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Solar neutrino oscillation: Recent aspects

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Abstract. The evidence of solar neutrino deficit can be interpreted as a signal of solar electron neutrinos conversion into different states. We present an updated analysis of the current solar neutrino phenomenology in the framework of flavor neutrino oscillations into active states, showing the zones of mass–mixing oscillation parameters compatible with all the data.

1 Introduction

The observation of solar neutrinos is the privileged tool to obtain direct information about the nuclear reactions powering the Sun. However, there is a strong evidence for a suppression of about a factor two of the solar neutrino flux [for a review on solar neutrino deficit, see Bahcall (1989)]. Although there is still room for an astrophysical explanation of this anomaly, the most plausible solution is to invoke a phenomenon of transition of the solar ν_e's in other states. Among other exotic possibilities, the more natural model for neutrino transitions are neutrino flavor oscillations mediated by a non–zero neutrino mass (Pontecorvo, 1967; Maki et al., 1962). Moreover, the interaction of the neutrinos with solar and earth matter can enhance the oscillations (Wolfenstein, 1978; Mikheyev and Smirnov, 1985, 1986).

In this note we analyze the recent solar ν phenomenology in the framework of two–generation neutrino oscillations. This paper is organized as follows: In Sec. 2 we briefly review the theory of solar neutrino oscillations. In Sec. 3 we show analyze the current solar neutrino data. In Sec. 4 we draw our conclusions.

2 Solar neutrino oscillations

If neutrinos are massive, flavor eigenstates ν_e, ν_μ, and ν_τ could not have a definite mass, but are related to three mass eigenstates ν_i ($i = 1, 2, 3$), with masses m_i, through a "mixing" matrix $\mathbf{U}$:

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i} \nu_i \, , \tag{1}$$

where $\alpha = e, \mu, \tau$. Although in principle solar neutrinos should be analyzed in a general 3ν framework, the 2ν approximation is sufficiently accurate (Gonzalez–Garcia et al., 2001; Fogli et. al., 2001a). In fact, solar neutrino are essentially described by the oscillations of the "quasi degenerate" doublet ν_1, ν_2 (with $m_1 \simeq m_2$), while the mixing with the "lone" state ν_3 ($m_3 > m_{1,2}$ or $m_3 < m_{1,2}$) must be very small ($U^2_{e3} < 0.1$) to fit recent data. For this reason, in the following, we limit our analysis to only two generations of neutrinos.

With only two neutrinos (that we conventionally call ν_e and ν_μ) the mixing matrix $\mathbf{U}$ can be parametrized in term of a single variable θ, called "mixing angle":

$$\mathbf{U} = \left[\begin{array}{cc} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{array} \right] . \tag{2}$$

Oscillation are thus described by the mixing angle θ and the difference of square masses $\Delta m^2 = m_2^2 - m_1^2$. Without loss of generality we can choose $\theta \in [0, \pi/2]$ and $\Delta m^2 \geq 0$. In absence of matter effect, the ν_e survival probability at distance L from the production point is given by:

$$P(\nu_e \to \nu_e, L) = 1 - \frac{1}{2}\sin^2 2\theta \left(1 - \cos\frac{\Delta m^2 L}{2E}\right) , \tag{3}$$

where E is the neutrino energy. (We have used the natural units $\hbar = c = 1$.)

When the neutrinos cross the matter, the ν_e component interacts with the electrons in the medium through neutral and charged current interactions, while the ν_μ (or ν_τ) component can interact with matter only through neutral current interactions. The net effect is a supplementary potential affecting the neutrino transition amplitude (Wolfenstein, 1978; Mikheyev and Smirnov, 1985, 1986). In particular, neutrino masses and mixing can assume different values in matter. Thus, the survival probability $P(\nu_e \to \nu_e)$ depends, in general, by the detailed profile of the electron density crossed by the neutrinos. For a nice review on vacuum and matter oscillations see Kuo and Pantaleone (1989).

