Massless "just-so" solution to the solar neutrino problem

M. M. Guzzo,[1] H. Nunokawa,[1] P. C. de Holanda,[1] and O. L. G. Peres[1,2]
[1]*Instituto de Física Gleb Wataghin, Universidade Estadual de Campinas, UNICAMP 13083-970 Campinas SP, Brazil*
[2]*The Abdus Salam International Center for Theoretical Physics, I-34100 Trieste, Italy*
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We study the effect of the nonresonant, vacuum oscillationlike neutrino flavor conversion induced by nonstandard flavor changing and nonuniversal flavor diagonal neutrino interactions with electrons in the Sun. We have found an acceptable fit for the combined analysis for the solar experiments total rates, the Super-Kamiokande energy spectrum and zenith angle dependence. Phenomenological constraints on nonstandard flavor changing and nonuniversal flavor diagonal neutrino interactions are considered.

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Nonstandard neutrino interactions with matter can generate neutrino flavor oscillations. This phenomenon was suggested by Wolfenstein in his seminal 1978 paper [1]. Applications of this idea to the solar neutrino problem were first suggested in 1991 [2,3] when it was observed that resonantly enhanced neutrino oscillations induced by nonstandard neutrino flavor changing (FC) as well as nonuniversal flavor diagonal (FD) neutrino interactions can explain the solar neutrino experimental data [4], which clearly indicates a solar neutrino flux smaller than what is predicted by the standard solar models [5].

Interestingly enough, such oscillations can be resonantly enhanced even if neutrinos are massless and no vacuum mixing angle exists [2], as a result of an interplay between the standard electroweak neutrino charged currents and nonuniversal nonstandard flavor diagonal neutrino interactions with matter. In fact, in this mechanism, resonance plays a crucial role in order to provide a viable solution to the solar neutrino problem [6–8].

It should be emphasized that if such nonstandard neutrino FC and FD interactions exist only with electrons, no resonant conversion can occur because the mixing angle in matter is constant, as we will see later, contrary to the case of the usual Mikheyev-Smirnov-Wolfenstein (MSW) effect [9], or the case with d-,u-quark FC and FD interactions. From this point of view, the oscillation induced by nonstandard neutrino interactions with electrons alone is similar to the vacuum oscillation mechanism despite the difference that it occurs only in matter, inside the Sun.

This nonresonant neutrino conversion was first mentioned as a solution to the solar neutrino problem in Ref. [6]. Nevertheless, so far, no quantitative analysis of this scenario has been presented.

In this Brief Report we investigate this possibility by performing a detailed fit to the most recent solar neutrino data. We conclude that nonresonant neutrino oscillations induced by nonstandard neutrino interactions can only provide an acceptable fit of the data when not only the total rates measured by Homestake, GALLEX/GNO, SAGE, and Super-Kamiokande (SK) [4] were taken into consideration but also the full SK recoil electron spectrum and the zenith angle dependence. We find also that this fit requires the new nonstandard neutrino interaction parameters to be close to their experimental upper bounds. Here we assume that neutrinos have nonstandard FC as well as FD interactions only with electrons which could be realized in some models such as the minimal supersymmetric standard model without R parity [10] or $SU(3)_C \otimes SU(3)_L \otimes U(1)_N$ (331) models [11].

In this work, we take a phenomenological approach by simply considering the following general evolution equation for massless neutrinos in matter [2],

$$i\frac{d}{dr}\begin{pmatrix} A_e(r) \\ A_l(r) \end{pmatrix} = \sqrt{2}G_F n_e(r)\begin{pmatrix} 1 & \epsilon_{el} \\ \epsilon_{el} & \epsilon'_{el} \end{pmatrix}\begin{pmatrix} A_e(r) \\ A_l(r) \end{pmatrix}, \qquad (1)$$

where $A_e(r)$ and $A_l(r)$ $(l=\mu,\tau)$ are, respectively, the probability amplitudes to detect a ν_e and ν_l at position r, and

