Solar Neutrinos: What We Have Learned\(^1\)

John N. Bahcall

Institute for Advanced Study, Olden Lane, Princeton, NJ 08540

Abstract. Four solar neutrino experiments are currently taking data. The results of these experiments confirm the hypothesis that the energy source for solar luminosity is hydrogen fusion. However, the measured rate for each of the four solar neutrino experiments differs significantly (by factors of 2.0 to 3.5) from the corresponding theoretical prediction that is based upon the standard solar model and the simplest version of the standard electroweak theory (zero-neutrino masses, no flavor mixing).

If standard electroweak theory is correct, the energy spectrum for $\bar{\nu}_e$ neutrinos created in the solar interior must be the same (to one part in $10^5$) as the known laboratory $\bar{\nu}_e$ neutrino energy spectrum. A direct comparison of the chlorine and the Kamiokande experiments, both of which are sensitive to $\bar{\nu}_e$ neutrinos, suggests that the discrepancy between theory and observations depends upon neutrino energy, in conflict with standard expectations. Monte Carlo studies with 1000 implementations of the standard solar model indicate that the chlorine and the Kamiokande experiments cannot be reconciled unless new weak interaction physics changes the shape of the $\bar{\nu}_e$ neutrino energy spectrum. The boundary conditions that the solar model luminosity equals the current observed photon luminosity and that the solar model must be consistent with helioseismological measurements are two of the strongest reasons that the predictions of the standard solar model are robust.

The results of the two gallium solar neutrino experiments strengthen the conclusion that new physics is required and help determine a relatively small allowed region for the MSW neutrino parameters. New experiments that will start in 1996 will test–independent of solar models–the inference that physics beyond the standard electroweak model is required to resolve the solar neutrino problem.

Keywords. Solar Neutrinos, Sun, Electroweak Physics

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1 Evry Schatzman and Nuclear Energy Generation

Like everyone here, I am indebted to Evry Schatzman for insight and for inspiration concerning a number of different problems that will be discussed in this symposium. But, I would like to draw special attention to a fundamental contribution that he made in 1951 which has become an essential element in the discussion of the solar neutrino problem and of the more general question of how main sequence stars shine. In an important paper in *Comtes Rendus*, Schatzman [1] pointed out that the most likely termination of the pp chain was via the reaction \( ^3He + ^3He \rightarrow ^4He + p + p \). He correctly stressed that the reaction he was proposing was most likely at relatively low stellar interior temperatures and at relatively high densities. The \(^3He - ^3He\) reaction involves the fusion of two ambient \(^3He\) nuclei and, to the best of my knowledge, had not been previously discussed. Equation (3) of Schatzman’s paper describes what is currently believed to be the dominant cycle for the fusion of four protons to provide energy in the solar interior. The suggestion of the dominant role of the \(^3He + ^3He\) reaction is only one of Schatzman’s many fundamental contributions but it illustrates the remarkable originality, depth, and breadth of his thinking.

2 Introduction

I will review the present status of solar neutrino astronomy and solar neutrino physics, with special emphasis on the discrepancy between the predicted and the observed counting rates in the experiments designed to detect solar neutrinos.

Since this symposium is partially a historical retrospective, it is interesting to begin with an ironic aspect of the proposal in 1964 [2, 3] that a practical solar neutrino experiment could be carried out using a chlorine detector. If you look back at those two papers, you will see that the only motivation presented for doing the experiment was to use neutrinos “...to see into the interior of a star and thus directly verify the hypothesis of nuclear energy generation in stars.” The energy-generating process being tested is

\[
4p \rightarrow ^4He + 2e^+ + 2\nu_e + 25 \text{ MeV},
\]

by which four protons are burned to form an alpha particle, two positrons, two neutrinos, and thermal energy.

The goal of demonstrating that Eq. (1) is the origin of sunshine has been achieved. Solar neutrinos have been observed in four experiments with, to usual astronomical accuracy (a factor of two or three), about the right numbers and about the right energies. Moreover, the
fact that the neutrinos come from the sun was established directly by the Kamiokande II experiment which showed that electrons scattered by neutrinos recoil in the forward direction from the sun. These experimental results represent, in my view, a great triumph for the physics, chemistry, and astronomy communities since they bring to a successful conclusion the development (which spanned much of the 20th century) of a theory of how main sequence stars shine.