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In the case of solar neutrinos, from quantum mechanical arguments we can derive the a general expression for probability that a ν_e produced in the interior of the Sun is detected as a ν_e on the Earth (Petcov and Rich, 1991; Lisi et al., 2001):

$$P(\nu_e \to \nu_e) = \frac{1}{2} + \left(\frac{1}{2} - P_c\right) \cos 2\theta \cos 2\theta_m^0 \\ - \sin 2\theta \cos 2\theta_m^0 \sqrt{P_c(1-P_c)} \cos \xi \,, \qquad (4)$$

where θ_m^0 is the mixing angle in matter in the production point, P_c is the "crossing probability" (i.e., the probability that a mass eigenstate in matter flips into the other) and:

$$\xi = \frac{\Delta m^2 L}{2E} + \delta \,, \qquad (5)$$

where L is the Earth–Sun distance and δ is a phase which depends on the solar electron density profile. Both the crossing probability P_c and the phase δ can be calculated through an accurate semianalytical approximation (Parke, 1986; Krastev and Petcov, 1988; Lisi et al., 2001). For $\Delta m^2 < 10^{-10}$ eV^2, $P_c \simeq \cos^2 \theta$ and $\theta_m^0 \simeq \pi/2$, so the vacuum oscillation probability (3) is recovered. This (vacuum) regime is called "Just So". Conversely, for $\Delta m^2 > 10^{-8}$ eV^2 the oscillating term in (4) is averaged away by many decoherence effects. In this regime, matter effects are dominant. In the intermediate range, $\Delta m^2 \in [10^{-10}, 10^{-8}]$ eV^2, both vacuum oscillations and matter effects are important. This so–called "Quasi Vacuum Oscillation" (QVO) regime have been studied recently by Friedland (2000) and Fogli et al. (2000a).

During nighttime, neutrinos cross the Earth before detection. The evolution inside the Earth can be computed by evolving analytically the MSW equations at any given nadir angle η, using the technique described in Lisi and Montanino (1997), which is based on a five-step biquadratic approximation of the Earth density profile from the Preliminary Reference Earth Model (PREM) (Dziewonski and Anderson, 1981) and on a first-order perturbative expansion of the neutrino evolution operator.

3 Solar neutrino data and analysis

Figure 1 shows the solar neutrino deficit as a discrepancy between data and expectations (total event rates) in the chlorine (Cl) Homestake experiment, Lande (2001)], gallium (Ga) [SAGE experiment, Gavrin (2001); GALLEX–GNO experiment, Bellotti (2001)], and SuperKamiokande (Suzuki, 2001). In each plane, the gray ellipses represent 99% C.L. contours for two degrees of freedom (i.e., $\Delta\chi^2 = 9.21$) for the experimental data (1 SNU= 10^{-36} neutrino captures per target atom and per second). The projection of an ellipse onto one of the axis gives approximately the $\pm 3\sigma$ range for the corresponding rate. White ellipses show the Standard Solar Model (SSM) theoretical expectation using the latest theoretical solar ν fluxes and uncertainties (Bahcall et al., 2000).[1] The calculation has been made taking into account the spectra for the relevant sources in the sun as well as the detectors characteristics (neutrino cross section, energy resolution, thresholds, etc.). For the technical details of the analysis and the statistical treatment of the data see Fogli et al. (1999) and references therein.