$$\epsilon_{el} \equiv \frac{G_{\nu_e \nu_l}}{G_F} \quad \text{and} \quad \epsilon'_{el} \equiv \frac{G_{\nu_l \nu_l} - G_{\nu_e \nu_e}}{G_F}, \qquad (2)$$

describe, respectively, the relative strength of the FC and FD (but nonuniversal) interactions, where $G_{\nu_\alpha \nu_\beta}$ $(\alpha,\beta=e,\mu,\tau)$ denotes the effective coupling of the respective interaction. In this mechanism the mixing angle in matter θ_m does not depend on the electron density, and is simply given by

$$\sin^2 2\theta_m = \frac{4\epsilon^2}{(1-\epsilon')^2 + 4\epsilon^2}. \qquad (3)$$

We see that no MSW-like resonance can occur because the mixing angle in matter is constant and does not change along the neutrino trajectory (however, see Ref. [12]).

Let us introduce the two variables r and ϕ which define the production point of neutrinos in the Sun, as shown in Fig. 1. Then, for given values of (ϵ,ϵ') and a given production point in the Sun defined by r and ϕ, the survival probability of electron neutrinos at the solar surface can be written as [6]

$$P(\nu_e \to \nu_e; r,\phi) = 1 - \sin^2 2\theta_m \sin^2\frac{\Psi(r,\phi)}{2}, \qquad (4)$$

where

$$\Psi(r,\phi) \equiv \sqrt{4\epsilon^2 + (1-\epsilon')^2}\sqrt{2}G_F \int_0^{x_{max}} N_e(r,\phi,x)dx, \qquad (5)$$

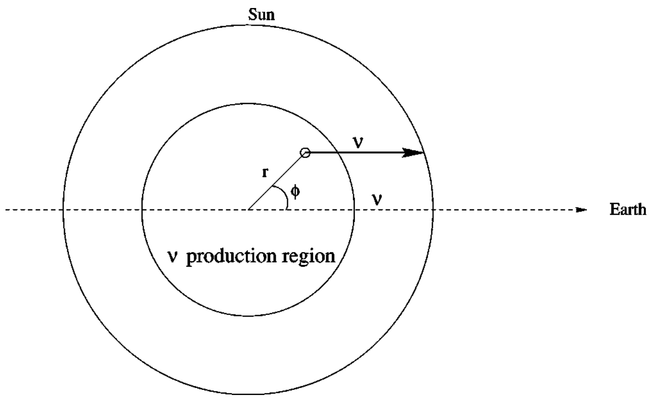

FIG. 1. Definitions of the variables r and ϕ. (The size of the neutrino production region was enlarged just for the purpose of illustration.)

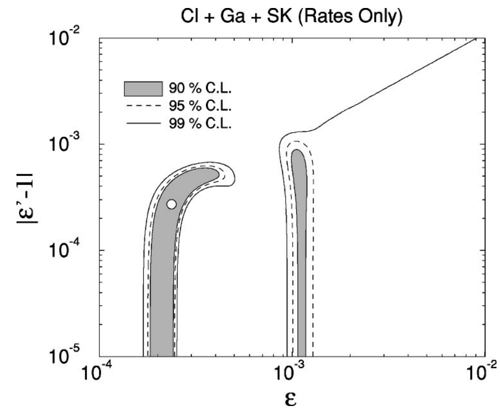

FIG. 2. Allowed parameter region. Region allowed by the total rates. The best fit is obtained when $|\epsilon|=2.4\times10^{-4}$ and $|\epsilon'-1|=2.7\times10^{-4}$, with $\chi^2_{min}=7.5$ for 2 d.o.f.

where $N_e(r,\phi,x)$ is the electron density profile along the neutrino trajectory which starts at the creation point (r,ϕ) corresponding to $x=0$, and ends at the solar surface corresponding to $x=x_{max}$. Note that there is no energy dependence in the probability.

