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SOLAR MODELS AND NEUTRINO DEFICIT *

G. Conforto, C. Grimani, F. Martelli and F. Vetrano

Università degli Studi, I-61029 Urbino, Italy
Istituto Nazionale di Fisica Nucleare, I-50125 Firenze, Italy

Abstract

The existing measurements of the solar neutrino flux are compared with the predictions of all models capable of reproducing the other solar observables. These predictions are supplemented by the hypothesis of neutrino oscillations with mass differences large enough to render energy-independent the depletion of the solar ν_e flux. It is concluded that the data are consistent with this hypothesis and that an energy-dependence of the solar neutrino deficit must be regarded as an attractive possibility but not as a compelling reality.

1 Introduction

In a previous paper [1] we have addressed the question of a possible energy-dependence of the solar-neutrino deficit coming to the conclusion that, at least for the time being, its existence must be regarded only as an attractive possibility and by no means as an established reality.

Our analysis was based on the comparison between the existing experimental data [2, 3, 4, 5] and the theoretical predictions, assumed to be well represented by those of the "reference model" of ref. [6].

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The latter assumption is actually rather questionable. There exist in fact several solar models capable of reproducing all experimentally known facts but giving rise to somewhat different neutrino flux predictions [7]. As different models of the same sun cannot be all simultaneously right, it follows that theoretical predictions can only be said to be known within indeterminations which are actually larger than those associated with the results of any single model.

In our previous analysis [1] we mentioned this effect but did not take it into account. In this paper, we try to quantify this additional theoretical uncertainty by looking at the spread of the various predictions. The procedure adopted is described in section 2. With modified theoretical predictions and their errors, the statistical analysis of ref. [1] is then repeated in section 3. Section 4 summarises our conclusions.

2 Solar models

An extensive review of solar models is presented in ref. [7]. We have restricted ourselves to "standard" models, i.e. to those capable of reproducing all solar observational results, including the helioseismology data.

The solar neutrino event rates for the Gallium (Ga), Clorine (Cl) and Kamiokande (Ka) experiments predicted by the four considered models [6, 8, 9, 10] are reported in table 1. Within each model, the quoted errors reflect the uncertainties on the input parameters. These errors are highly correlated. However, it is only for the model of ref. [6] that the error correlation matrix is readily available [11, 1]. Consequently, we have taken the errors of this model to be typical of and to apply to all this type of calculations.

Although rather similar, the central values of the rates are not identical. This is due to different assumptions entering in the various models. To take this effect into account, we have treated these results as independent determinations of the same quantity with a common variance. Accordingly, we have calculated the average values of the predicted rates and the components of their errors due to their spread. This procedure yields the results

$$(133.4 \pm 2.1)\,\mathrm{SNU},\ (8.57 \pm 0.45)\,\mathrm{SNU}\ \text{and}\ (6.12 \pm 0.33) \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

for the Ga, Cl and Ka experiments respectively. The final covariance matrix on the average rate values is then obtained by adding in quadrature the

Table 1: Solar neutrino event rates for the Clorine (Cl), Gallium (Ga) and Kamiokande (Ka) experiments predicted by the four "standard" models.

Experiment (Units)	Ga(SNU)	Cl(SNU)	Ka(10^6 cm^{-2} s^{-1})
Ref.[6]	$136.8\pm^{8}_{7}$	$9.5\pm^{1.2}_{1.4}$	$6.62\pm^{0.93}_{1.12}$
Ref.[8]	$136\pm^{7}_{6}$	8.9±1.1	6.4±0.9
Ref.[9]	132.8±6.9	8.5±1.1	6.3±0.9
Ref.[10]	128±6	7.4±0.8	5.16±0.75

errors above to the diagonal elements of the covariance matrix of the model of ref. [6]. These results are reported in table 2.