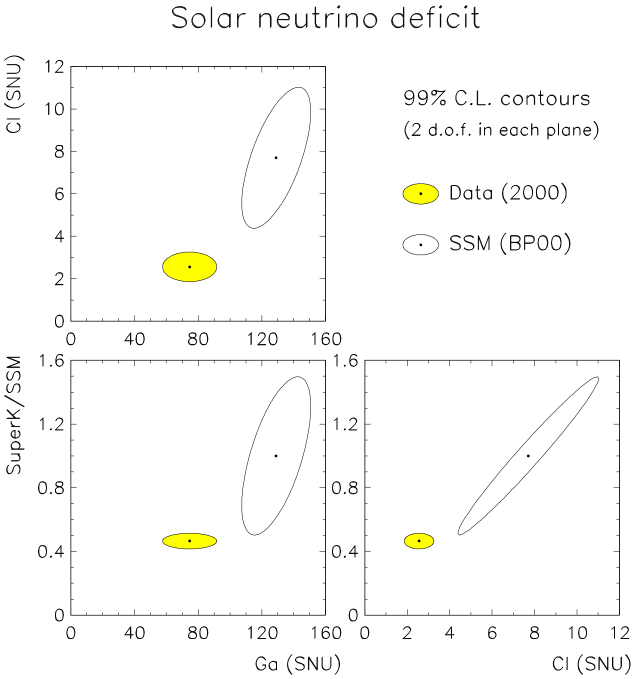

Fig. 1. The solar neutrino deficit. See the text for details.

Figure 2 shows the allowed zones at 90, 95, and 99% C.L. in the oscillation parameter space $(\Delta m^2, \tan^2 \theta)$ by the *total rate* information coming from the SuperKamiokande (SK), Homestake (Cl), SAGE, and GALLEX–GNO (Ga) experiments. The survival probability has been calculated as in Eq. (4) and integrated over the neutrino production zone for each neutrino source. One can notice three solutions at large mixing angle (LMA, LOW and "Just So" solutions) and one at small mixing angle (SMA solution). The best fit is (for total rates only) reached for the SMA solution. Figure 3 shows the experimental and the theoretical ellipses (as in Fig. 1) for case of the SMA solution. Notice the excellent agreement between data and theory.

Besides the measurement of the total neutrino rate, SuperKamiokande has provided information about the scattered electron energy spectrum (which is related to the original neutrino spectrum) during day and night time (Suzuki, 2001). The spectral information is crucial for a solar model independent confirmation that oscillations (or, at least, energy–dependent transitions) are at work. In fact, the survival probability in Eq. (4) is energy–dependent in general. Moreover, differences in the spectrum between daytime and nighttime would be a signal of neutrino conversion into the Earth matter. Unfortunately, there is no evidence for spectral distorsion or time dependence of the signal. Figure 4 shows the zone correspondingly excluded by the SK day and night spectra.

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[1] Tables and other information about the SSM can be found at the J.N. Bahcall homepage, http://www.sns.ias.edu/~jnb.

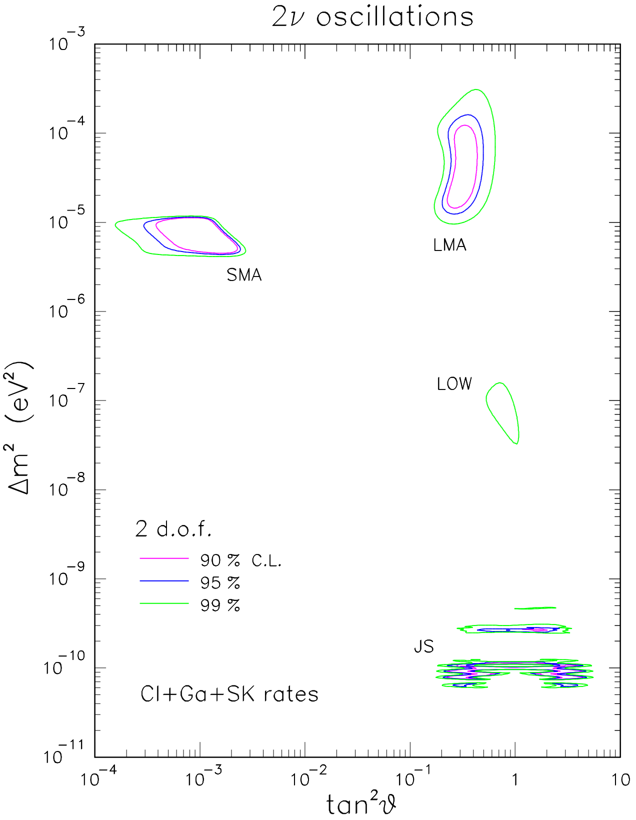

Fig. 2. Solutions to the solar neutrino problem at 90, 95 and 99% C.L. of Cl+Ga+SK rates. LMA = Large Mixing Angle; SMA = Small Mixing Angle; JS = Just So (vacuum) solution.

