Has a Standard Model Solution to the Solar Neutrino Problem been Found?

John N. Bahcall, C. A. Barnes, J. Christensen-Dalsgaard, B. T. Cleveland, S. Degl'Innocenti, B. W. Filippone, A. Glasner, R. W. Kavanagh, S. E. Koonin, K. Lande, K. Langanke, P. D. Parker, M. H. Pinsonneault, C. R. Proffitt and T. Shoppa

1Institute for Advanced Study, School of Natural Sciences, Princeton, NJ 08540
2Also, Institute for Nuclear Theory, University of Washington, Seattle, Washington, 98195
3W. K. Kellogg Radiation Laboratory, Caltech, Pasadena, CA 91125
4Institut for Fysik og Astronomi, Aarhus Universitet, DK-8000, Aarhus C, Denmark
5Physics Department, University of Pennsylvania, Philadelphia, PA 19104-6394
6Departamento di Fisica dell'Università di Ferrara and Instituto Nazionale di Fisica Nucleare, Sezione di Ferrara, I-44100, Ferrara, Italy
7Racah Institute of Physics, Hebrew University, Jerusalem, Israel and Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637
8Physics Department, Yale University, New Haven, CT 06511
9Department of Astronomy, Ohio State University, Columbus, OH 43210
10Computer Sciences Corporation, IUE Observatory, Code 684.9, Goddard Space Flight Center, Greenbelt, MD 20771

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HAS A STANDARD MODEL SOLUTION TO THE
SOLAR NEUTRINO PROBLEM BEEN FOUND?

JOHN N. BAHCALL¹,², C. A. BARNES³, J. CHRISTENSEN-DALSGAARD⁴,
B. T. CLEVELAND⁴, S. DEGL'INNOCENTI⁵,², B. W. FILIPPONE⁵,
A. GLASNER⁷,², R. W. KAVANAGH³, S. E. Koonin³, K. LANDE⁵,²,
K. LANGANKE², P. D. PARKER⁸,², M. H. PINSONNEAULT⁹,²,
C. R. PROFFITT¹⁰,², and T. SHOPPA³

ABSTRACT

The claim by Dar and Shaviv that they have found a standard model solution
to the solar neutrino problem is based upon an incorrect assumption made in
extrapolating nuclear cross sections and the selective use of a small fraction of
the nuclear physics and of the neutrino data. In addition, five different solar
model codes show that the rate obtained for the chlorine experiment using the
Dar-Shaviv stated parameters differs by at least 14σ from the observed rate.

1. Introduction

In a widely circulated preprint, Dar and Shaviv¹ claim to have provided a
standard solar model solution to the solar neutrino problem. Their preprint has
aroused sufficient curiosity that we feel compelled to point out its most obvious
defects, although we do not plan to publish our response in a refereed journal
unless the Dar and Shaviv preprint is also published in a refereed journal.

To summarize our response, Dar and Shaviv have not solved the solar neutrino
problem. They have made an incorrect assumption in extrapolating nuclear cross
sections and have used nuclear and neutrino data selectively. Most surprisingly,
their solar model results are not reproducible. We obtain from five independent
solar neutrino codes and the Dar-Shaviv input parameters, neutrino fluxes that
are inconsistent with the values reported by Dar and Shaviv. With the Dar

¹Institute for Advanced Study, School of Natural Sciences, Princeton, NJ 08540
²Also, Institute for Nuclear Theory, University of Washington, Seattle, WA 98195
³W. K. Kellogg Radiation Laboratory, Caltech, Pasadena, CA 91125
⁴Institut for Fysik og Astronomi, Aarhus Universitet, DK-8000, Aarhus C, Denmark
⁵Physics Department, University of Pennsylvania, Philadelphia, PA 19104-6394
⁶Department di Fisica dell'Università di Ferrara and Instituto Nazionale di Fisica Nucleare,
Sezione di Ferrara, I-44100, Ferrara, Italy
⁷Racah Institute of Physics, Hebrew University, Jerusalem, Israel and Department of Astronomy
and Astrophysics, University of Chicago, Chicago, IL 60637
⁸Physics Department, Yale University, New Haven, CT 06511
⁹Department of Astronomy, Ohio State University, Columbus, OH 43210
¹⁰Computer Sciences Corporation, IUE Observatory, Code 684-9, Goddard Space Flight Center,
Greenbelt, MD 20771
vientional to define the astrophysical $S$-factor,

$$S(E) = \sigma(E) \exp\{2\pi\eta(E)\}. \quad (1)$$

The Sommerfeld parameter is given by

$$\eta(E) = \frac{Z_1 Z_2 e^2}{\hbar v}, \quad (2)$$

where $v$ is the relative velocity of the two particles in the entrance channel, $E$ is their relative energy, and $Z_1, Z_2$ are their charges. The form of Eq. (1) accounts explicitly for the energy dependence of $s$-wave tunneling through the Coulomb barrier of two pointlike particles and a kinematic flux factor. In the absence of near-threshold resonances, the energy dependence of the $S$-factor is expected to be small at low energies. However, in order to carry out a reliable extrapolation, the energy-dependent effects that are not accounted for in Eq. (1) must be allowed to show up in $S(E)$. These effects include nuclear structure, the strong interaction, energy dependent operators in the transition matrix elements, antisymmetrization between the colliding nucleons, finite nuclear size, the final-state phase space, and the contributions from other partial waves. In fact, for all the reactions of importance for the solar $p - p$ chain, the observed energy dependence of the various reactions agrees well with that calculated in theoretical models which account explicitly for the known nuclear effects that are omitted from Eq. (1). In particular, it was demonstrated more than thirty years ago\textsuperscript{7} that the complete Coulomb wave function provides a good description of the measured cross section factor for the $^{2}\text{H}(p, \gamma)^{3}\text{He}$ reaction down almost to solar thermal energies (16 keV).