From Eq. (4) we can estimate the oscillation length as

$$L_{osc}\equiv\frac{2\pi}{\sqrt{2}G_FN_e\sqrt{(1-\epsilon')^2+4\epsilon^2}}$$

$$\simeq\frac{2.4\times10^2}{\sqrt{(1-\epsilon')^2+4\epsilon^2}}\left[\frac{65\ \text{mol/cc}}{N_e}\right]\quad\text{km},\qquad(6)$$

where we take $N_e=N_e(R\simeq0.1R_\odot)\simeq65$ mol/cc as a reference value. From Eq. (6) we see that if either $|1-\epsilon'|$ or $|\epsilon|$ is of the order of 0.01, the oscillation length is typically less than a few percent of the solar radius in the neutrino production region. This implies that for such values of ϵ and ϵ' there are many oscillations before neutrinos reach the solar surface, and that the final survival probability which is averaged over the neutrino production point will be

$$\langle P(\nu_e\to\nu_e)\rangle\simeq1-\frac{1}{2}\sin^2 2\theta_m\qquad(7)$$

for any values of r and ϕ and therefore for any sources of neutrinos [6]. Therefore, such a rapid oscillation cannot fit the solar neutrino data well.

As pointed out in Ref. [6], an interesting possibility remains if both $|1-\epsilon'|$ and $|\epsilon|$ are smaller than ~0.01. For such ϵ' and ϵ, if $\Psi\sim(2n+1)\pi$ with small n, neutrinos produced as ν_e can be almost ν_x $(x=\mu,\tau)$ at the solar surface. On the other hand, if $\Psi\sim2n\pi$, ν_e remains as ν_e at the solar surface.

Since neutrinos from different nuclear reaction origins have different production distributions, there is a possibility that neutrinos from different reaction origins could have different oscillation probabilities. In principle, this could occur if neutrinos oscillate only once or a few times before they reach the solar surface, similar to what happens in the case of the long-wavelength vacuum oscillation solution to the solar neutrino problem [13].

In order to settle this issue we have performed a detailed χ^2 analysis in the same way as we did in our previous work [8], using the latest standard solar model (SSM) of Bahcall, Basu, and Pinsonneault [5] (BBP98) as well the latest results of the current solar neutrino experiments coming from Homestake, GALLEX/GNO, SAGE, and SK [4]. In our analysis, we compute the solar neutrino rates assuming the probability given in Eq. (4), with neutrino production distributions [5] properly taken into account.

In Fig. 2 we show the allowed parameter region determined by our χ^2 analysis. We have used only the total observed rates of solar neutrinos by four experiments. The best fit is obtained at $(|\epsilon|,|\epsilon'-1|)=(2.4,2.9)\times10^{-4}$ with $\chi^2_{min}=7.5$ for 4 (data) -2 (free parameters) $=2$ d.o.f. which corresponds to 2.4% C.L., indicating a poor fit. This is because the integrations of the survival probability over the variables r and ϕ tend to kill the "just-so" suppressions of the neutrino fluxes, and the final averaged probabilities from different sources end up with rather similar values to each other. We have also performed a χ^2 analysis allowing ^8B flux to vary freely but we do not find any significant change of the fit.

The whole situation significantly improves when we include the energy spectrum and zenith angle dependence observed by SK in our χ^2 analysis. This is because, consistent with the data, the mechanism we are analyzing in this paper does not distort the ^8B energy spectrum and, for the values obtained for the parameters ϵ and ϵ', the neutrino oscillation length in the Earth is much larger than the radius of the planet, inducing no significant zenith angle dependence.

The total combined χ^2_{min} can be computed by simply adding two constant contributions from the spectrum and zenith angle without affecting the allowed parameter region presented in Fig. 2. In this case, we have obtained $\chi^2_{min}=25.6$ for 24 d.o.f., which corresponds to 37.4% C.L. This makes this solution to the solar neutrino problem comparable, in the quality of its fit, to the standard solutions based on usual neutrino oscillations, 36–50% C.L., depending of the spe-