Fig. 1 illustrates the results of the models. The predictions from the four solar models and their average values are shown in the Ga-Cl-Ka space. The ellipses centered on the stars are the 1σ contour for the model of ref. [6], calculated by averaging the asymmetric errors. The black dot represents the average rate values and the smaller and larger ellipses centered on it are respectively the estimated uncertanties on the average rate values due to their differences and the 1σ contour for the average rate values (see table 2), calculated for averaged asymmetric errors.

3 Statistical analysis

The experimental input data used in the analysis are shown in table 3 [12]. For each result, statistical and systematic errors have been combined in quadrature. For the Ga and Ka experiments the weighted averages of the two available results have been used.

Following ref. [1], the hypothesis of an energy-independent depletion of the solar ν_e flux due to oscillations is tested by studying the function

$$\chi^2(F) = \Sigma_i \Sigma_j \ (e_i - p_i) \ (e_j - p_j) \ (S^{-1})_{ij}$$

where:

- F is the common factor by which all calculated ν_e fluxes are reduced;

Table 2: Average predicted rates P_i and their covariance matrix V_{ij}. The convention for the indices i, j is 1=Ga, 2=Cl, 3=Ka. The two values on the diagonal elements correspond to the positive or negative choice of the asymmetric errors, the four values on the non-diagonal elements to the positive-positive, negative-positive, positive-negative and negative-negative choices.

	$P_1 = 133.4$ SNU	$P_2 = 8.57$ SNU	$P_3 = 6.12 \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$
		6.30	4.81
	68.5	5.51	5.52
	53.5	7.35	5.79
		6.43	5.06
	6.30		1.09
	5.51	1.64	1.27
V =	7.35	2.16	1.31
	6.43		1.53
	4.81	1.09	
	5.52	1.27	0.97
	5.79	1.31	1.36
	5.06	1.53	

Table 3: Solar neutrino experimental results [12].

Experiment (Units)	Result
Gallex (SNU)	$69.7 \pm 6.7 \pm^{3.9}_{4.5}$
Sage (SNU)	$73 \pm^{10}_{11}$
Chlorine (SNU)	$2.54 \pm 0.14 \pm 0.14$
Kamiokande ($10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$)	$2.80 \pm 0.19 \pm 0.33$
Superkamiokande($10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$)	$2.44 \pm 0.06 \pm^{0.25}_{0.09}$

