Global analysis of solar neutrinos

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Abstract. The recent data from SNO is analysed with the global data from the other solar neutrino experiments, first in a model independent way and then assuming two-flavor oscillations. Neutrino oscillations to active flavors can best explain the global data with the LMA solution emerging as the best-fit. However transitions to "mixed" states with upto 30% sterile mixture are still allowed at 1σ.

Introduction: For over four decades solar neutrino experiments at Homestake (Cl), Sage, Gallex-GNO (Ga) [1] and Super-Kamiokande (SK) [2] have observed a deficit of the observed solar neutrino flux from that predicted by the Standard Solar Model (SSM) [3]. The Sudbury Neutrino Observatory (SNO) has provided the direct evidence for oscillations of solar ν_e to another non-electron type active neutrino by simultaneously observing the charged current (CC) and neutral current (NC) interactions of neutrinos on deuteron [4, 5]. This single experiment gives evidence for the presence of another active neutrino flavor in the solar neutrino beam at the 5.3σ level. When combined with the electron scattering (ES) data from SK, oscillations to active neutrinos is confirmed at the 5.5σ level.

Model Independent Analysis: We first use just the data on total rates from SK and SNO and obtain model independent bounds on the total ^8B flux normalization factor f_B and the solar neutrino suppression rate P_{ee} [6, 7]. Since both SK and SNO are consistent with no spectral distortion we use it as an emperical justification to assume that P_{ee} is effectively energy independent and express the SK, CC and NC rates as

$$R_{SK}^{el} = f_B P_{ee} + f_B r P_{ea}, \quad R_{SNO}^{CC} = f_B P_{ee}, \quad R_{SNO}^{NC} = f_B(P_{ee} + P_{ea}) \qquad (1)$$

where P_{ea} is the transition probability to active neutrino and $r = \sigma_{\nu_\mu,\tau}/\sigma_{\nu_e} \simeq 0.157$ is the ratio of ν_μ to ν_e scattering cross-section folded with the ^8B neutrino spectrum and averaged over energy.

If we assume that the solar neutrinos are completely transformed to active neutrinos then $P_{ea} = 1 - P_{ee}$. We use eq.(1) to show in figure 1 the 1σ and 2σ contours in the $f_B - P_{ee}$ plane from the combinations SK + CC (the outer lines) and SK + CC + NC (the inner lines). The best-fit f_B comes at 1, consistent with the SSM. The inclusion of the NC data narrows down the ranges of f_B and P_{ee}. The error in f_B after inclusion of the NC data is almost half the size of the corresponding error from SSM.

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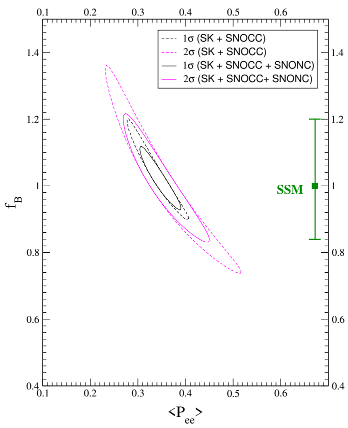

Figure 1: The 1σ and 2σ contours of solutions to the ^8B neutrino flux f_B and the ν_e survival probability P_{ee} assuming ν_e to ν_a transition. The 1σ SSM error bar for f_B is indicated on the right.

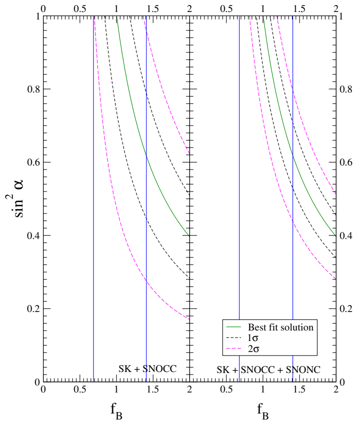

Figure 2: Best fit value of the ^8B neutrino flux f_B shown along with its 1σ and 2σ limits against the model parameter $\sin^2\alpha$, representing ν_e transition into a mixed state $(\nu_a \sin\alpha + \nu_s \cos\alpha)$. The verticle lines denote the $\pm 2\sigma$ limits of the SSM. The left-hand panel is for a combination of SK+CC. The right-hand panel corresponds to SK+CC+NC data combined.