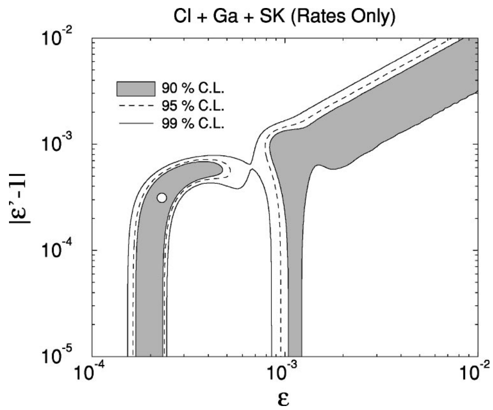

FIG. 3. Same as in Fig. 2, but the systematic error in the Homestake experiment was assumed to be three times larger. The best fit is obtained when $|\epsilon|=2.3\times10^{-4}$ and $|\epsilon'-1|=3.1\times10^{-4}$, with $\chi^2_{min}=3.3$ for 2 d.o.f.

cific solution of solar neutrino problem [14].

Here let us consider, as an interesting exercise, the case when the systematic error of the Homestake is assumed to be three times larger than it has been reported. In Fig. 3 we present the region allowed by the rates under this assumption. We have obtained $\chi^2_{min}=3.3$ for 2 d.o.f. (19.2% C.L.) for rates only. Including the energy spectrum data and zenith angle dependence reported by SK, we obtained $\chi^2_{min}=21.4$ for 24 d.o.f., corresponding to 61.5% C.L. This indicates a significant improvement over the case presented in Fig. 2. We note that this kind of exercise could be worthwhile to consider when taking into account the possibility of some unknown systematic effect of the Homestake experiment, as this has not been calibrated with a radioactive source.

Let us consider if the required magnitudes for the nonstandard parameters of the FC and nonuniversal FD neutrino interactions with electrons are compatible with constraints on lepton flavor violation. Our statistical analysis shows that although the FC parameter ϵ does not need to be very high ($\epsilon_{el}\approx10^{-3}$), the nonuniversal FD parameter ϵ'_{el} is found to be of the order of 1.

The value of the FC parameter ϵ is compatible with the available phenomenological tests to the flavor conservation law. In fact, the most stringent constraints on this parameter are due to the upper bounds on $\mu^-\to e^-e^+e^-$ and $\tau^-\to e^-e^+e^-$ [15]:

$$\mathrm{BR}(\mu^-\to e^-e^+e^-)<1.0\times10^{-12},$$

$$\mathrm{BR}(\tau^-\to e^-e^+e^-)<2.9\times10^{-6} \tag{8}$$

at 90% C.L. Normalizing the above bounds to the measured rates of the related lepton flavor conserving decays, $\mathrm{BR}(\mu^-\to e^-\overline{\nu}_e\nu_\mu)\approx100\%$ and $\mathrm{BR}(\tau^-\to e^-\overline{\nu}_e\nu_\tau)=0.178$ [15], we obtain [8]

$$\epsilon_{e\mu}\equiv G_{e\mu}/G_F<1.0\times10^{-6},$$

$$\epsilon_{e\tau}\equiv G_{e\tau}/G_F<4.2\times10^{-3}. \tag{9}$$

Note, furthermore, that these bounds on ϵ can be also relaxed by a factor of 5–6 due to the breaking of the $SU(2)_L$ symmetry [8]. Therefore, assuming that the neutrino transitions involve the first and third families, the required value of ϵ is compatible with the phenomenological limits.

The challenge to this solution is related to the required value of the parameter ϵ'_{el}, since universality experimental tests in the leptonic sector are very much stringent. In Ref. [16] constraints involving the second and third lepton families, i.e., interactions involving transitions of the type $\nu_\mu\leftrightarrow\nu_\tau$ were obtained. It was found that [16]

$$\epsilon'_{\mu\tau}<3.8\times10^{-3}. \tag{10}$$

Note, however, that the parameter relevant for our present analysis of the solution to the solar neutrino problem necessarily involves the first neutrino family (ν_e). Such a constraint can be obtained following the same steps as in Ref. [6]. No direct limit can be obtained for $\epsilon'_{e\tau}$. Nevertheless, since $\epsilon'_{e\tau}=\epsilon'_{e\mu}-\epsilon'_{\mu\tau}$, limits on this parameter are found considering the experimental constraints of Eq. (10) and limits on $\epsilon'_{e\mu}$.