However, most of the current interest in solar neutrinos is focused on an application of solar neutrino research that was not discussed or even considered at the time of the original experimental and theoretical proposals. It has subsequently been realized that one can use solar neutrinos for studying experimentally aspects of the weak interactions that are not currently accessible in laboratory experiments. These studies of new physics are based upon the quantitative discrepancy between the predictions and the observations for solar neutrinos. To evaluate the significance of these discrepancies, one must carry out more precise calculations and pay closer attention to the theoretical uncertainties than is conventional in most stellar interior studies. I will therefore discuss at some length the uncertainties in the theoretical calculations.

Nearly everyone in this room is an astronomer. Therefore, you will immediately recognize how the possible discovery of new physics with solar neutrinos differs from the astronomical discoveries with which you are familiar. Astronomical discoveries, like the finding of quasars, of pulsars, of x-ray binaries with neutron stars or black holes, of strong infrared sources, of x-ray bursters and γ-ray bursters, of very young stars and very old galaxies, all resulted from pointing telescopes with exceptional equipment and finding something unpredicted but recognizable by qualitative features. Unfortunately, discoveries made using solar neutrinos are different. No one has an intuitive feel for how many solar neutrino events ought (or ought not) to be seen per year in a large detector. Precise quantitative predictions must be made in order to determine if we have learned something new. The estimated uncertainties in those predictions are crucial for deciding on whether discoveries have been made.

When we compare solar neutrino calculations with solar neutrino observations, we begin with a combined standard model, the standard model of electroweak theory plus the standard solar model. We need the standard solar model to tell us how many neutrinos of what energies are produced in the solar interior. And, we need the standard electroweak model—or some modification of the standard electroweak model—to tell us what happens to the neutrinos after they are created. We need to know how neutrinos are affected when they pass through the enormous amount of matter in the sun and travel the great distance from the solar interior to detectors on earth.
Do neutrinos change their flavor from electron-type to some other type during their journey from the sun to the earth? The simplest version of the standard electroweak model says: "No." Neutrinos have zero masses in this model and lepton flavor is conserved. Nothing happens to the neutrinos after they are created.

It turns out that one can learn an enormous amount about neutrinos by observing experimentally what happens to solar neutrinos after they are created. This fact is largely responsible for the great current interest in solar neutrinos.

There are four operating solar neutrino experiments, three of which use radiochemical detection (one chlorine and two gallium detectors) and one detector which is electronic (the Kamiokande pure water detector).

The first, and for two decades the only, solar neutrino experiment uses a radiochemical chlorine detector to observe electron-type neutrinos via the reaction (2):

\[
\nu_e + ^{37}\text{Cl} \rightarrow e^- + ^{37}\text{Ar}.
\]

The \(^{37}\text{Ar}\) atoms produced by neutrino capture are extracted chemically from the 0.6 kilotons of fluid, \(C_2\text{Cl}_4\), in which they are created and are then counted using their characteristic radioactivity in small, gaseous proportional counters. The threshold energy is 0.8 MeV. The chlorine solar neutrino experiment is described by Davis [4] and references quoted therein.

The second solar neutrino experiment to have been performed, Kamiokande II [5, 6, 7] is based upon the neutrino-electron scattering reaction,

\[
\nu + e \rightarrow \nu' + e',
\]

which occurs inside the fiducial mass of 0.68 kilo-tons of ultra pure water. Only 8 solar neutrinos are detectable in the Kamiokande II experiment, for which the lowest published value for the detection threshold is 7.5 MeV. In the Kamiokande II experiment, the electrons are detected by the Cerenkov light that they produce while moving through the water. Neutrino scattering experiments provide information that is not available from radiochemical detectors, including the direction from which the neutrinos come, the precise arrival times for individual events, information about the energy spectrum of the neutrinos, and some sensitivity to muon and tau neutrinos.

The fact that the neutrinos are coming from the sun is established by the Kamiokande II experiment since the electrons are scattered in the forward direction in reaction Eq. (3). The observed directions of the scattered electrons trace out the position of the sun in the sky.