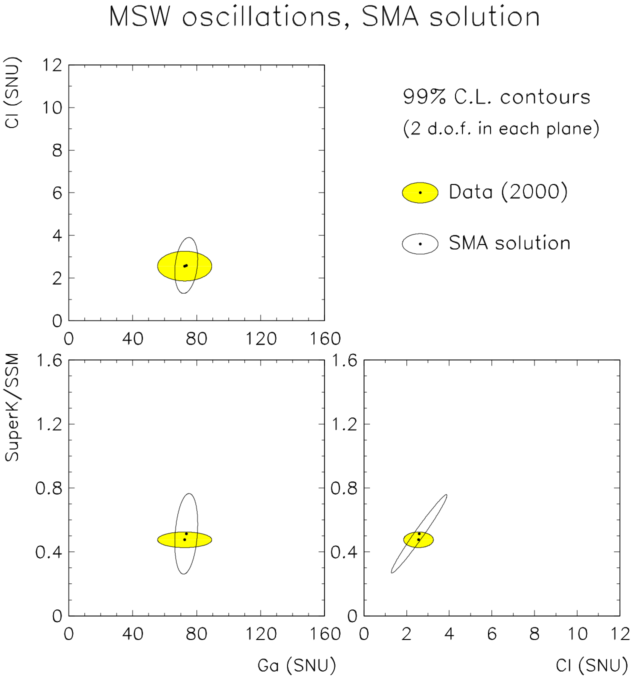

Fig. 3. The SMA solution at best fit (total rates only). Note the excellent agreement between theory and observations.

Combining the data used in Fig. 2 and Fig. 4, we obtain the allowed zones for all the current solar neutrino phenomenology in Figure 5. The best fit is now reached for the LMA solution ($\chi^2 = 35.1$, 36 d.o.f. for $\Delta m^2 = 4.7 \times 10^{-5}$ eV^2 and $\tan^2\theta = 0.36$). The SMA solution is now disfavoured but not yet excluded by the data ($\chi^2 = 40.3$, not a bad fit for 36 d.o.f.). Conversely, the JS solution is now excluded, since in this case a strong distorsion of the recoil spectrum would be expected. As a result of a compromise between the rate and the spectrum data, a new solution appear roughly in the range $\Delta m^2 \in [10^{-9}, 10^{-7}]$ eV^2, corresponding to the QVO regime described in Sec. 2.

4 Discussion and conclusion

In this paper we have analized the current solar neutrino phenomenology in the framework of the flavor oscillation hypothesis. We have found the zones of the mass–mixing parameters compatible with both the measurement of the total rates and the day and night electron energy spectrum information from SuperKamiokande. The results of this combined analysis is shown in Fig. 5. In particular, the solutions at large angle are favored by all the data, while the small mixing angle solution (SMA) seems disfavored (although not excluded) by the non observation of a distorsion in the SK recoil spectrum.

Unfortunately, at the moment there are no “smoking guns” in favor of oscillations, and an astrophysical solution to the solar neutrino problem cannot be ruled out definitely. A conclusive proof in favor of solar neutrino oscillations should come from new experiments. In particular, the Subdury Neutrino Observatory [SNO, McDonald (2001)] is now taking data. This experiment uses heavy water as target for neutrinos. The number of the neutral current (NC) dissociation ($\nu_\alpha + d \to \nu_\alpha + p + n$) events is a measure of the absolute neutrino flux while the number of charge current (CC) interaction ($\nu_e + d \to e^- + 2p$) is a measure of the ν_e flux. An anomalous CC/NC ratio would be a proof of neutrino conversion in active states. Moreover, the combined analysis of SK and SNO CC recoil spectrum could give information about the ν_μ, ν_τ component of the flux (Fogli et al., 2001b).

