Updated solution to the solar neutrino problem based on non-standard neutrino interactions

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We present an updated version of the solution to the solar neutrino problem based on non-standard flavor changing neutrino interactions (FCNI) and non-universal flavor diagonal neutrino interactions (FDNI). We find a good fit not only to the total rates measured by all solar neutrino experiments but also to the day-night and seasonal variations of the event rate, as well as the recoil electron energy spectrum measured by the SuperKamiokande collaboration.

In this paper we update the recent analysis [1] of the solution to the solar neutrino problem based on non-standard neutrino interactions including the most recent available experimental data from Homestake [2], GALLEX [3], SAGE [4] and SuperKamiokande [5]. We assume that the mechanism first discussed by Wolfenstein [6], who observed that non-standard neutrino interactions (NSNI) with matter can also generate neutrino oscillations, can be relevant to solar neutrinos interacting with the dense solar matter along their path from the core of the sun to its surface [7–13]. We consider massless neutrinos which resonantly enhanced conversion can occur due to an interplay between the standard electroweak neutrino interactions and non-universal flavor diagonal neutrino interactions (FDNI) with matter [7,14]. For the solar input we take the solar neutrino fluxes and their uncertainties as predicted in the standard solar model by Bahcall and Pinsonneault (hereafter BP98 SSM) [15].

We assume that the existence of FCNI and FDNI will generate a time evolution matrix for massless neutrinos that interact with matter via the standard weak interactions and the non-standard interactions[7,8]:

$$U(\epsilon_{\nu_\ell},{\epsilon'}_{\nu_\ell}) = \sqrt{2}G_F \begin{pmatrix} n_e(r) & \epsilon^f_{\nu_\ell} n_f(r) \\ \epsilon^f_{\nu_\ell} n_f(r) & {\epsilon'}^f_{\nu_\ell} n_f(r) \end{pmatrix}, \quad (1)$$

where (here and below) $f = u, d, e$ and $\ell = \mu, \tau$ and $\alpha = e, \mu, \tau$ and

$$n_f(r) = \begin{cases} n_n(r) + 2n_p(r) & f = u \\ 2n_n(r) + n_p(r) & f = d \end{cases} \quad (2)$$

is the respective fermion number density at position r in terms of the proton [neutron] number density $n_p(r)$ [$n_n(r)$] and

$$\varepsilon = \epsilon^f_{\nu_\ell} \equiv \frac{G^f_{\nu_e\nu_\ell}}{G_F} \quad (3)$$

$$\varepsilon' = {\epsilon'}^f_{\nu_\ell} \equiv \frac{G^f_{\nu_\ell\nu_\ell} - G^f_{\nu_e\nu_e}}{G_F}, \quad (4)$$

describe, respectively, the relative strength of the FCNI and the new flavor diagonal, but non-universal interactions. $G^f_{\nu_\alpha\nu_\beta}$ $(\alpha,\beta = e,\mu,\tau)$ denotes the effective coupling of the four-fermion operator $\mathcal{O}^f_\nu \equiv (\overline{\nu_\alpha}\,\nu_\beta)(\bar f f)$ that gives rise to such interactions.

In order to obtain the values of ε and ε' parameters that can explain the experimental observations without modifying the standard solar model predictions we use the minimal χ^2 statistical treatment of the data following the analyses of Refs. [16,17]. In Fig. 1 the allowed regions in the parameter space of ϵ^d_ν and ${\epsilon'}^d_\nu$ for neutrino scattering off d-quarks are shown at 90, 95 and 99 % confidence level (CL). The best fit point of this analysis is found at

$$\epsilon^d_\nu = 3.2 \times 10^{-3} \qquad \text{and} \qquad {\epsilon'}^d_\nu = 0.61\,, \quad (5)$$

with $\chi^2_{min} = 1.67$ for $4-2=2$ degrees of freedom (DOF). Similar plots for scattering off u-quarks were obtained. The best fit point of this analysis is found at

$$\epsilon^u_\nu = 1.3\times 10^{-3} \qquad \text{and} \qquad {\epsilon'}^u_\nu = 0.43\,, \qquad (6)$$

with $\chi^2_{min} = 1.68$ for two DOF(See Fig. 1).