There are two gallium experiments in progress, GALLEX [8, 9] and SAGE [10, 11, 12], that provide the first observational information about the low energy neutrinos from the
basic proton-proton reaction. The GALLEX and SAGE experiments make use of neutrino absorption by gallium,

$$\nu_e + ^{71}\text{Ga} \rightarrow e^- + ^{71}\text{Ge},$$

which has a threshold of only 0.23 MeV for the detection of electron-type neutrinos. This low threshold makes possible the detection of the low energy neutrinos from the proton-proton (or $pp$) reaction; the $pp$ reaction initiates the nuclear fusion chain in the sun by producing neutrinos with a maximum energy of only 0.42 MeV. Both the GALLEX and the SAGE experiments use radiochemical procedures to extract and count a small number of atoms from a large detector, similar to what is done in the chlorine experiment.

Figure 1 shows a comparison between the predictions of the standard model [13] and the four operating solar neutrino experiments [4, 5, 6, 7, 8, 9, 10, 11, 12]. The unit used for the three radiochemical experiments is a $SNU = 10^{-36}$ events per target atom per second. The result for the Kamiokande water experiment is expressed, following the experimentalists, in terms of a ratio to the predicted event rate. The errors shown are, in all cases, effective $1\sigma$ uncertainties, where I have combined quadratically the quoted statistical and systematic errors. I will use throughout this review the standard solar model results of Bahcall and Pinsonneault [13] since this is the only standard solar model published so far to take account of helium diffusion. However, accurate solar models without helium diffusion have been published by many other authors and are in good agreement with the Bahcall-Pinsonneault solar model without helium diffusion.

All four of the solar neutrino experiments yield values less than the predicted value for that detector and outside the combined errors. I shall present later in this talk a detailed comparison between the theoretical predictions and the measured rates. However, one fact is apparent already from Figure 1. The discrepancy between theory and observation is about a factor of 3.5 for the chlorine experiment, whereas the discrepancy is only a factor of 2.0 for the Kamiokande experiment. These two experiments are primarily sensitive to the same neutrino source, the rare, high-energy $8\bar{\nu}$ solar neutrinos (maximum neutrino energy of 15 MeV). Thus the disagreement between theory and experiment seems to depend upon the threshold for neutrino detection, being larger for chlorine (0.8 MeV threshold) than for the Kamiokande (water) experiment (7.5 MeV threshold). This may be the most significant fact about the solar neutrino problem.
Table 1. Neutrino Fluxes

| Source | Flux |
|--------|------|
| (10^{10} \text{ cm}^{-2}\text{s}^{-1}) | p-p 6.0 (1 \pm 0.007) |
| pep & 1.4 \times 10^{-2} (1 \pm 0.012) |
| hep & 1.2 \times 10^{-7} |
| 7\text{Be} & 4.9 \times 10^{-1} (1 \pm 0.06) |
| 8\text{B} & 5.7 \times 10^{-4} (1 \pm 0.14) |
| 13\text{N} & 5 \times 10^{-2} (1 \pm 0.17) |
| 15\text{O} & 4 \times 10^{-2} (1 \pm 0.19) |

3 Theoretical Neutrino Fluxes

Table 1 shows the solar neutrino fluxes computed with the aid of the standard solar model. The \(pp\) neutrino flux is predicted to be the largest flux by an order of magnitude, but is not observable in the chlorine and in the Kamiokande experiments. Only the gallium experiments have a low enough threshold to be sensitive to the \(pp\) neutrinos. The second most abundant neutrino source is \(7\text{Be}\), which produces two lines. The \(7\text{Be}\) neutrinos are expected to contribute a small amount to the capture rate in the chlorine experiment (15\% of the total standard model prediction) and a somewhat larger fraction (25\% of the total rate) to the gallium experiment, but are below threshold in the Kamiokande experiment.

The most easily detected neutrinos are the very rare, but higher-energy, \(8\) neutrinos. They are predicted to be four orders of magnitude rarer than the low-energy \(pp\) neutrinos, but because the \(8\) neutrinos have relatively high energies they dominate the predicted capture rate for the chlorine experiment (almost 80\% of the total predicted rate) and are the only neutrino source to which the Kamiokande experiment is sensitive.

Table 1 shows the most important neutrino fluxes and the effective 1\(\sigma\) error bars that have been calculated with the standard solar model. The size of the uncertainties is of critical importance. I have therefore devoted a full chapter, Chapter 7, in my book *Neutrino Astrophysics* to the estimation of the errors in each neutrino flux. For a recent detailed calculation of the errors and a comparison with the uncertainties estimated by different authors, see Ref. [13].

