PHYSICAL REVIEW D VOLUME 47, NUMBER 4 15 FEBRUARY 1993

Do solar-neutrino experiments imply new physics?

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(Received 24 August 1992)

None of the 1000 solar models in a full Monte Carlo simulation is consistent with the results of the chlorine or the Kamiokande experiments. Even if the solar models are forced artificially to have a ^{8}B neutrino flux in agreement with the Kamiokande experiment, none of the fudged models agrees with the chlorine observations. The GALLEX and SAGE experiments, which currently have large statistical uncertainties, differ from the predictions of the standard solar model by 2σ and 3σ, respectively.

PACS number(s): 96.60.Kx, 12.15.Ff, 14.60.Gh

Four solar-neutrino experiments [1–4] yield results different from the combined predictions of the standard solar model and the standard electroweak model with zero neutrino masses. The question physicists most often ask each other about these results is: Do these experiments require new physics beyond the standard electroweak model? We provide a quantitative answer using the results of a detailed Monte Carlo study of the predictions of the standard solar model.

The basis for our investigation is a collection of 1000 precise solar models [5] in which each input parameter (the principal nuclear reaction rates, the solar composition, the solar age, and the radiative opacity) for each model was drawn randomly from a normal distribution with the mean and standard deviation appropriate to that variable. In the calculations described in this paper, the uncertainties in the neutrino cross sections [5] for chlorine and for gallium were included by assuming a normal distribution for each of the absorption cross sections with its estimated mean and error. Since for gallium the estimated uncertainties in the neutrino absorption cross sections are not symmetric with respect to the best-estimate absorption cross sections, two different normal distributions were used to simulate the detection uncertainties for each neutrino flux to which gallium is sensitive. This Monte Carlo study automatically takes account of the nonlinear relations among the different neutrino fluxes that are imposed by the coupled partial differential equations of stellar structure and by the boundary conditions of matching the observed solar luminosity, heavy element to hydrogen ratio, and effective temperature at the present solar age.

This is the first Monte Carlo study that uses large numbers of standard solar models that satisfy the equations of stellar evolution and that is designed to determine if physics beyond the standard electroweak theory is required.

Related investigations have been carried out assuming [6–8] that each solar model could be represented by a single parameter, its central temperature. The flux of neutrinos from each nuclear source is represented in these studies by a power law in the central temperature. This simplification, while providing a semiquantitative understanding of some of the important relationships, leads to serious errors in some cases. For example, the parametrization in terms of central temperature predicts a ^{8}B flux for the maximum rate model that is too low by more than a factor of 4 [9]. Just as detailed Monte Carlo calculations are necessary in order to understand the relative and absolute sensitivities of complicated laboratory experiments, a full Monte Carlo calculation is required to determine the interrelations and absolute values of the different solar neutrino fluxes. The Sun is as complicated as a laboratory accelerator or a laboratory detector, for which we know by painful experience that detailed simulations are necessary. For example, the fact that the ^{8}B flux may be crudely described as $\phi(^8\mathrm{B}) \propto T^{18}_{\mathrm{central}}$ and $\phi(^7\mathrm{Be}) \propto T^{8}_{\mathrm{central}}$ does not specify whether the two fluxes increase and decrease together or whether their changes are out of phase with each other. The actual variations of the calculated neutrino fluxes are determined by the coupled partial differential equations of stellar evolution and the boundary conditions, especially the constraint that the model luminosity at the present epoch be equal to the observed solar luminosity. Fortunately, the simplified method and the full Monte Carlo calculation yield similar results for the probability that new physics is required, although the full Monte Carlo calculation yields a more accurate numerical statement.

Figures 1(a)–1(c) show the number of solar models with different predicted event rates for the chlorine solar neutrino experiment, the Kamiokande (neutrino-electron scattering) experiment, and the two gallium experiments (GALLEX and SAGE). For the chlorine experiment, which is sensitive to neutrinos above 0.8 MeV, the solar model with the best input parameters predicts [5] an event rate of about 8 solar neutrino units (SNU). None of the 1000 calculated solar models yields a capture rate below 5.8 SNU, while the observed rate is [1]

$$\langle \phi\sigma \rangle_{\mathrm{Cl\,exp}} = (2.2 \pm 0.2)\ \mathrm{SNU}, \quad 1\sigma \text{ error} . \tag{1}$$

The discrepancy that is apparent in Fig. 1(a) was for two decades the entire "solar neutrino problem." Figure 1(a) implies that something is wrong with either the standard solar model or the standard electroweak description of the neutrino.