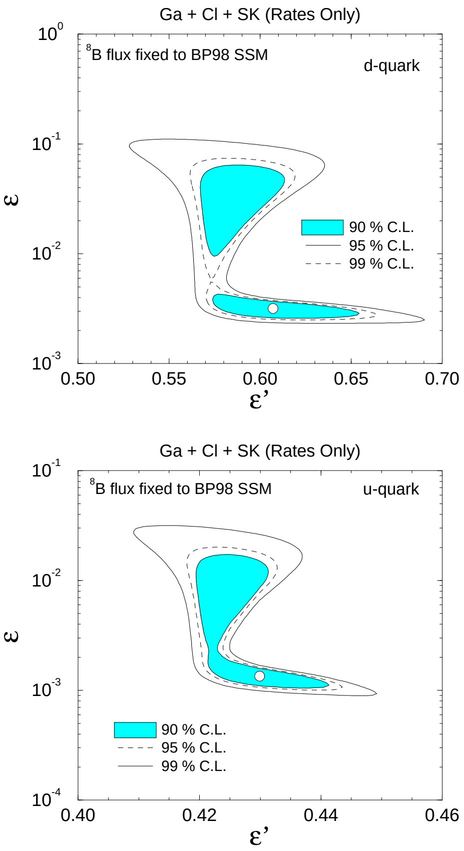

Figure 1. Region of ε and ε' which can explain the total rates measured by the four solar neutrino experiments considered.

Our final result is the fit derived from the combined analysis of all presently available solar neutrino data. In Fig. 2 we show the allowed regions for $(\varepsilon, \varepsilon')$ using both the results from the total rates from the Chlorine, GALLEX, SAGE and SuperKamiokande solar neutrino experiments together with the 6 bins from the SuperKamiokande zenith angle data discussed previously. Although adding the spectral information to our analysis does not change the shape of allowed regions nor the best fit points, it is included in order to determine the quality of the global fit.

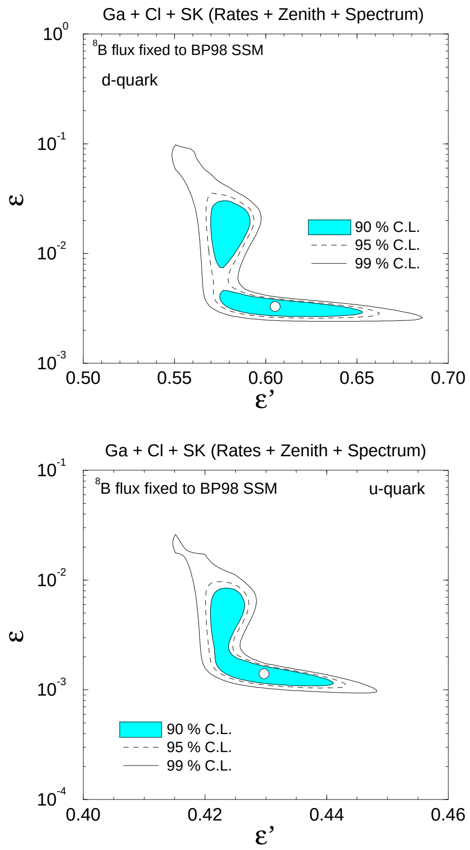

Figure 2. Region of ε and ε' which can explain the total rates measured by the four solar neutrino experiments considering the zenith angle dependence measured by SuperKamiokande.

For neutrino scattering off d-quarks the best fit for the combined data is obtained for

$$\epsilon^d_\nu = 0.0033 \qquad \text{and} \qquad {\epsilon'}^d_\nu = 0.60 \qquad (7)$$

with $\chi^2_{min} = 19.6$ for $28-4=24$ DOF. For neutrino scattering off u-quarks the best fit for the combined data is obtained for

$$\epsilon_\nu^u = 0.0014 \qquad \text{and} \qquad \epsilon'^u_\nu = 0.43 \tag{8}$$

with $\chi^2_{min} = 19.65$ for $28 - 4 = 24$ DOF (see Fig. 2).

According to our χ^2 analysis NSNI can provide a good fit to the solar neutrino data provided that there are rather large non-universal FDNI (of order $0.5\,G_F$) and small FCNI (of order $10^{-2} - 10^{-3}\,G_F$). The fit to the observed total rate, day-night asymmetry, seasonal variation and spectrum distortion of the recoil electron spectrum is comparable in quality to the one for standard neutrino oscillations.

Even though we consider the conventional oscillation mechanisms as the most plausible solutions to the solar neutrino problem, it is important to realize that in general New Physics in the neutrino sector include neutrino masses and mixing, as well as new neutrino interactions. While it is difficult to explain the atmospheric neutrino problem [18] and the LSND anomalies [19] by NSNI [20,21], we have shown in this paper that a solution of the solar neutrino problem in terms of NSNI is still viable. The ultimate goal is of course a direct experimental test of this solution. The upcoming solar neutrino experiments will provide a lot of new information which hopefully will reveal the true nature of the solar neutrino problem.

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