The \(pp\) neutrinos are calculated with a precision that is better than 1\%. The next most abundant neutrinos, the \(7\text{Be}\) neutrinos, are calculated with an uncertainty of \(\pm 6\%\). The rare
8 neutrinos are calculated with the least accuracy, ±14%. Unfortunately, the easier solar neutrinos are to detect, the more difficult they are to calculate.

4 Comparison of the Chlorine and the Electron-Scattering Experiments with Theory

We will now compare the results of the chlorine and the electron-scattering (Kamiokande) experiments with the theoretical expectations for each experiment. The predicted event rate, $8 \pm 1$ SNU, for the chlorine experiment is dominated by the 6.2 SNU from the rare $^8$Be neutrinos. The next most important source, according to the standard model, for this experiment is the electron-capture line from $^7$Be, which is predicted to produce a 1.2 SNU capture rate. The $^{pep}$ and CNO neutrinos are expected to produce together a rate of 0.6 SNU.

The experimental rate is $2.28 \pm 0.23$ SNU.

In order to assess the significance of the disagreement between theory and observation for the solar neutrino experiments, I have performed a series of Monte Carlo calculations. The results are shown in Figure 2, which was constructed using the results from a thousand implementations of the standard solar model. For each model, all of the important input parameters (including nuclear reaction rates and chemical composition) were chosen from normal distributions that had means and standard distributions equal to the experimentally-determined values. For each solar model, every parameter was chosen from its own normal distribution and the solar calculations were iterated to match the observed characteristics of the present-day sun. This procedure is required in order to take account of the strong effects of boundary conditions and the coupling of different calculated neutrino fluxes that exists among the solutions of the coupled partial differential equations of stellar evolution.

None of the 1,000 solar models represented in Figure 2 has a neutrino flux that is in agreement with the observed rate.

Figure 3 shows a similar comparison for the neutrino-electron scattering (Kamiokande II) experiment and the 1000 solar models. The Kamiokande II experiment is only sensitive to the high-energy side of the $^8$ neutrino energy spectrum. Although for the Kamiokande II experiment none of the 1000 solar models are consistent with the observed value, the discrepancy is only a factor of two [6, 7] in this case (compared to the factor of 3.5 for the chlorine experiment which has an energy threshold an order-of-magnitude lower).

Can one understand why the Monte Carlo simulations produce such well-defined theoretical predictions? Yes, there are at least five reasons, which I list below in what I judge to be the relative order of importance. 1) The luminosity boundary condition requires that
the computed photon luminosity of the present-day solar model equals the measured solar luminosity, \( L_\odot \), which is known experimentally to an accuracy of about two parts in a thousand. If one oversimplifies the problem of stellar evolution and represents the output of a solar model in terms of just the central temperature, \( T_c \) (as is done in several recent papers by different authors), then the flux of the most-sensitive neutrino branch, the \(^8\)B neutrinos is \( \phi(8\text{B}) \propto T_c^{18} \) and the luminosity \( L_\odot \propto T_c^4 \). One concludes by this argument that the uncertainty in the \(^8\)B neutrino flux is very small,

\[
\frac{\Delta \phi(8\text{B})}{\phi(8\text{B})} = \frac{18}{4} \times \frac{\Delta L_\odot}{L_\odot} < 0.01.
\]  

(5)