We next take up a general case where the ν_e oscillate into a state ν', where $\nu' = \nu_{\text{active}} \sin\alpha + \nu_{\text{sterile}} \cos\alpha$, $\sin^2\alpha(\cos^2\alpha)$ being the fraction of active(sterile) component in the resultant beam on Earth. In this case $P_{ea} = \sin^2\alpha(1 - P_{ee})$ and for each value of $\sin^2\alpha$ we show in figure 2 the central and the 1σ and 2σ ranges of f_B. We note that transition to pure active components ($\sin^2\alpha = 1$) is completely consistent while transitions to pure sterile states ($\sin^2\alpha = 0$) are completely forbidden. Combining the $1\sigma(2\sigma)$ lower limit of f_B from this fit with the $1\sigma(2\sigma)$ upper limit from SSM (vertical lines are the 2σ limit) gives a lower limit of $\sin^2\alpha > 0.68(0.45)$. This means that at $1\sigma(2\sigma)$ we can still have upto 32%(65%) admixture of sterile component in the solar neutrino beam. While we have obtained the bound on $\cos^2\alpha$ in a (quasi)model independent way, the same can be obtained in the framework of neutrino oscillations [8, 9]. Our bound is in excellent agreement with the bounds obtained in [8, 9].

Model Dependent Analysis: We now look at the implications of the global solar neutrino data in the framework of two-generation oscillations‖. Since SNO disfavors the sterile option at 5.5σ we consider transitions to active flavors only. For the global data we consider the total rates observed in Cl and Ga (SAGE, GALLEX and GNO combined), the 1496 day SK zenith angle energy spectrum data and the recent data from SNO. Since it is not yet possible to identify the ES, CC and NC events separately in SNO, they have made available their results as a combined CC+ES+NC data in 17 day and 17 night energy bins. We employ this full day-night SNO spectrum in our statistical analysis. For the details of our data analysis procedure and the definition of the χ^2 function we refer to [10, 11]. The results of the global χ^2 analysis is shown in Table 1 [10]. The best-fit comes in the LMA region as before [11] but LOW is still allowed with a very high probability. However SMA is seen to be virtually ruled out by the data.

‖ A complete list of references on global analyses including the recent SNO data can be found in [10].

Nature of Solution	Δm^2 in eV^2	$\tan^2\theta$	χ^2_{min}	goodness of fit (%)
LMA	6.06×10^{-5}	0.41	68.19	75%
LOW	1.09×10^{-7}	0.59	77.49	46%
VO-QVO	6.49×10^{-10}	1.42	83.12	30%
SMA	4.97×10^{-6}	1.57×10^{-3}	99.46	4%

Table 1: The χ^2_{min}, the goodness of fit and the best-fit values of the oscillation parameters obtained for the analysis of the global solar neutrino data including the full SNO day-night spectrum.

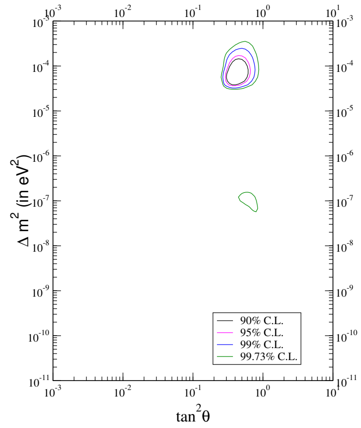

Figure 3: The regions in the parameter space allowed from the analysis of global solar neutrino data.

Figure 3 shows the allowed areas in the $\Delta m^2 - \tan^2\theta$ plane from the analysis of the global solar neutrino data in the framework of two-generation $\nu_e - \nu_{\rm active}$ oscillations. We note that the (i) NC rate disfavors the LOW solution which appears only at 3σ, (ii) values of Δm^2 above 3.5×10^{-4} eV^2 are disfavored, (iii) maximal Mixing is disfavored at 3σ, (iv) *dark Side* solutions are gone, which implies that $\Delta m^2_{\rm solar} > 0$.

Conclusions: We perform a detail analysis of the solar neutrino data. We use the SK and SNO rates to obtain bounds on f_B, P_{ee} and $\cos^2\alpha$ in a (quasi)model independent way. We find that transitions to states with about 30% sterile mixture is still allowed at 1σ. We analyse the global data in the framework of oscillations and present the best-fit solutions and the allowed areas in the two-flavor parameter space. The LMA solution emerges as the only undisputed solution to the solar neutrino problem.

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