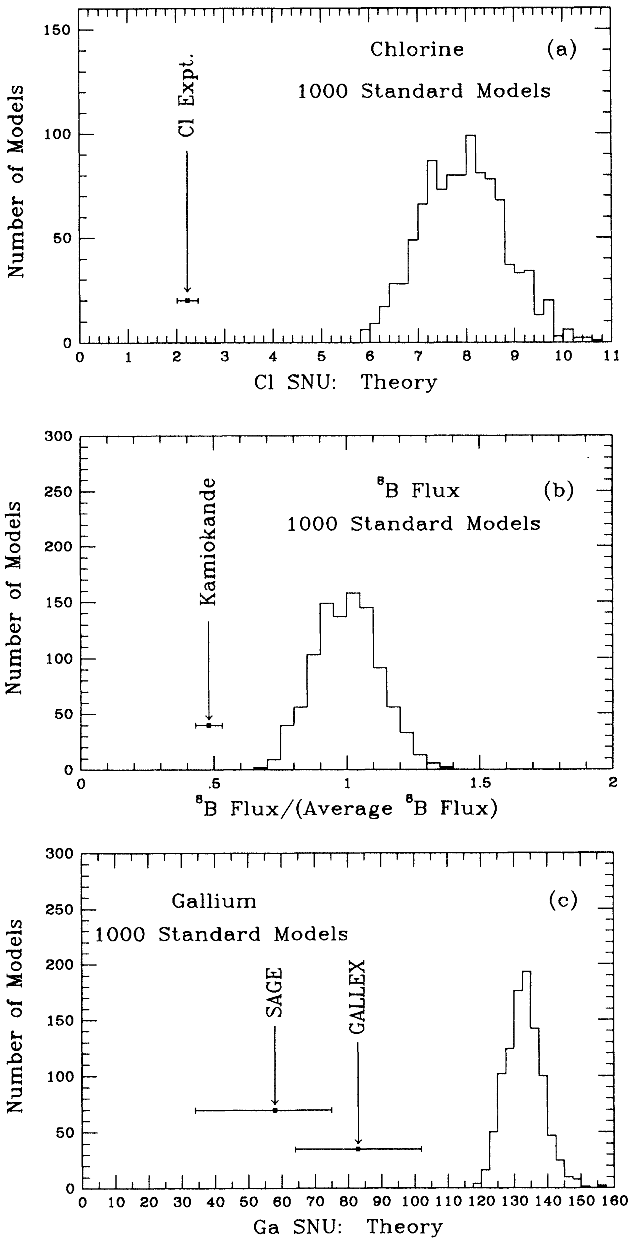

FIG. 1. 1000 solar models vs experiments. The number of precisely calculated solar models that predict different solar neutrino event rates are shown for the chlorine (a), Kamiokande (b), and gallium (c) experiments. The solar models from which the fluxes were derived satisfy the equations of stellar evolution including the boundary conditions that the model luminosity, chemical composition, and effective temperature at the current solar age be equal to the observed values [5]. Each input parameter in each solar model was drawn independently from a normal distribution having the mean and the standard deviation appropriate to that parameter. The experimental error bars include only statistical errors (1σ).

Figure 1(b) shows the number of solar models with different ^{8}B neutrino fluxes. For convenience, we have divided each ^{8}B flux by the average ^{8}B flux so that the distribution is peaked near 1.0. The rate measured for neutrinos with energies above 7.5 MeV by the Kamiokande II and III experiments is [2]

$$\langle \phi(^8\mathrm{B})\rangle = [0.48\pm0.05(1\sigma)\pm0.06(\mathrm{syst})]\langle \phi(^8\mathrm{B})\rangle_{\mathrm{average}} \tag{2}$$

for recoil electrons with energies greater than 7.5 MeV. Here $\langle \phi(^8\mathrm{B})\rangle_{\mathrm{average}}$ is the best-estimate theoretical prediction. None of the 1000 standard solar models lie below $0.65\langle \phi(^8\mathrm{B})\rangle_{\mathrm{average}}$. If one takes account of the Kamiokande measurement uncertainty (±0.08) in the Monte Carlo simulation, one still finds that none of the solar models is consistent with the observed event rate. These results provide independent support for the existence of a solar neutrino problem.

