

New Constraints on Neutrino Oscillations in Vacuum as a Possible Solution of the Solar Neutrino Problem

P. I. Krastev*

*Institute of Field Physics, Department of Physics and Astronomy, The University of North Carolina at Chapel Hill,
CB-3255, Phillips Hall, Chapel Hill, North Carolina 27599-3255*

S. T. Petcov*

*Scuola Internazionale Superiore di Studi Avanzati, and Istituto Nazionale di Fizica Nucleare, Sezione di Trieste,
Via Beirut 2-4, I-34013 Trieste, Italy
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Two-neutrino oscillations in vacuum are studied as a possible solution of the solar neutrino problem. New constraints on the parameter $\sin^2 2\theta$, characterizing the mixing of the electron neutrino with another active or sterile neutrino, as well as on the mass-squared difference Δm^2 of their massive neutrino components, are derived using the latest results from the four solar neutrino experiments. Oscillations into a sterile neutrino are ruled out at 98% C.L. by the observed mean event rates even if one includes the uncertainties of the standard solar model predictions in the analysis.

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Neutrino oscillations in vacuum [1,2] have been discussed in connection with the solar neutrino experiments [3] and as a possible solution of the solar neutrino problem [4] for about 26 years [5]. In this scenario it is assumed that the state vector of the electron neutrino produced in the center of the Sun is a coherent superposition of the state vectors of neutrinos having definite but different masses. The flavor content of the neutrino state vector changes periodically between the Sun and the Earth due to the different time evolution of the vector's massive neutrino components. The neutrinos that are being detected in the solar neutrino detectors on Earth are thus in states representing, in general, certain superpositions of the states of ν_e , ν_μ , ν_τ , and ν_s , the latter being sterile neutrino. As the muon, tau, and sterile neutrinos interact more weakly with matter than with electron neutrinos, the measured signals should be depleted with respect to the expected ones. This could explain the solar neutrino problem.

In order to make specific predictions for the signals in the solar neutrino detectors one should (i) average over the neutrino production region in the Sun, (ii) take into account the changing distance between the Earth and the Sun [6], and (iii) integrate over the neutrino energy spectrum [7]. Qualitatively, the required depletion of the solar ν_e flux can take place only if [5] the neutrino oscillation length in vacuum, L_ν , is of the order of the distance between the Earth and the Sun, L_{se} : for $L_\nu \gg L_{se}$ there will be no time for the oscillations to develop, and in the opposite case, $L_\nu \ll L_{se}$, the depletion is neutrino energy independent and can be at most $1/N_f$, where N_f is the number of weak eigenstate neutrinos taking part in the oscillations. Despite this "tuning" problem which has been addressed in several papers [8] and which is absent in the case of the Mikheyev-Smirnov-Wolfenstein (MSW) solution [9] of the solar neutrino problem, the vacuum oscillations provide an attractive explanation of

the solar neutrino observations which should be further tested experimentally.

Analyses of solar neutrino data in terms of two-neutrino oscillations in vacuum have been made previously by several groups [10–13]. It was found that a small region of values of the two parameters Δm^2 and $\sin^2 2\theta$ characterizing the oscillations, $\Delta m^2 \approx (0.55-1.1) \times 10^{-10} \text{ eV}^2$ and $\sin^2 2\theta \approx 0.75-1.0$ [12], is allowed by the data. After the studies [10–13] were completed new data have been accumulated and published by three of the four operating experiments.