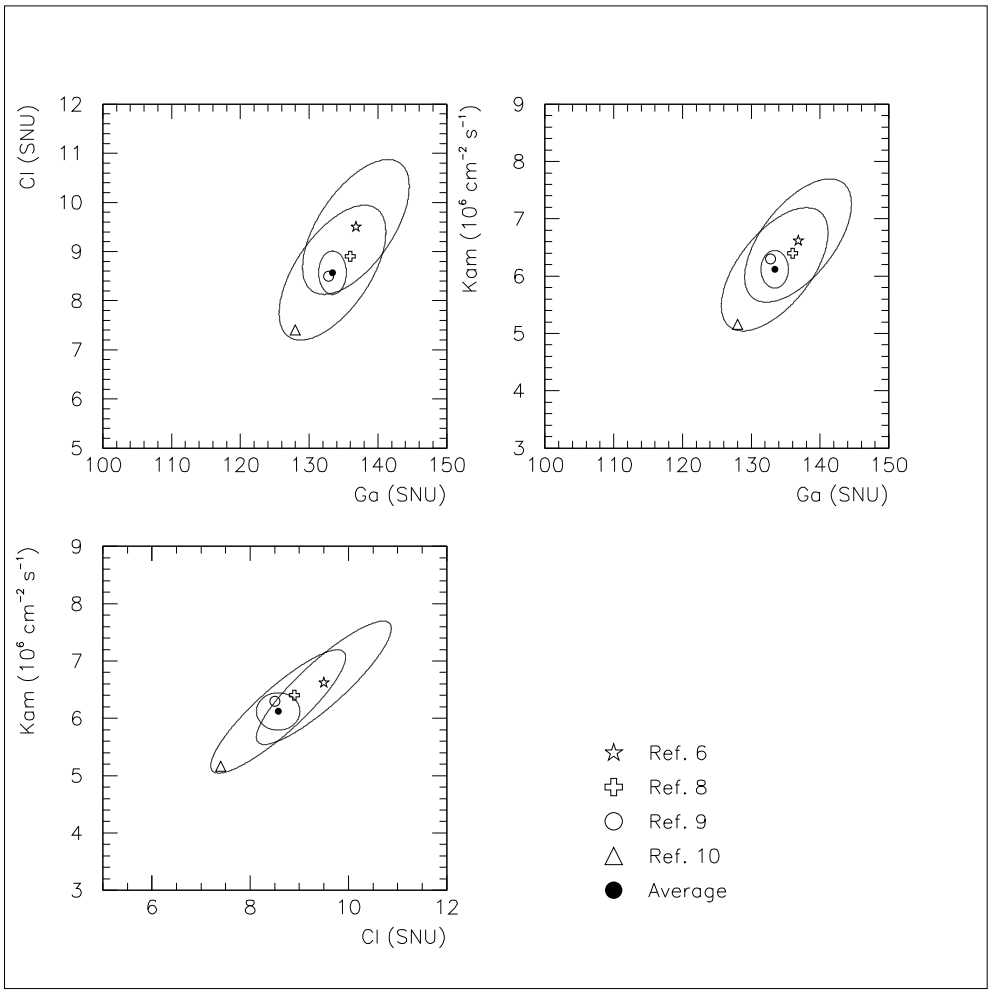

Figure 1: Predictions from the four solar models of ref. [6, 7, 8, 9, 10] and their average values. The ellipses centered on the stars are the 1σ contour for the model of ref. [6], calculated by averaging the asymmetric errors. The black dot represents the average rate values and the smaller and larger ellipses centered on it are respectively the estimated uncertanties on the average rate values due to their differences and the 1σ contour for the average rate values (see table 2), calculated for averaged asymmetric errors.

- the indices i and j run over the three (Ga, Cl and Ka) experiments;
- e_i are the experimental results;
- p_i are the theoretical predictions. They are obtained from the P_i of table 2 through the relations

$$\begin{aligned} p_{Ga,Cl} &= F P_{Ga,Cl} \\ p_{Ka} &= F(1-f)P_{Ka} + f P_{Ka} \end{aligned}$$

  where $f = 0.155$ is the fraction of the Kamiokande detection efficiency due to flavour-blind Neutral Currents;
- S is the covariance matrix obtained from that of table 2 by multiplying the elements V_{ij} with $i, j \neq 3$ by F^2, those with either i or $j = 3$ by $[F^2(1-f)+Ff]$ and V_{33} by $[F(1-f)+f]^2$ and by adding in quadrature the experimental errors to the diagonal elements.

We have at first replaced all asymmetric errors by their average values. With this procedure, the χ^2 analysis yields

$$F = 0.504 \pm 0.064$$

with $\chi^2_{min} = 8.13$ corresponding to a Confidence Level (C.L.) of 1.7 %.

For comparison, if the theoretical predictions and their covariance matrix are taken from the model of ref. [6] alone, one obtains

$$F = 0.437 \pm 0.056$$

with $\chi^2_{min} = 14.46$ corresponding to a C.L. of 0.072 %.

To test the sensitivity of these results to the procedure adopted in treating the errors, we have introduced a modification. In all operations involving two quantities (weighted averages of the two Ga and Ka results and evaluations of the χ^2 terms) we have used the positive (negative) error on the first and the negative (positive) error on the second if the first quantity was smaller (larger) than the second. In this case the results are

$$F = 0.508 \pm 0.066$$

with $\chi^2_{min} = 7.61$ corresponding to a C.L. of 2.2 %.

The results obtained by using the second procedure are shown in fig. 2. In each plane the two ellipses are the projections of the volumes in which the points representing respectively the experimental and calculated rates lie with 68.27 % probability.