This argument suggests that the uncertainty in the \(^8\)B neutrino flux is less than 1%. Actually, the uncertainty I estimate is very much larger, 14%. The reason for the discrepancy between Eq. (5) and the uncertainty obtained from a detailed analysis is that the representation of a solar model in terms of just a central temperature is a gross oversimplification. (The computed neutrino flux is an integration of the local production rate over the temperature-density profile of the model sun and also depends, for example, in different ways upon the different input nuclear cross sections.) Nevertheless, you can see by this argument that the luminosity boundary condition provides a severe constraint on the allowed values of the neutrino fluxes. 2) The precision of the input parameters has greatly improved over the years as many individuals and groups (physicists, chemists, and astronomers) have remeasured and recalculated the quantities required to determine the solar model neutrino fluxes. The recently-evaluated uncertainties are relatively small, in large part, because of this successful community effort. 3) Helioseismologists have measured the frequencies of thousands of solar pressure modes to an accuracy of better than one part in a thousand. The standard solar modes used to calculate solar neutrino fluxes reproduce the measured \( p-mode \) eigenfrequencies to typically one part in a thousand, establishing the basic correctness of the solar model to a depth of at least half the solar radius. One no longer has the freedom to speculate about radically different possible solar models because of the many precisely measured helioseismological frequencies. 4) The sun is in a simple state of stellar evolution, the main sequence, and we know more about it experimentally than about any other star. The physics of the interior of the sun is relatively simple; for example, detailed corrections to the equation of state are only of order of a few percent. 5) There are many input parameters, including the cross sections for all of the relevant nuclear reactions, the solar luminosity, and the surface heavy element abundances. In any particular time period, the improvements in some of these parameters cause the calculated neutrino event rates to increase and the improvements in other parameters cause the calculated neutrino event rates to decrease. On the average, the best-estimate for the chlorine experiment has remained within a narrow range over the past
25 years (see Figure 1.2 of Ref. [14]). If we consider all of my published calculations in which a full evaluation was made including an estimated theoretical error, then the range over the last quarter century has been between 5.8 SNU and 10.5 SNU, the midpoint of which is within 0.3 SNU of the current best estimate.

5 Direct Comparison of Chlorine and Electron-Scattering Experiments

The chlorine and the Kamiokande experiments are sensitive, to a large extent, to the same neutrino source, the rare $^8\bar{\nu}$ neutrinos. The Kamiokande experiment measures only $^8\bar{\nu}$ neutrinos. For the chlorine experiment, about 78% of the standard-model calculated rate is from the same source. The chlorine and the Kamiokande experiments differ in that the threshold for chlorine (0.8 MeV) is about an order-of-magnitude larger than for Kamiokande (7.5 MeV).

We will compare directly the results for these two experiments using a lemma, proved in Ref. [15], that states that the shape of the $^8\bar{\nu}$ neutrino spectrum that is produced in the center of the sun is the same, to an accuracy of one part in $10^5$, as the shape of the known spectrum that is produced in terrestrial laboratories. The largest imprints of the solar environment are caused by Doppler shifts and by the gravitational redshift, but both of these effects are negligibly small for our purposes. Therefore, the shape of the neutrino spectrum must be the same in a terrestrial laboratory and in the center of the sun unless physics beyond the standard electroweak model causes energy-dependent changes in the neutrino spectrum.

We know from the Kamiokande experiment how many $^8\bar{\nu}$ neutrinos reach the earth with energies about 7.5 MeV. If standard electroweak theory is correct, then we can extend the laboratory $^8\bar{\nu}$ spectrum, normalized by the Kamiokande results, down to 0.8 MeV, the threshold for the chlorine experiment. This leads to a minimum predicted rate for the chlorine experiment based on scaling the Kamiokande results down to the chlorine threshold and on ignoring all other neutrino sources except the rare $^8\bar{\nu}$ neutrinos. This minimum value is

$$\text{Cl Rate (}^8\text{B only)} = \left( \frac{\text{Rate Observed}}{\text{Rate Predicted}} \right)_{\text{Kamiokande}} \times 6.2 \text{ SNU},$$

or

$$\text{Cl Rate (}^8\text{B only)} \geq 3.1 \text{ SNU} > 2.2 \text{ SNU}.$$
In Eq. (6), 6.2 SNU is the capture rate for chlorine that is predicted by the standard model for just the \( \bar{8} \) neutrinos. The result shown in Eq. (7) indicates that the flux of just \( \bar{8} \) neutrinos that are seen in the Kamiokande II experiment is by itself sufficient to yield a capture rate in excess of the chlorine experimental value of \( 2.28 \pm 0.23 \) SNU. The additional neutrinos from other, more reliably calculated branches of the \( pp \) fusion chain, further increase the discrepancy.

What is the most serious mistake that we could have made in the solar model calculations? The most crucial error would have been to have calculated wrongly the \( \bar{8} \) neutrino flux since only \( \bar{8} \) neutrinos are observed in the Kamiokande experiment and \( \bar{8} \) neutrinos also account for nearly 80% of what is expected in the chlorine experiment. Suppose that this flux was calculated wrongly, perhaps because all of the laboratory nuclear physics measurements of the reaction that produces \( \bar{8} \) have been seriously in error. Would it then be possible to reconcile the chlorine and the Kamiokande experiments?