In this Letter the results of a joint analysis of the available data (including the latest results) from all solar neutrino experiments are presented. The first one is the pioneer Cl-Ar experiment by Davis and his group [14]. Data from 84 runs of measurements performed between 1971 and 1991 are available from this experiment. The first and the last day of the data taking period for each individual run have been taken from the table published in [15]. The second experiment is the one conducted by the Kamiokande collaborations which recently published their latest average results [16]. Data from 13 separate "runs" taken between 1986 and 1990 are also available. Each "run" is 3 months long, only the last being slightly longer. The third experiment is the Ga-Ge experiment conducted by the SAGE collaboration at the Baksan Neutrino Laboratory. Only the last result [17] for the mean value of the ^{71}Ge production rate has been used by us. Finally, the fourth experiment is the Ga-Ge one conducted by the GALLEX collaboration, from which new data have become available recently [18]. Both the data from the 15 accomplished runs of GALLEX-I and the GALLEX-I+GALLEX-II result have been used in our study.

The data analysis has been performed in two different ways. First, we perform a χ^2 analysis of the mean values of the event rates in each of the four detectors. We com-

pare the event rates expected, assuming neutrino oscillations in vacuum take place between the Sun and the Earth, with the experimentally measured event rates. The expected event rates without oscillations as well as the spectra of the different components (pp , ${}^7\text{Be}$, ${}^8\text{Be}$, etc.) of the solar neutrino flux have been taken from [19]. For the ratios of measured to expected event rates in each solar neutrino detector the following mean values and their corresponding error bars have been used:

$$R_{\text{CI}} = 0.28 \pm 0.03, \quad (1)$$

$$R_{\text{SAGE}} = 0.53 \pm 0.19, \quad (2)$$

$$R_{\text{GALLEX}} = 0.62 \pm 0.15, \quad (3)$$

$$R_{\text{Kamioka}} = 0.51 \pm 0.07. \quad (4)$$

The errors in (1)–(4) are the added in quadrature statistical and systematic errors as separately estimated by each collaboration.

It has been argued [19–21] that the theoretical uncertainties of the standard solar model alone cannot account for the discrepancy between theoretical predictions and the experimental results. However, these uncertainties have to be taken into account in a conservative analysis of the data, as in some cases they are bigger than the experimental errors. We include in our analysis the theoretical uncertainties, as well as the correlations between the uncertainties in the predicted event rates in the different solar neutrino detectors, as described in [22] for an analogous MSW analysis. The uncertainties of the different solar neutrino fluxes and detection cross sections estimated in [19] have been used. We include an uncertainty of 2% for the low energy electron-neutrino scattering cross section which has not been measured with high enough precision at the neutrino energies of interest. Finally, we prefer to treat the SAGE and GALLEX results as independent measurements and do not use the corresponding weighted average result.

The probability for a ν_e to remain ν_e has been averaged over a period of 1 yr taking into account the ellipticity of the Earth orbit, as described in [12]. Both the change of the survival probability and the change of the total flux with the distance between the Sun and the Earth have been included in the calculation.

The comparison between expected and measured event rates in each detector has been made for a sufficiently large number of pairs Δm^2 and $\sin^2 2\theta$. For oscillations into active neutrinos, $\nu_e \leftrightarrow \nu_a$; ν_a being either ν_μ or ν_τ , the minimal χ^2 (χ_{\min}^2) is 3.72. With four experimental results (2 degrees of freedom) this means that as a solution of the solar neutrino problem the $\nu_e \leftrightarrow \nu_a$ oscillations are ruled out at 68% C.L., but are allowed at 90% C.L. Accepting the hypothesis that the $\nu_e \leftrightarrow \nu_a$ oscillations provide the solution of the solar neutrino problem, the 90% C.L. and 95% C.L. allowed regions of values of Δm^2 and $\sin^2 2\theta$ are shown in Fig. 1. The results depicted in Fig.

