavor-changing interactions, but not due to the FC induced oscillation we will consider here, has been discussed in Ref. [9] where such possibility was discarded and we do not discuss it here.) We also consider the possibility to test such kind of interactions by future neutrino oscillation experiments at neutrino factories.

From a phenomenological point of view FC interactions of neutrinos alone (regardless of the presence of the FD interactions) can induce flavor conversion when neutrinos travel through matter [1] even if neutrinos are massless. Moreover, the presence of FD interactions in addition to the FC one can induce a MSW-like resonant conversion of massless neutrinos in matter [2–4].

Several models which can induce such massless neutrino conversion in matter exist. The simplest example of such mechanism was first considered in Ref. [2] where it is shown its possible implication for supernova neutrinos rather than solar and/or atmospheric neutrinos. The most plausible candidate of model which could be relevant for both solar and atmospheric neutrinos is the minimal supersymmetric standard model without $R$ parity [10] as it was first considered in Ref. [4]. The other example (though less relevant for solar neutrinos) is the model based on the extended gauge structure $SU(3)_C \otimes SU(3)_L \otimes U(1)_N$ (331 models) [11].

Our approach here is completely phenomenological. We simply assume the existence of a tree-level process $\nu_\alpha + f \rightarrow \nu_\beta + f$ with an amplitude proportional to $g_{\alpha f} g_{\beta f} / 4 m^2$ ($\equiv \epsilon_{\alpha \beta} \sqrt{2} G_F$) where $\alpha$ and $\beta$ are flavor indices, $f$ stands for the interacting elementary fermion (charged lepton, $d$-like or $u$-like quark) and $g_{\alpha f}$ is the coupling involved in the vertex where a $\nu_\alpha$ interacts with $f$ through a scalar or vector boson of mass $m$. We try to fit the solar as well as atmospheric neutrino data treating $\epsilon_{\alpha \beta}$ as free parameters.

Secs. 2 and 3 are devoted for solar and atmospheric neutrinos, respectively. In sec. 4, we discuss the possibility to test this kind of interactions by future oscillation experiments at neutrino factories. In sec. 5, we give conclusions.

2. Solar neutrino

The disagreement between the expected solar neutrino event rates from theoretical predictions [12] and the observed ones is known as the solar neutrino problem [14]. While the most plausible solutions can be provided by the neutrino oscillation induced by mass and mixing [15,16] it has been proposed that massless neutrino conversion induced by non-standard interactions can also explain the observed deficit [17].

Here, for simplicity, we consider the system of two neutrino flavors, $\nu_e - \nu_x (x = \mu, \tau)$ which are massless or degenerate in mass. In the presence of FC and FD interactions in matter neutrino evolution equation is given as [18]:

$$i \frac{d}{dr} \begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix} = H \begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix},$$

(1)
where 
\[
H = \sqrt{2} G_F \begin{pmatrix} n_e(r) & en_f(r) \\ en_f(r) & e'n_f(r) \end{pmatrix}
\] (2)

where, \(\nu_a \equiv \nu_a(r)\), \(a=e, \mu, \tau\) are the probability amplitudes to find these neutrinos at a distance \(r\) from their creation position, \(\sqrt{2} G_F n_f(r)e \) is the forward scattering amplitude and \(\sqrt{2} G_F n_f(r)e' \) is the difference between the \(\nu_e-f\) and \(\nu_x-f\) elastic forward scattering amplitudes, with \(n_f(r)\) being the number density of the fermions which induce such processes.

A resonance conversion similar to MSW \[16\] can occur at some point where the condition
\[
e' n_f(r_{res}) = n_e(r_{res})
\]
as well as the corresponding adiabaticity condition are satisfied \[13\]. We note that such resonant flavor conversion can not occur for the case where the relevant fermion is electron \((f = e)\) alone, and hence we do not consider this case here (see, however, Ref. \[17\]).

In this mechanism the conversion probability does not depend on neutrino energy and hence one might think it is impossible to explain the solar neutrino data which indicate some energy dependent suppression of neutrino fluxes. However, due to the difference in neutrino production distributions in the solar core, it is possible to suppress differently the neutrinos from difference nuclear reactions in the solar core \[4,6,7\].