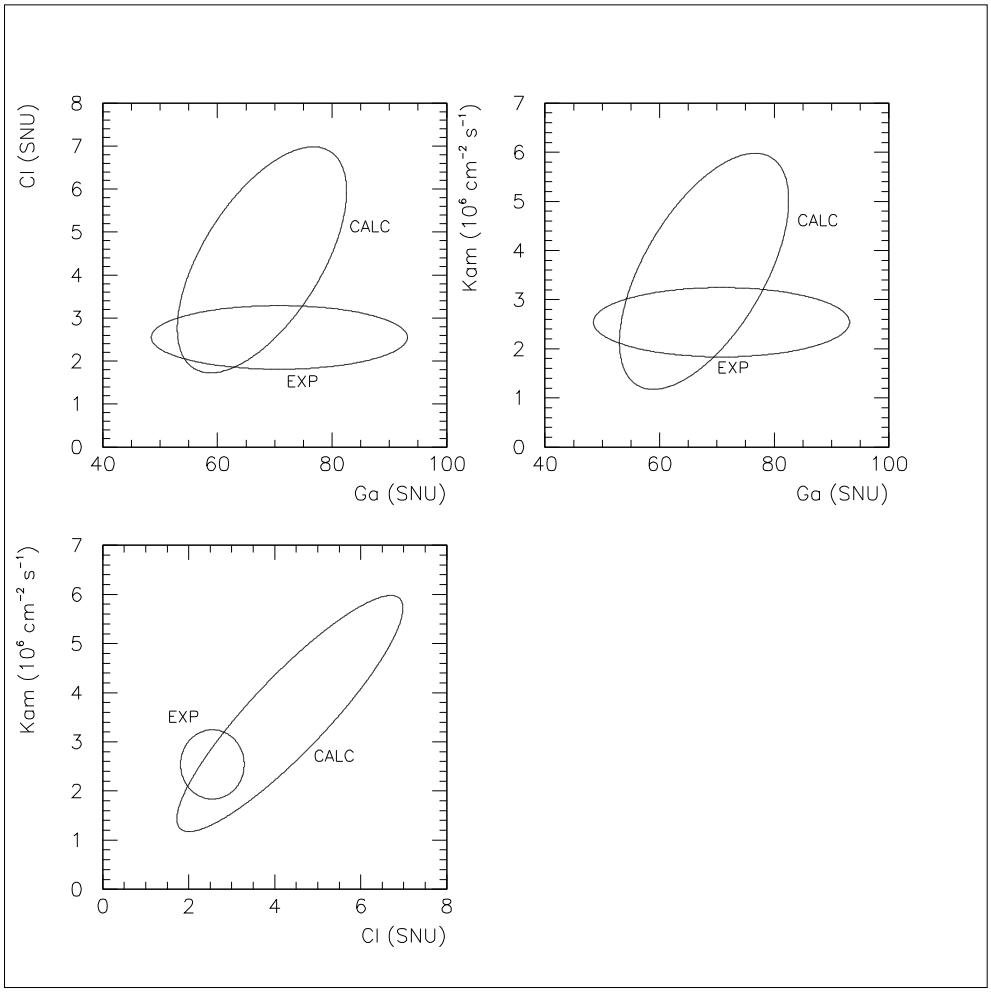

Figure 2: Comparison between the experimental and calculated rates. The latter are obtained from the average rates of the models of ref. [6, 7, 8, 9, 10] supplemented by the hypothesis of neutrino oscillations with mass differences large enough to render energy-independent the depletion of the solar ν_e flux. In each plane the two ellipses are the projections of the volumes in which the points representing respectively the experimental and calculated rates lie with 68.27 % probability.

4 Conclusions

Although not unacceptably low, the confidence level for an energy-independent depletion of the solar ν_e flux due to oscillations obtained using the results of the model of ref. [6] is admittedly rather marginal.

In the analysis presented in this paper we have used the average values of the predictions of four models introducing also additional few-percent uncertainties on them due to their spread. The confidence levels obtained are remarkably good.

In conclusion, for the time being, oscillation solutions of the solar neutrino problem based on an energy modulation of the solar neutrino deficit must be considered as perhaps suggested but certainly not compelled by the data.

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