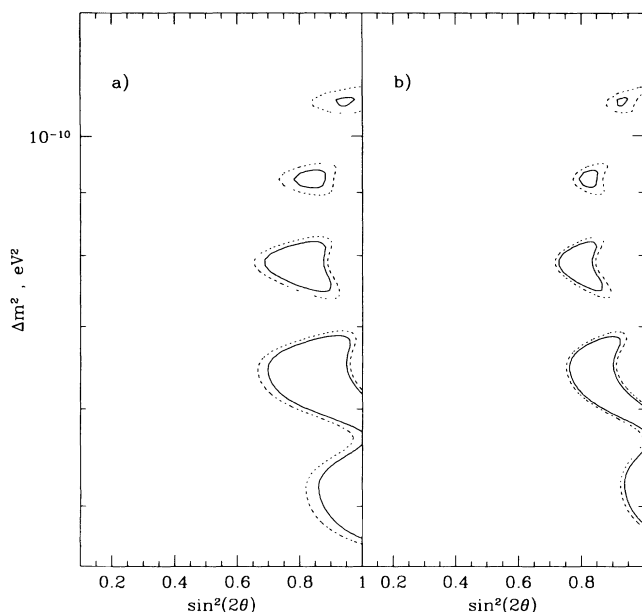


FIG. 1. Regions of values of the parameters Δm^2 and $\sin^2 2\theta$ allowed at 90% C.L. (solid line) and 95% C.L. (dashed line) in the case of vacuum $\nu_e \leftrightarrow \nu_{\mu(\tau)}$ oscillations of solar neutrinos. The mean event rates measured by the Homestake, Kamiokande, SAGE, and GALLEX collaborations, and the SSM predictions of Bahcall and Pinsonneault have been used in the χ^2 analysis. The results shown have been obtained (a) by including and (b) without including the theoretical uncertainties in the analysis.

1(a) have been obtained with the theoretical uncertainties taken into account as discussed earlier, while the results shown in Fig. 1(b) have been derived without including the theoretical uncertainties in the analysis.

For solar neutrino oscillations into a sterile neutrino, $\nu_e \leftrightarrow \nu_s$, the same analysis shows that $\chi_{\min}^2 = 8.68$. Thus, the $\nu_e \leftrightarrow \nu_s$ oscillations are ruled out at 98% C.L. as a solution of the solar neutrino problem. (This result depends slightly on the threshold used in the Kamiokande detector, which here was assumed to be 7.5 MeV.) In case one accepts combining the results of the two Ga-Ge detectors and having only three data points, the oscillations into sterile neutrinos are excluded at 99.5% C.L. If the combined result of GALLEX-I and GALLEX-II is used in the analysis, these oscillations are marginally allowed only at 99.5% C.L. (A similar result holds also for the MSW solution in terms of two-neutrino ν_e transitions into a sterile neutrino ν_s ; i.e., they are excluded at 90% C.L. by the latest solar neutrino data [23].)

Let us note that in none of the previous studies [10–13] were the constraints derived on Δm^2 and $\sin^2 2\theta$ following from the mean event rate data only.

A second approach to the analysis of the solar neutrino data has been proposed and described in detail in [12]. It is more suited for an analysis of data that is supposed to vary periodically with time. In such a case the time inter-

vals over which the detected signal is averaged should be chosen shorter than the period of the anticipated variations in order not to smear out the latter. Therefore, for neutrino oscillations in vacuum data averaged over shorter than 1 yr periods should be used and the comparison should be made on a "run by run" basis. This method allows one to rule out certain regions of parameters that are allowed by the analysis which makes use only of the mean values of the measured event rates. Although the individual runs have large error bars, the effect of a systematic discrepancy between predicted and observed event rates results in a higher χ^2 for certain values of Δm^2 and $\sin^2 2\theta$. On the other hand, the opposite effect might also occur. When introducing more degrees of freedom the overall χ^2 might increase slower than the value of the percentage point, χ_p , for the corresponding number of degrees of freedom. Therefore, values of the parameters ruled out by the analysis using mean values only might become allowed if one utilizes the "run by run" data.