Figure 1. Allowed region obtained by rates only for d-quark (upper panel) and u-quark (lower panel) interactions. The open circle (solid square) indicates the best fit (local best fit) point. (Taken from Ref. \[7\].)

Figure 2. Same as in Fig. 1 but for the combined (rates+zenith+spectrum) analysis. The open circle (solid square and cross) indicates the best fit (local best fit) point. (Taken from Ref. \[7\].)

In Fig. 1 and 2 we present the region allowed by the total rates obtained by all the current solar neutrino experiments \[13\] assuming the non-standard interactions with d-quark and u-quark in matter, respectively. In Fig. 3 and 4 we present the region allowed by the combined data of the total rates, SK spectrum and SK zenith angle dependence. In Table I, we also present the values of \(\chi^2_{min}\) for each case. From these results we conclude that the quality of the fit is quite good.

Here let us briefly comment that \(\epsilon\) and \(\epsilon'\) parameters can be constrained model independently due to the absence of the lepton flavor-violating process or lepton universality violation as was discussed in Ref. \[13\]. It is found in Ref. \[7\] that
the magnitudes of $\epsilon$ and $\epsilon'$ parameters required to solve solar neutrino problem are still allowed for $\nu_e - \nu_\mu$ channel by the current experimental limits but not allowed for the $\nu_e - \nu_\tau$ one. This is because effects of such new physics (beyond the standard model) are much more constrained between the first and the second generations than that between the first and the third ones.

Table 1
\begin{tabular}{|c|c|c|c|}
\hline
Case & Rates & Zenith & Combined \\
\hline
$d$-quark & 2.44 & 1.11 & 29.1 \\
$u$-quark & 2.75 & 1.44 & 28.5 \\
\hline
\end{tabular}

More detailed discussions of our solar neutrino analysis can be found in Ref. [7].

3. Atmospheric neutrino

Atmospheric neutrino data obtained by several experiments [18], in particular the ones by the SuperKamiokande (SK) [19] can be quite well accounted for by $\nu_\mu \rightarrow \nu_\tau$ mass induced neutrino oscillation and for this reason this was considered to be a very compelling evidence for non-zero neutrino masses [20].

Although such mass induced oscillation seems to be the most plausible explanation (see, for e.g., [21] for a recent analysis), it was pointed out in Ref. [8] that there is another interesting possibility of explaining the SK sub-GeV (SG) and multi-GeV (MG) atmospheric neutrino data by means of massless neutrino conversion $\nu_\mu \rightarrow \nu_\tau$ induced by FC as well as FD interactions with matter in the Earth. In this case the evolution equation for the system of $\nu_\mu - \nu_\tau$ is described by the same form as in (1) but without the standard matter potential $\sqrt{2} G_F n_e(r)$ in the Hamiltonian matrix in eq. (1).

This proposal has been criticized in Ref. [22] where it was claimed that such FC induced neutrino oscillation solution would be ruled out if one takes into account the upward going passing muon ($P_\mu$) as well as the stopping muon ($S_\mu$) data.

We have reexamined in Ref. [23] the FC/FD solution following the prescriptions described in Ref. [24]. By the method of a $\chi^2$ analysis we compare the expected number of SG and MG events as well as $P_\mu$ and $S_\mu$ fluxes obtained by our computations to that of the SK data, corresponding to 52 kTy for the SG and MG samples, 923 days for $P_\mu$ and 902 days for $S_\mu$ muons [23].

In Figs. 3 and 4, we show the best fitted zenith angle distributions for (SG, MG) and (P_\mu, S_\mu), respectively. From these plots we can see the the fit to the data is quite poor for the passing muon sample (see thick curves in Fig. 4).

In order to compare quantitatively the quality of the fit of the FC/FD induced oscillation with the mass induced one, in Table 1 we show $\chi^2_{min}$ values and C.L. (in %) for both scenarios, for individual SK samples as well as for several combinations. From this table we notice that the fit is very poor if $P_\mu$ sample is combined with any other SK samples. If we exclude $P_\mu$ from the fit FC/FD solution can be considered as good as the mass induced one. While these results are based on somewhat old data, this conclusion does not seem to change even if we would have used the
most recent SuperKamiokande data [21].

