Correlation of neutrino fluxes in the standard Bahcall–Ulrich solar model in connection with the solar-neutrino problem

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The ratios of the fluxes of solar neutrinos from the CNO cycle to those of boron neutrinos are less model-dependent than the fluxes themselves in the standard Bahcall–Ulrich solar model. The uncertainties for these ratios are calculated at the level of three standard deviations. Their importance in the overall formulation of the problem of detecting solar neutrinos is discussed.

The solar-neutrino problem, which arose because of the deficiency of solar neutrinos in the Davis experiment,[1] is one of the most interesting problems in neutrino astrophysics today. The most natural way to reconcile the experimental data which have been obtained to date[1–4] is to suggest that we are observing a significant suppression of the flux of solar neutrinos from ^{7}Be decay and a partial suppression of the flux of boron neutrinos, while the flux of *pp* neutrinos is extremely close to the theoretical prediction. It then becomes possible to determine the parameters of the neutrino oscillations for the MSV effect[5] or for long-wave vacuum oscillations.[6,7] Although a complete resolution of the solar-neutrino problem will require substantial improvements in measurement accuracy and a greater diversity of methods of study, some extremely impressive directions have been defined

From the very beginning, the problem of neutrino spectroscopy of the sun as formulated in the studies by Kuzmin and Zatsepin[8] and also Bahcall[9] has included measurements of the fluxes of solar neutrinos from the CNO cycle, primarily in order to study the role played by this cycle in the overall picture of fusion reactions in the sun, and also in order to study the distribution of heavy elements in the central part of the sun. However, the fluxes of neutrinos from the decay of ^{15}O and ^{13}N have approximately the same temperature dependence as the flux of boron neutrinos, and the intensities of the former are higher by a factor of about 100, while the average energies are lower than those of boron neutrinos by a factor of 10. If the flux of boron neutrinos is below the theoretical prediction because of a lower temperature at the center of the sun, the fluxes of neutrinos from the CNO cycle must be correspondingly lower. If the reason for the suppression of the flux of boron neutrinos instead lies in neutrino oscillations, then the suppression factors for the boron neutrinos and the neutrinos from the CNO cycle may be quite different, because of the large difference in neutrino energies. For this reason, measurements of the fluxes of neutrinos from the CNO cycle are an extremely promising direction for solving the solar-neutrino problem.

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TABLE I. Fluxes of solar neutrinos.

Source	Energy, MeV	Flux, 10^{10} cm$^{-2}\cdot$s^{-1}
pp	$0-0.42$	$6.0(1\pm 0,02)$
pep	1.44	$1.4\cdot 10^{-2}(1\pm 0.05)$
Be-7	0,86	$4.7\cdot 10^{-1}(1\pm 0.15)$
B-8	$0-14$	$5.8\cdot 10^{-4}(1\pm 0.37)$
N-13	$0-1.2$	$6.1\cdot 10^{-2}(1\pm 0.50)$
O-15	$0-1.73$	$5.2\cdot 10^{-2}(1\pm 0.58)$

Decisive considerations in the formulation of the final conclusions are the accuracy of the experimental data available and the model-related uncertainties in the theoretical predictions of the fluxes of solar neutrinos. Table I shows the model-related uncertainties at the 3σ level according to 1000 calculations (realizations) based on the standard Bahcall–Ulrich solar model.[10]

It can be seen from Table I that the fluxes of boron neutrinos, particularly those of neutrinos from the CNO cycle, are highly model-dependent. This situation is a severe complication in attempts to unambiguously interpret experimental data. However, one might suggest that since many of the input parameters of the solar model enter the calculated flux values in approximately the same way, these uncertainties should tend to cancel each other out in calculations of the *ratios* of these fluxes. As a result, the ratios of neutrino fluxes should be less model-dependent. Our calculations based on the results of 1000 realizations of the standard Bahcall–Ulrich model support this suggestion. According to these calculations, the ratios of neutrino fluxes are

$$\Phi(^{15}\mathrm{O})/\Phi(^{8}\mathrm{B})=[0.95\pm 0.25(3\sigma)]\times 100$$
$$\Phi(^{13}\mathrm{N})/\Phi(^{8}\mathrm{B})=[1.13\pm 0.28(3\sigma)]\times 100\ .$$