Figure 1(c) shows the number of solar models with different predicted event rates for gallium detectors and the recent measurements by the SAGE [3,10] [$58^{+17}_{-24}\pm14$(syst) SNU] and GALLEX [$83\pm19(1\sigma)$ ±8(syst) SNU] Collaborations [4]. With the current large statistical errors, the results differ from the best-estimate theoretical value [5] of 132 SNU by approximately 2σ (GALLEX) and 3.5σ (SAGE). The gallium results provide modest support for the existence of a solar neutrino problem, but by themselves do not constitute a strong conflict with standard theory.

Can the discrepancies between observation and calculation that are summarized in Fig. 1 be resolved by changing some aspect of the solar model? We have argued previously [11] that this is difficult to do because the energy spectrum of any specific neutrino source is unchanged by the solar environment [12] and because the uncertainties in all of the important sources except ^{8}B are relatively small. A comparison of Figs. 1(a) and 1(b) shows that the discrepancy with theory appears to be energy dependent. The larger discrepancy occurs for the chlorine experiment, which is sensitive to lower neutrino energies than is the Kamiokande experiment. If one normalizes the ^{8}B flux by the best-estimate measurement from Kamiokande [see Eq. (2)], then the implied rate in the chlorine experiment from ^{8}B alone is 3.0 SNU. We also argued that the other neutrino fluxes would most likely yield at least another 1 SNU, implying a minimum total rate of about 4 SNU. On this basis, we concluded that the two experiments, chlorine and Kamiokande, are inconsistent with the combined standard electroweak and solar models. However, our argument did not take into account in a well-defined way the errors in the predictions and in the measurements. We remedy this shortcoming in the following discussion using the previously described Monte Carlo simulation.

Figure 2 provides a quantitative expression of the difficulty in reconciling the Kamiokande and chlorine experiments by changing solar physics. We constructed Fig. 2 using the same 1000 solar models as were used in constructing Fig. 1, but for Fig. 2 we artificially replaced the ^{8}B flux for each standard model by a value drawn ran-

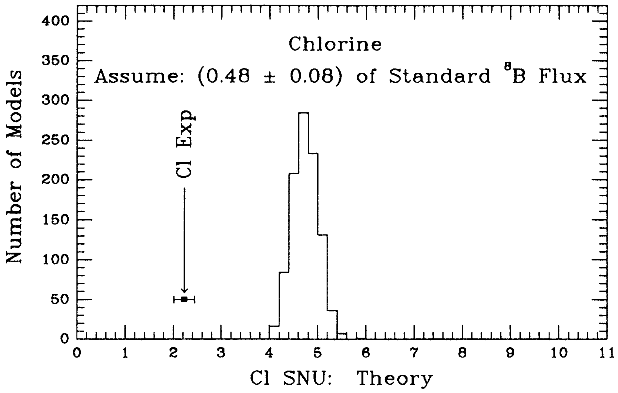

FIG. 2. 1000 artificially modified fluxes. The ^{8}B neutrino fluxes computed for the 1000 accurate solar models were replaced in the figure shown by values drawn randomly for each model from a normal distribution with the mean and the standard deviation measured by the Kamiokande experiment [2].

domly for that model from a normal distribution with the mean and the standard deviation measured by Kamiokande [see Eq. (2)]. This *ad hoc* replacement is motivated by the fact that the ^{7}Be$(p,\gamma)^8$B cross section is the least accurately measured of all the relevant nuclear fusion cross sections and by the remark that the ^{8}B neutrino flux is more sensitive to solar interior conditions than any of the other neutrino fluxes. The peak of the resulting distribution is moved to 4.7 SNU (from 8 SNU) and the full width of the peak is decreased by about a factor of 3. The peak is displaced because the measured (i.e., Kamiokande) value of the ^{8}B flux is smaller than the calculated value. The width of the distribution is decreased because the error in the Kamiokande measurement is less than the estimated theoretical uncertainty ($\approx 12.5\%$) and because ^{8}B neutrinos constitute a smaller fraction of each displaced rate than of the corresponding standard rate.