A second experiment, BOREXINO, is now in preparation (Ranucci, 2001). This experiment will measure the flux of neutrinos coming from the monoenergetic ^{7}Be source. Several tests have been proposed in order to discriminate among solutions, based on the study of day–night [see, for example, Fogli et al. (2000b)] and seasonal (Fogli et al., 2000c; De Gouvea et al., 2001) variations of the signal in SK, SNO, GNO, and BOREXINO. Finally, a very long baseline reactor experiment (∼ 200 km), KAMLAND, is now starting operations and will be able to (dis)prove directly the LMA solution (Barger et al., 2001).

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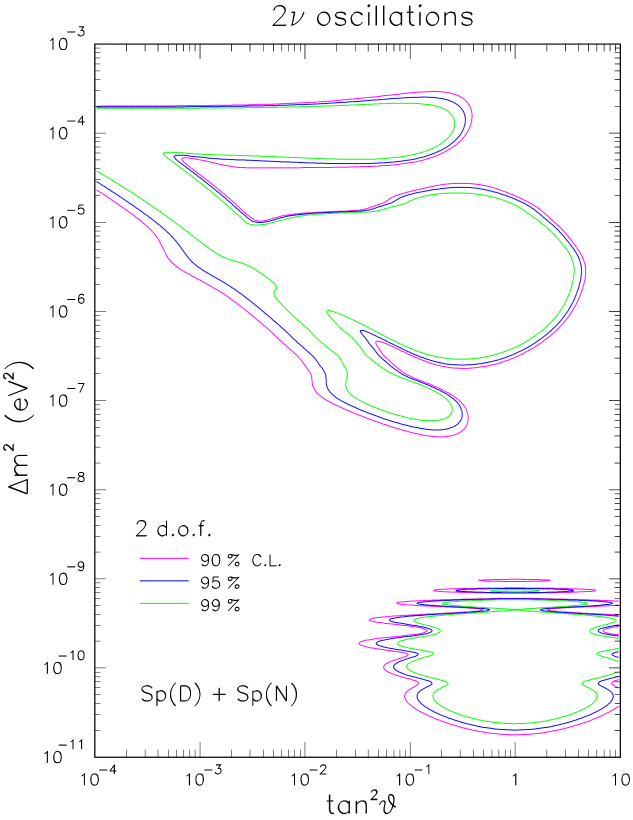

Fig. 4. The excluded zone by the SK day and night recoil spectra.

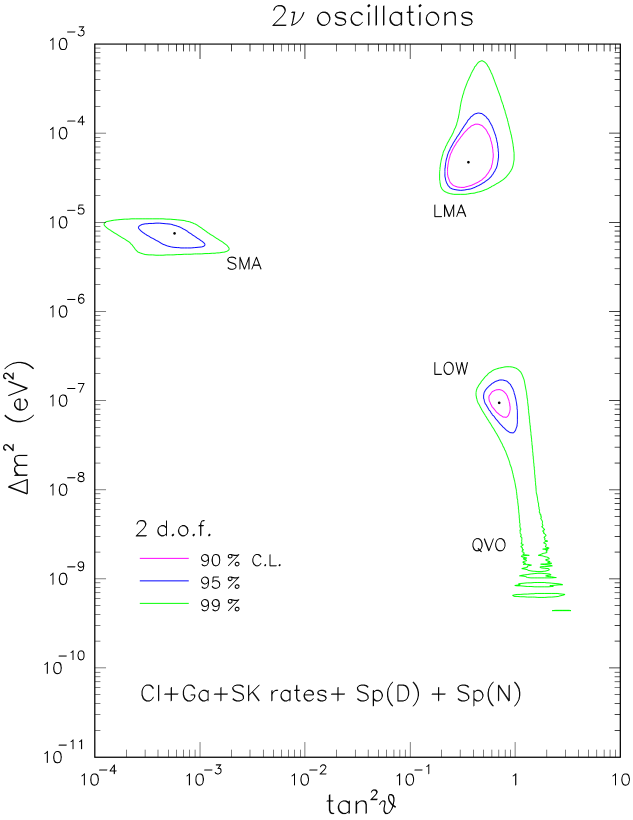

Fig. 5. Solutions to the solar neutrino problem at 90, 95 and 99% C.L. including all data. The points are the local best fits for each solution.