The uncertainties listed here correspond to the 3σ level. With a statistical base of 1000 realizations, only a few points could thus lie outside these intervals. A comparison of the uncertainties found in the flux ratios with the corresponding uncertainties in the fluxes themselves unambiguously shows that the ratios of the fluxes are much less model-dependent and that their uncertainties are smaller than the uncertainties in the fluxes themselves by a factor of nearly 2. Figure 1 shows a family of 1000 points in the $\Phi(^{15}\mathrm{O})$–$\Phi(^{8}\mathrm{B})$ plane; Fig. 2 shows the results in the $\Phi(^{13}\mathrm{N})$–$\Phi(^{8}\mathrm{B})$ plane. There is an obvious correlation between the fluxes of boron neutrinos and the CNO neutrinos. The temperature dependence is approximately the same for these fluxes. The latter agreement means that we can expect their ratio to be less model-dependent than the fluxes themselves, as in nonstandard models.

The lithium detector is the most promising one for detecting neutrinos from the CNO cycle. Table II shows the rates at which solar neutrinos would be captured in various detectors according to the predictions of the standard Bahcall–Ulrich model.[11]

Here 1 SNU (solar neutrino unit) corresponds to one capture of a neutrino per second by 10^{36} target atoms. The fraction of neutrinos from the CNO cycle in a lithium detector is seen to correspond to 12.7 SNU, and the fraction of boron neutri-

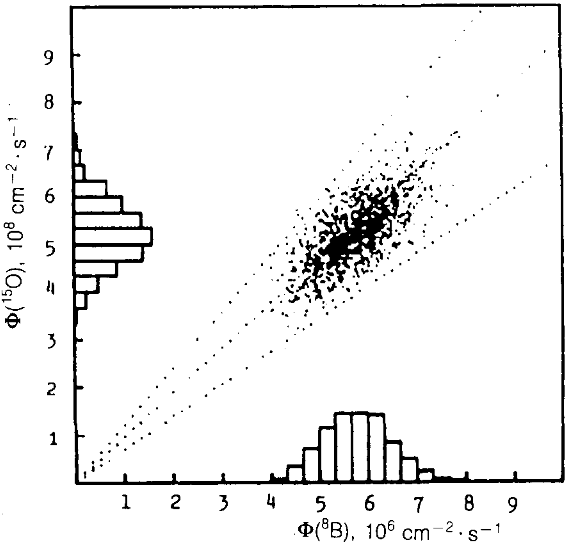

FIG. 1. A thousand realizations of the standard Bahcall–Ulrich solar model in the $\Phi(^{15}O)$–$\Phi(^{8}B)$ plane. Points—Values of the neutrinos fluxes; histograms—corresponding frequencies, in arbitrary units; straight lines—the interval at the 3σ level for the ratios of neutrino fluxes.

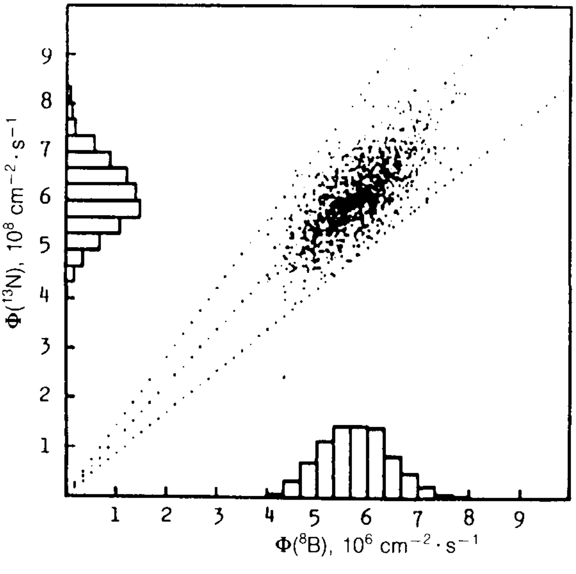

FIG. 2. A thousand realizations of the standard Bahcall–Ulrich solar model in the $\Phi(^{13}N)$–$\Phi(^{8}B)$ plane. The notation is the same as in Fig. 1.