Dar and Shaviv have chosen to factor out a slightly different energy dependence from the cross section data by defining a modified $S$-factor, $\tilde{S}(E)$, as

$$\tilde{S}(E) = \sigma(E) \exp\{2\pi\eta(E)[1 + 2/\pi(2\sqrt{z} - \arcsin\sqrt{z} - \sqrt{z(1 - z)})]\}, \quad (3)$$

with $z = E/E_c$ and the Coulomb energy $E_c = Z_1 Z_2 e^2/R$ at a radius parameter $R$. With this definition, $\tilde{S}(E)$ attempts to account for the finite size of the nuclei. However, $\tilde{S}(E)$ is still expected to be dependent on $E$, because of the other effects listed above that introduce an energy dependence in the finite size of the nucleus. The theoretical models that have been used previously\textsuperscript{8-10} to extrapolate the cross section data to solar energies properly take account of the finite nuclear size effects along with the other effects discussed above. Obviously both definitions, Eqs. (1) and (3), must lead to the same results for the low energy $S$-factor when proper account is taken of the additional energy dependence not included explicitly in the respective equations.

Dar and Shaviv did not take account of the additional energy dependences nor of all of the available nuclear physics data. For the determination of the low-energy cross section factor, $S_{34}$, for the $^{3}\text{He}(\alpha, \gamma)^{7}\text{Be}$ reaction, Dar and Shaviv apparently adjusted the radius parameter $R$ (see Eq. 3 above) so that the energy dependence of $\tilde{S}(E)$ is mostly removed for two of the nine\textsuperscript{10} existing experiments.
I specify in their preprint many of the important input quantities in their model; they did not state what they used for the element abundances, the radiative opacities, the equation of state, and the neutrino cross sections. They did not say which of the several available prescriptions for diffusion they used. We have therefore carried out calculations using a variety of different choices for these quantities, namely, the choices made previously as their best estimates by the six different authors who used five independent stellar evolution codes. 

The results are shown in Table 1. The first column identifies the computer code used in constructing the solar model; the second column indicates whether or not particle diffusion was included. The third, fourth and fifth columns give the calculated rates predicted for the chlorine, gallium, and Kamiokande solar neutrino experiments, respectively. The numbers in parentheses indicate the number of standard deviations quoted by the experimentalists (adding statistical and systematic errors quadratically) by which the calculated rates differ from the measured rates. For gallium, we have compared with the most recent GALLEX determination (which has smaller quoted uncertainties). The last two columns of Table 1 give the fluxes of $^{13}$N and $^{15}$O solar neutrinos. Some details regarding the solar models are given in the footnotes to the table.

| Solar Code          | Diffusion | $^{37}$Cl (SNU) | $^{71}$Ga (SNU) | $^8$B | $^{13}$N | $^{15}$O |
|---------------------|-----------|----------------|----------------|------|--------|--------|
| Dar and Shaviv      | Yes       | 4.2(8σ)        | 109(2.6σ)      | 2.8(0σ) | 0.7     | 0.2     |
| YALE$^a$            | Yes       | 6.3(17σ)       | 125(4σ)        | 4.2(6σ) | 5.9     | 5.1     |
| AARHUS$^b$          | No        | 5.6(14σ)       | 122(4σ)        | 3.6(4σ) | 5.4     | 5.4     |
|                     | Yes       | 6.1(16σ)       | 124(4σ)        | 4.0(5σ) | 5.8     | 5.8     |
| Profitt$^c$         | Yes       | 6.3(17σ)       | 126(4σ)        | 4.2(6σ) | 6.3     | 5.5     |
| FRANEC$^d$          | No        | 5.8(15σ)       | 123(4σ)        | 3.9(5σ) | 4.9     | 4.2     |
| ASTRA$^e$           | No        | 5.7(15σ)       | 123(4σ)        | 3.7(4σ) | 4.2     | 3.5     |

$^\dagger$Units: $10^6$ cm$^{-2}$s$^{-1}$; $^*$Units: $10^6$ cm$^{-2}$s$^{-1}$.

$^a$cf. Ref.18 Includes helium and heavy element diffusion, as well as other improvements.

$^b$cf. Ref.21 Second model includes helium diffusion.

$^c$cf. Ref.19 Includes helium and heavy element diffusion.

$^d$cf. Ref.20 Does not include diffusion.

$^e$cf. Ref.22 Analogous to the Best model without diffusion of ref.15.
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