For the analysis of the data from the solar neutrino experiments in terms of neutrino oscillations in vacuum, this approach was first pursued in [12] using only the results of the Homestake and Kamiokande-II experiments. Here the same procedure is applied adding the additional information about the measured ^{71}Ge production rate in each of the 15 individual runs completed by the GALLEX collaboration. In the case of vacuum neutrino oscillations the variations of the event rates in any solar neutrino detector resulting from the change of distance between the Sun and the Earth (apart from the standard geometrical one) are mostly due to ^7Be neutrinos. The latter have a very narrow spectrum [24] which can be approximated by a line. Therefore the averaging over the continuous spectrum of the other components of the solar neutrino flux leads to much less pronounced variations of the signals due to these neutrinos as compared with the signals due to ^7Be neutrinos [12,23] (see also [7]). In the Homestake detector the ^7Be neutrinos contribute only about 14% of the total expected signal, whereas in the Ga-Ge detectors they contribute $\sim 25\%$ of the signal. Therefore, if vacuum neutrino oscillations are the solution of the solar neutrino problem, the seasonal variations of the signal in Ga-Ge detectors should be somewhat stronger than in Cl-Ar ones. As the GALLEX data seem to be rather constant with time, one expects that certain regions of Δm^2 and $\sin^2 2\theta$ parameters can be ruled out. However, the results obtained within the more detailed approach cannot be directly compared with those presented in Fig. 1 as data for short time intervals from the Kamiokande experiment for the period since 1990 have not been published yet. In order to compare the effectiveness of the two approaches we give below also the constraints following from the mean values of the measured to expected event rates for the Homestake experiment, Eq. (1), the GALLEX-I, Eq. (3), and the Kamiokande-II experiment:

$$R_{\text{Kamioka}} = 0.46 \pm 0.08. \quad (5)$$

Note also that we have not included the theoretical uncertainties in the run by run analysis because of the formidable computational difficulties of inverting large correlation matrices.

Our results for the case of $\nu_e \leftrightarrow \nu_a$ oscillations are shown in Fig. 2. When only the mean values are taken into account one obtains $\chi^2_{\min} = 2.0$. For 3 data points (1 degree of freedom) this implies that the hypothesis of $\nu_e \leftrightarrow \nu_a$ oscillations being the solution of the solar neutrino problem cannot be ruled out at 90% C.L. The regions of $\sin^2 2\theta$ and Δm^2 allowed at 90% C.L. and 95% C.L. in this case are shown in Fig. 2(a).

With the run by run event rates used in the analysis we have $\chi^2_{\min} = 110$ for 112 degrees of freedom, which implies a good quality of the fit. The allowed regions of parameters Δm^2 and $\sin^2 2\theta$ at 90% C.L. and 95% C.L. are shown in Fig. 2(b). They are considerably narrower than those depicted in Fig. 2(a). The region around $\Delta m^2 = 1.1 \times 10^{-10} \text{ eV}^2$, which is allowed at 90% C.L. if one uses mean values in the analysis, disappears at 90% C.L., and a smaller allowed region appears at 95% C.L.

The same analysis has been performed for the hypothesis of solar neutrino oscillations into a sterile neutrino, $\nu_e \leftrightarrow \nu_s$. With only the mean values used in the analysis the minimal χ^2 is equal to 5.4. Consequently,