Figure 2 was constructed by assuming that something is seriously wrong with the standard solar model, something that is sufficient to cause the ^{8}B flux to be reduced to the value measured in the Kamiokande experiment. Nevertheless, there is no overlap between the distribution of fudged standard model rates and the measured chlorine rate. None of the 1000 fudged models lie within 3σ (chlorine measurement errors) of the experimental result.

The results presented in Figs. 1 and 2 suggest that new physics is required beyond the standard electroweak theory if the existing solar neutrino experiments are correct within their quoted uncertainties. Even if one abuses the solar models by artificially imposing consistency with the Kamiokande experiment, the resulting predictions of all 1000 of the "fudged" solar models are inconsistent with the result of the chlorine experiment (see Fig. 2).

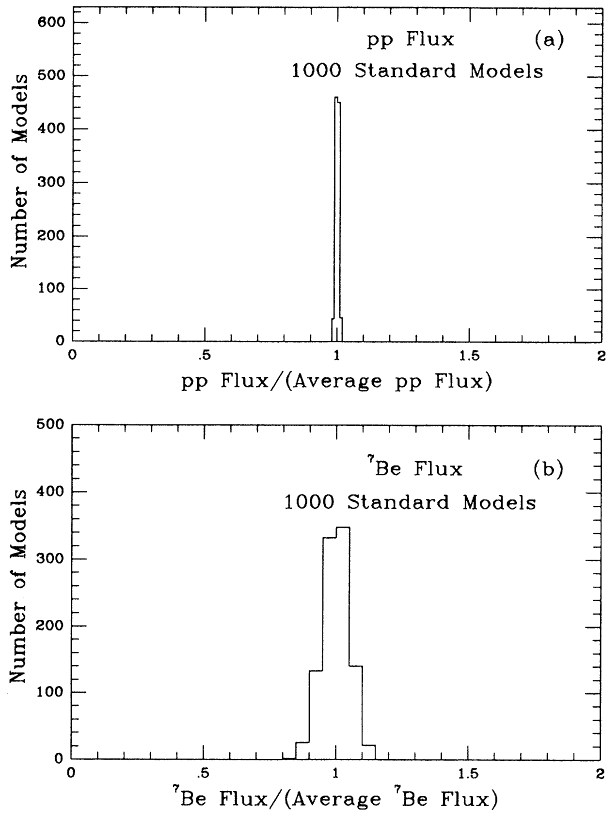

FIG. 3. The *pp* and ^{7}Be neutrino fluxes. The histogram of the number of 1000 precisely calculated solar models that predict different *pp* neutrino fluxes is shown in (a) and the number that predict different ^{7}Be neutrino fluxes is shown in (b). The individual neutrino fluxes are divided by their respective average values.

Figure 3 shows the relatively high precision with which the *pp* and ^{7}Be neutrino fluxes can be calculated. Since the 1σ theoretical uncertainty in the flux of ^{7}Be neutrinos is only $\simeq 5\%$ [5,9], an accurate measurement of this quantity in the proposed Borexino experiment [13] will constitute another important test of the standard model.

All of the arguments in this paper depend to some extent on our understanding of the solar interior. In the future, it will be possible to use solar neutrinos to test electroweak theory independent of solar models by measuring the energy spectrum of the ^{8}B neutrinos with the Super-Kamiokande [14], the Sudbury Neutrino Observatory (SNO) [15], and the Imaging of Cosmic and Rare Underground Signals (ICARUS) experiments [16] and by measuring the ratio of charged to neutral currents with the SNO experiment [15].

This work was supported in part by the NSF via Grant No. PHY-92 45317 at IAS and PHY-87-15272 at Cornell.

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