TABLE II. Rates at which solar neutrinos are captured.

Neutrino source	Chlorine, SNU	Gallium, SNU	Lithium, SNU
pp	0,0	70,8	0,0
pep	0.2	3,1	9,2
Be-7	1,2	35,8	4,7
B-8	6,2	13,8	22,1
N-13	0,1	3,0	2,1
O-15	0.3	4,9	10.6
Sum	8.0 ± 3.0	131.5 ± 20	48.7 ± 15

nos is no more than 10 SNU—if we incorporate a suppression by a factor of at least 2 of the flux of boron neutrinos in accordance with data from the Davis and Kamiokande experiments. The other neutrinos correspond to *pep* and Be-7. In order to find the effect due to CNO neutrinos, we need to subtract from the overall effect the effect from boron, *pep*, and Be-7 neutrinos. The solar-neutrino superdetectors presently under construction (such as Super–Kamiokande,[12] SNO,[13] and Borexino[14]) and also the large chlorine–argon neutrino telescope with 3000 metric tons of perchloroethylene[15] (among others) will make it possible to determine the fluxes of boron neutrinos and Be-7 neutrinos from the entire set of results found. As statistical bases are built up in the GALLEX and SAGE projects, it will become possible to determine the flux of *pp* neutrinos fairly accurately. Figure 3 shows a family of 1000 points of the standard Bahcall–Ulrich model in the $\Phi(pep)$–$\Phi(pp)$ plane. We see that in the standard model these 1000 points are localized in a very small region in the plane, so we can work from the results of a gallium experiment to determine the contribution of *pep* neutrinos in the lithium detector both in the absence of neutrino oscillations and with fixed parameters of the MSV conversion. By comparing the data obtained in different neutrino telescopes one can thus determine the effect due to CNO neutrinos in a lithium detector, and one can also find the ratio of the fluxes of CNO and boron neutrinos. The most important factor here is the accuracy of the experimental data.

Conclusion. It has been shown in this paper that there is a correlation in the fluxes of boron neutrinos and the neutrinos from the CNO cycle in the standard solar model. Uncertainties at the level of three standard deviations have been found for the ratios of neutrino fluxes from ^{15}O (^{13}N) and from ^{8}B. These results unambiguously demonstrate that the ratios of neutrino fluxes are less model-dependent than the fluxes themselves. This circumstance adds to the reliability of an analysis of the experimental data carried out to find the answer to the primary question: Is MSV conversion responsible for the deficiency of solar neutrinos, or is it a lower temperature at the center of the sun? From this standpoint, the most promising detector is a radiochemical lithium detector.

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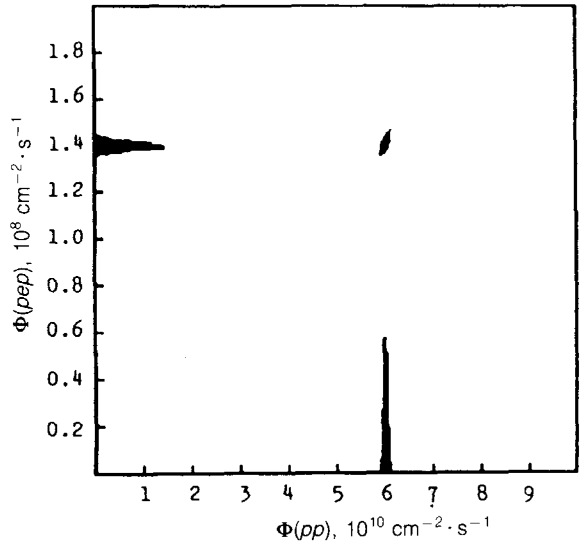

FIG. 3. A thousand realizations of the standard Bahcall–Ulrich solar model in the $\Phi(pep)$–$\Phi(pp)$ plane. The spot in the plane contains the 1000 points. The corresponding frequencies, in arbitrary units, are shown along the axes.

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