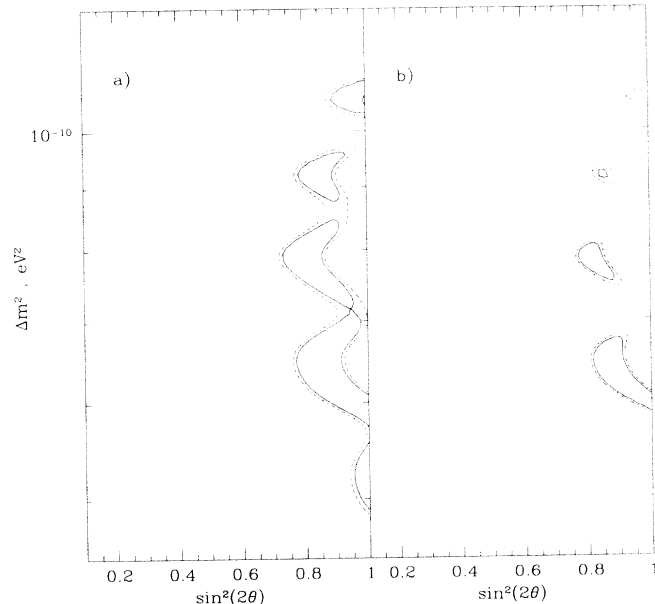


FIG. 2. Regions of values of the solar neutrino $\nu_e \leftrightarrow \nu_{\mu(\tau)}$ oscillation parameters Δm^2 and $\sin^2 2\theta$ allowed at 90% C.L. (solid line) and 95% C.L. (dashed line). (a) has been obtained by using only mean event rates [Eqs. (1), (3), and (5); see text]. The results of the extended χ^2 analysis based on 84 runs of the Homestake experiment, 15 runs of the GALLEX-I experiment, and 13 3-month time intervals of the Kamiokande-II experiment are given in (b).

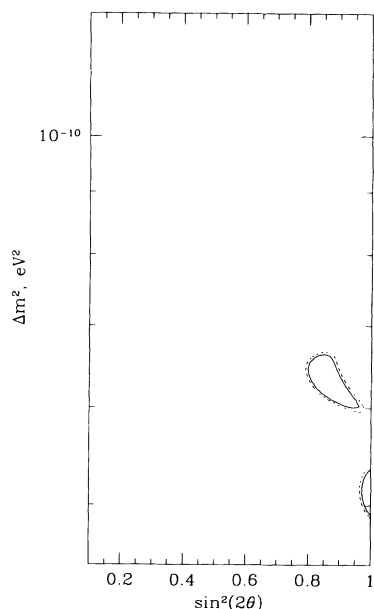


FIG. 3. The same as in Fig. 2(b) for solar neutrino oscillations into sterile neutrino in vacuum: $\nu_e \leftrightarrow \nu_s$.

the $\nu_e \leftrightarrow \nu_s$ oscillations give a poor fit of the mean event rate data (1), (3), and (5): They are marginally allowed only at 98% C.L. The situation is quite different when the variations are taken into account. In this case $\chi^2_{\min} = 116$, which means that the $\nu_e \leftrightarrow \nu_s$ oscillations are now allowed even at 68% C.L. The corresponding 90% C.L. and 95% C.L. allowed regions of Δm^2 and $\sin^2 2\theta$ are shown in Fig. 3. It should be noted that the latest GALLEX-I results not only do not further constrain the allowed values of the parameters Δm^2 and $\sin^2 2\theta$, but actually slightly relax the constraints obtained from the Homestake and Kamiokande-II data only. Thus we see that the mean event rate data are much more restrictive in the case of vacuum oscillations into sterile neutrino (to the point of practically excluding them as a possible solution of the solar neutrino problem) than the run by run data. The inverse is true for the $\nu_e \leftrightarrow \nu_{\mu, \tau}$ oscillations: The stronger restrictions on the parameters follow from the run by run results.

In conclusion, the solution of the solar neutrino problem in terms of two-neutrino oscillations in vacuum has been confronted with the latest data from all solar neutrino experiments. It has been shown that previously allowed regions of the parameters $\sin^2 2\theta$ and Δm^2 are ruled out by the data from individual runs of the Homestake and GALLEX experiments, and data from the Kamiokande-II detector, averaged over 3-month periods. The χ^2 analysis of the current mean event rates in the Homestake, Kamiokande, SAGE, and GALLEX detectors based on the Bahcall-Pinsonneault theoretical predictions ruled out two-neutrino ν_e oscillations into sterile states as a solution of the solar neutrino problem at 98% C.L., with the uncertainties in the theoretical predictions

included in the analysis.

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*Permanent address: Institute of Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, BG-1784 Sofia, Bulgaria.

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