References

J.N. Bahcall, *Neutrino Astrophysics* (Cambridge University Press, Cambridge, England, 1989).

B. Pontecorvo, Zh. Eksp. Teor. Fiz. **53**, 1717 (1967) [Sov. Phys. JETP **26**, 984 (1968)].

Z. Maki, M. Nakagawa, and S. Sakata, Prog. Theor. Phys. **28**, 675 (1962).

L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978).

S.P. Mikheyev and A.Yu. Smirnov, Yad. Fiz. **42**, 1441 (1985) [Sov. J. Nucl. Phys. **42**, 913 (1985)].

S.P. Mikheyev and A.Yu. Smirnov, Nuovo Cim. C **9** (1986), 17.

M.C. Gonzalez–Garcia, M. Maltoni, C. Pena–Garay, J.W.F. Valle, Phys. Rev. D **63**, 033005 (2001).

G.L. Fogli, E. Lisi, A. Marrone, D. Montanino, and A. Palazzo, in the Proceedings of *Moriond 2001*, 36th Rencontres de Moriond on Electroweak Interactions and Unified Theories (Les Arcs, France, 2001), to appear; hep-ph/0104221 (2001a).

T.K. Kuo and J. Pantaleone, Rev. Mod. Phys. **61** 937 (1989).

S.T. Petcov and J. Rich, Phys. Lett. B **224**, 426 (1989).

E. Lisi, A. Marrone, D. Montanino, A. Palazzo, and S.T. Petcov, Phys. Rev. D **63**, 093002 (2001).

S.J. Parke, Phys. Rev. Lett. **57**, 1275 (1986).

P.I. Krastev and S.T. Petcov, Phys. Lett. B **207**, 64 (1988); *erratum*, **214**, 661 (1988).

A. Friedland, Phys. Rev. Lett. **85**, 936 (2000).

G.L. Fogli, E. Lisi, D. Montanino, and A. Palazzo, Phys. Rev. D **62**, 113004 (2000a).

E. Lisi and D. Montanino, Phys. Rev. D **56**, 1792 (1997).

A. M. Dziewonski and D. L. Anderson, Phys. Earth Planet. Inter. **25**, 297 (1981).

K. Lande, in the Proceedings of *Neutrino 2000*, 19th International Conference on Neutrino Physics and Astrophysics (Sudbury, Canada, 2000), Nucl. Phys. B (Proc. Suppl.) **91**, (2001), p. 50.

V. Gavrin, in the Proceedings of *Neutrino 2000*, Nucl. Phys. B (Proc. Suppl.) **91**, (2001), p. 36.

E. Bellotti, in the Proceedings of *Neutrino 2000*, Nucl. Phys. B (Proc. Suppl.) **91**, (2001), p. 44.

Y. Suzuki, in the Proceedings of *Neutrino 2000*, Nucl. Phys. B (Proc. Suppl.) **91**, (2001), p. 29.

J.N. Bahcall, M.H. Pinsonneault, and S. Basu, astro-ph/0010346 (2000).

G.L. Fogli, E. Lisi, D. Montanino, and A. Palazzo, Phys. Rev. D **62**, 013002 (2000).

A.B. McDonald, in the Proceedings of *Neutrino 2000*, Nucl. Phys. B (Proc. Suppl.) **91**, (2001), p. 21.

G.L. Fogli, E. Lisi, A. Palazzo, and F.L. Villante, Phys. Rev. D **63**, 113016 (2001b).

G. Ranucci, in the Proceedings of *Neutrino 2000*, Nucl. Phys. B (Proc. Suppl.) **91**, (2001), p. 58.

V. Barger, D. Marfatia, and B.P. Wood, Phys. Lett. B **498**, 53 (2001).

G.L. Fogli, E. Lisi, D. Montanino, and A. Palazzo, Phys. Rev. D **62**, 113003 (2000b).

G.L. Fogli, E. Lisi, D. Montanino, and A. Palazzo, Phys. Rev. D **61**, 073009 (2000c).

A. de Gouvea, A. Friedland, and H. Murayama, JHEP, 0103 (2001).