Table 2

| Sample     | FC/FD   | Mass     | d.o.f. |
|------------|---------|----------|--------|
| SG         | 3.3(91) | 3.2(92)  | 8      |
| MG         | 7.8(45) | 7.6(47)  | 8      |
| $P_{\mu}$  | 12.9(12)| 13.0(11) | 8      |
| $S_{\mu}$  | 1.2(75) | 1.6(66)  | 3      |
| SG+MG      | 11.2(89)| 13.7(75)| 18     |
| $P_{\mu} + S_{\mu}$ | 41.2(0.01) | 17.1(82) | 13     |
| SG+MG+$P_{\mu}$ | 91.7(10$^{-6}$) | 32.8(24) | 28     |
| SG+MG+$S_{\mu}$ | 13.7(94) | 20.0(64) | 23     |
| All        | 109.3(10$^{-8}$) | 37.4(28) | 33     |
| All (P$_{\mu}$ 30 % $\nearrow$) | 54.9(1) | $\cdots$ | 33     |

Our results described above can be qualitatively understood if we note the fact that observed $P_{\mu}$ is indicating rather weak deficit $\sim 15$ % whereas all the other SK samples are indicating substantially stronger deficits $\sim 50$ % of upward going neutrino fluxes, which is difficult to reconcile by any energy independent conversion mechanism.

Moreover, as it was pointed out in Ref. [22], the observed value of the double ratio of the passing over stopping sample $R(s/p) \equiv (\text{stop/through})_{\text{data}}/(\text{stop/through})_{\text{MC}} = 0.63 \pm 0.1$ [23] is significantly smaller than unity which also disfavors FC/FD conversion scenario because it predicts $R(s/p)$ to be almost unity. It seems the only possibility to recover FC/FD induced oscillation as an acceptable solution is to assume a significantly larger (> 30 %) $P_{\mu}$ flux than currently expected value but without increasing the other lower energy neutrino fluxes.

We note that several features of our results and observations are qualitatively similar to the ones obtained in Ref. [27] but not quantitatively the same. Our results disfavor pure FC/FD oscillation solutions more strongly than Ref. [27] but weaker than that in the first paper in Ref. [22]. This is essentially because the correlations of errors assumed in our $\chi^2$ analysis are substantially stronger than the ones used in Ref. [27] though they are weaker than the ones considered in the first paper in Ref. [23].

We also note that in Ref. [28], magnitudes of $\epsilon$ and $\epsilon'$ parameters relevant for atmospheric neutrinos has been disfavored by the model independent analysis based on the negative results of the lepton flavor-violating decay or lepton universality violation searches. Finally, let us stress that the suggested FC/FD solution could be independently tested or excluded by the long-baseline neutrino oscillation experiments [29].

4. Neutrino Factory

Finally, let us briefly discuss the possibility to test this kind of new interactions at future neutrino oscillation experiments at neutrino factory which use intense neutrino beams from a muon storage ring [30].

We first consider the case where solar neutrino problem is solved by massless neutrino oscillation induced by FC as well as FD interactions. Since only $\nu_e \rightarrow \nu_\tau$ transitions are viable, an independent test would require a $\nu_\tau$ ($\bar{\nu}_\tau$) appearance experiment using an intense beam of $\nu_\tau$ ($\bar{\nu}_\tau$), which could be created at future neutrino factories [30].

Assuming a constant density and using the approximation that $n_\mu \approx n_u \approx 3n_e$ in the earth, and the approximation $n_e \sim 2$ mol/cc (which is valid close to the earth surface), we find that for the case of non-standard neutrino scattering off $d$-quark, $P_{\tau\tau} \equiv P(\nu_\tau \rightarrow \nu_\tau) \sim \text{few} \times 10^{-4}$ for the K2K distance ($L = 250$ km) and $P_{\tau\tau} \sim \text{few} \times 10^{-5}$ for the MINOS one ($L = 732$ km) for our best fit parameters. Similarly for $u$-quark, $P_{\tau\tau} \sim \text{few} \times 10^{-5}$ for the K2K distance and $P_{\tau\tau} \sim \text{few} \times 10^{-4}$ for the MINOS one for the best fit parameters. These estimates imply that it would be hard but not impossible, at least for the case of scattering off $d$-quarks, to obtain some signal of $\nu_e \rightarrow \nu_\tau$ conversions due to FC/FD interactions by using an intense $\nu_\tau$ beam which can be created by a muon storage ring [30]. Of course, it must be confirmed that the signal is not due to the mass induced oscillation by studying for e.g. the energy dependence of the conversion probability.