Nonzero values for ϵ_{ee} ($\epsilon_{\mu\mu}$) give additional contributions to the $\nu_e e\to\nu_e e(\nu_\mu e\to\nu_\mu e)$ cross section, and can put constraints on ϵ_{ee} and $\epsilon_{\mu\mu}$ [6]. We use the most recent data about the $\nu_e e\to\nu_e e$ total cross section [17]. This cross section is a function of ϵ_{el} and $G^A_{\nu_e\nu_e}/G_F$ (the axial part of the effective coupling of the respective interaction). We obtained

$$-2.56<G_{\nu_e\nu_e}/G_F<0.63 \tag{11}$$

at 90% C.L. for arbitrary $G^A_{\nu_e\nu_e}/G_F$. This is not a trivial result. We are considering neutrinos propagating in an unpolarized medium. In this case, $\epsilon'_{e\tau}\sim1$ implies that the forward amplitudes of $\nu_e e$ and $\nu_\tau e$ scatterings are very close to each other. Nevertheless this does not necessarily mean that the cross sections $\sigma(\nu_e e)$ and $\sigma(\nu_\tau e)$ are identical. This is because the unpolarized medium averages out the axial contribution to the forward scattering [18], while both axial and vectorial couplings have to be taken into account in the calculation of the cross section. The standard model limit is also included in Eq. (11) for $G_{\nu_e\nu_e}/G_F=G^A_{\nu_e\nu_e}/G_F=0$.

To avoid large effects in $e^+e^-\to l^+l^-$ ($l=e,\mu,\tau$) scattering at the (CERN) e^+e^- colliders LEP-I and LEP-II energies, the only possible option is the case where the exchanged particle is a charged Higgs boson [15]. The Michel parameters for the decays of μ and τ can be used to test the hypothesis of a charged Higgs boson [19]. We found, by arguments similar to those of Ref. [19], that only Higgs triplets or doublets plus triplets can be allowed to have $\epsilon_{ee}\approx1$.

Taking the value quoted by Barger *et al.* [6], $-0.18<G_{\nu_\mu\nu_\mu}/G_F<0.14$, we obtained that $\epsilon'_{e\mu}$ is bounded to

$$-0.81<\epsilon'_{e\mu}<2.70, \tag{12}$$

at 90% C.L. Using the constraints from Eqs. (10) and (12), we finally obtain

$$-1.81 < \epsilon'_{e\tau} - 1 < 1.70 \tag{13}$$

at 90% C.L. From this constraint, we conclude that it is possible to satisfy the experimental constraints of FD couplings, and at the same time to be compatible with the allowed region of the solar neutrino analysis. Additional caution is necessary, because the same FD couplings that induce neutrino oscillations can also change the detection cross section $\sigma(\nu_e e \to \nu_e e)$ used for SK. We check that the absolute values of the elastic cross section inside the range given in Eq. (11) are compatible with the assumed theoretical errors of the solar neutrino fluxes used in the solar neutrino analysis. Also the shape of recoil electron in SK is not changed significantly due to the FD couplings.

Concluding, we have shown here for the first time a quantitative analysis of nonstandard flavor changing and nonuniversal flavor diagonal neutrino interactions with electrons as a possible candidate to solve the solar neutrino problem. Using the parameters $|\epsilon'_{el} - 1| \ll 1$ and $\epsilon_{el} \approx 10^{-4} - 10^{-3}$, we can obtain a fit for the combined analysis of the solar experiments total rates, the SK energy spectrum, and the SK zenith angle dependence, comparable in quality to the most accepted solution to the solar neutrino anomaly based on usual neutrino oscillations. We conclude that constraints on flavor violation and nonconservation of universality still allow us a small $\epsilon_{e\tau}$ and a large value for $\epsilon'_{e\tau}$, which are compatible with the preferred values of our solar neutrino analysis. In this solution, no spectrum distortion, no significant zenith angle dependence, and no seasonal effects are expected. Also, only negative results are expected in long-baseline experiments due to the very large oscillation length.

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