For atmospheric neutrinos, as we have discussed in sec. 3, it seems unlikely that FC/FD induced oscillation is the dominant cause of the deficit since the fit is quite poor. However, to some extent FC/FD interactions can induce some subdominant effect in the usual mass induced ones which would not lead to any contradiction with the observed data. Assuming that atmospheric neutrino data is mainly explained by the mass induced oscillation one can test the presence of such non-standard interactions by the future oscillation experiment at neutrino factories [31].

It can be shown [31] that FC/FD interactions can induce some “fake” CP violating effect in matter even if the CP violating phase is absent. Let use define $\Delta P(\nu_\mu \rightarrow \nu_\tau)$ as $\Delta P(\nu_\mu \rightarrow \nu_\tau) \equiv P(\nu_\mu \rightarrow \nu_\tau) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau)$ where $\Delta P$ is in gen-
Figure 5. $\Delta P(\nu_\mu \rightarrow \nu_\tau) \equiv P(\nu_\mu \rightarrow \nu_\tau) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau)$ is plotted for various different neutrino energies and values of $\epsilon$ (we set $\epsilon' = 0$) as a function of distance from the source. Here, FC interaction with $d$ (or $u$) quarks is assumed with the approximation $n_d = n_u = 3n_e$ with the constant electron number density $n_e = 2$ mol/cc. Here, also non-zero neutrino masses and mixing angles are assumed only for $\nu_\mu$ and $\nu_\tau$ system with $\Delta m^2 = 3.5 \times 10^{-3} \text{ eV}^2$, and $\sin^2 2\theta = 1.0$ assuming oscillation solution to the atmospheric neutrino observation.

Several functions of mass-mixing parameters, neutrino energy, the distance of the neutrino source to the detector as well as FC/FD parameters ($\epsilon$ and $\epsilon'$) we are assuming. We can say that if $\Delta P(\nu_\mu \rightarrow \nu_\tau)$ is larger than the maximally expected value from the pure mass-induced oscillation with CP violating phase, this could be an indication of such FC/FD interactions or the presence of 4 (or more) neutrino mixing with sterile neutrino(s).

Based on this idea we have computed $\Delta P$ as a function of the distance of the source for various values of FC interaction parameter as well as neutrino energy. In Figs. 5 and 6 we plot our results for the case with pure 2 generation and 3 generation, respectively. From Fig. 5 we can see that even for 2 generation, $\Delta P$ can be non-zero and can be relatively large for $L \gtrsim$ few 1000 km even for $\epsilon$ smaller than 1%. If $\nu_\mu$ is mixed only with $\nu_\tau$, $\Delta P \neq 0$ can be an indication of the presence of FC/FD interactions.

If there are mixing in 3 generation and CP violating phase things are more complicated since $\Delta P$ could be different from zero either due to the standard matter effect or due to the CP violating phase or the combinations of both effects and we need to see if such effect, especially the standard matter effect (since the effect of CP phase is expected to be small), is small enough in order to constrain FC/FD interactions.

In deed, we can see from Fig. 6 that for higher energy, the standard matter effect as well as the CP violating effect from pure mass induced oscillation are suppressed compared with the case of lower energy. Therefore, at such higher energy, the FC/FD effects are enhanced with respect the the standard matter and/or CP violating effect and $\Delta P \neq 0$ can be an indication of the presence of FC/FD interactions, or the absence of such effect can constrain these interactions. More detailed discussions will be presented in Ref. [31].

5. Conclusions

Although the mass induced oscillation is the most plausible explanations for the solar as well as atmospheric neutrino observations, it is interesting to consider some alternative solutions, which must eventually be excluded (or confirmed) by the experiments. We have studied if neutrino oscillations induced by FC as well as FD interactions can be such solutions. We found that while it is unlikely that atmospheric neutrinos can be explained only by such interactions, solar neutrinos can be well accounted for by the massless neutrino oscillations induced by such non-standard interactions. We have also discussed
that future neutrino oscillation experiments can
test such kind of non-standard interactions.

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