The answer to this question is given in Figure 4 and is “No”. For each of the 1000 solar models discussed earlier, I have replaced the calculated \( \bar{8} \) flux by a value drawn from a normal distribution with the mean and the standard deviation determined by the Kamiokande experiment. This assumption reduces ad hoc the mean rate by about 3.1 SNU, as indicated by Eq. (7). The resulting histogram is now centered just below 5 SNU, instead of at 8 SNU, as in the unfudged original calculations (see Figure 2). In addition, the width of the histogram is much narrower than in the actual calculations because the contribution of the \( \bar{8} \) neutrinos is reduced and \( \bar{8} \) neutrinos are the most uncertain of all the solar neutrino sources.

Even in the worst case scenario shown in Figure 4, in which the normalization of the \( \bar{8} \) neutrino flux is artificially adjusted to equal the measured Kamiokande II value, the calculated rate for the chlorine experiment is many experimental standard deviations larger than the observed rate. Hans Bethe and I have concluded [16] on the basis of Figure 4 that either new physics (beyond the standard electroweak model) is required to change the shape of the \( \bar{8} \) neutrino energy spectrum or one of the two experiments (chlorine and Kamiokande II) is wrong.

6 The Gallium Experiments: Further Evidence

More than half (54%), or 71 SNU, of the predicted standard model event rate, \( 132^{+7}_{-6} \) SNU, in the gallium experiments comes from the low-energy \( pp \) neutrinos. The standard flux of these neutrinos can be calculated with precision (accuracy exceeding 1%). They are not observable with any of the other currently-operating experiments (or even other funded experiments under development). The \( ^7Be \) neutrinos, which can be calculated with moderately high
precision (6%), also contribute significantly to the predicted standard capture rate, 36 SNU, or 27% of the total gallium rate. The 8 neutrinos, which dominate—according to the standard model—the chlorine and the Kamiokande II experiments, contribute less than 10% to the standard theoretical rate.

As shown in Figure 1, the capture rates measured in the GALLEX and the SAGE solar neutrino experiments are both about 2.9 SNU below the standard model predictions. These results strengthen the conclusion that new physics is required to explain the solar neutrino problem. Since the gallium experiments are most sensitive to low energy neutrinos and the chlorine and Kamiokande II experiments are most sensitive to higher-energy neutrinos, the results from the SAGE and GALLEX experiments cannot be compared directly with the chlorine or the Kamiokande II experiments without introducing a specific theoretical model.

### 7 Which New Physics?

The two most popular mechanisms for explaining the solar neutrino problem via new physics are vacuum neutrino oscillations, first discussed in this connection by Gribov and Pontecorvo [17] in an epochal paper, and matter-enhanced neutrino oscillations, the MSW effect, a beautiful idea discovered by Wolfenstein [18] and by Mikheyev and Smirnov [19]. Other solutions have been proposed for the solar neutrino problem that involve new weak interaction physics. These other solutions include rotation of the neutrino magnetic moment [20], matter-enhanced magnetic moment transitions [21], and neutrino decay [22].

If new physics is required, then the MSW effect is in my view the most likely candidate. Non-zero neutrino masses and mixing angles are required for the MSW effect to occur in a plausible way, but the indicated masses and mixing angles are within the range that is expected on the basis of Grand Unified Theories. The MSW effect can work without fine tuning and with a natural extension of the simplest version of the standard electroweak model. If the MSW effect is the explanation of the solar neutrino problem, then the chlorine, gallium, and Kamiokande experimental results (summarized in Figure 1) imply that at least one neutrino coupled to the electron-flavor neutrino has mass and mixing angle that satisfy [23]:

\[
\delta m^2 \sim 10^{-5} \text{ eV}^2 \quad \text{and} \quad \sin^2 2\theta \sim 10^{-2} \quad \text{or} \quad \delta m^2 \sim 10^{-5} \text{ eV}^2 \quad \text{and} \quad \sin^2 2\theta \sim 0.6.
\]

### 8 New Experiments

Table 2 describes the five new solar neutrino experiments that are funded for operation or for development. Each of the modes of each of the experiments listed in Table 2 is expected to yield more than 3,000 neutrino events per year (except for the $\nu - e$ scattering mode of
Table 2. New Solar Neutrino Observatories

| Observatory     | $E_{TH}(\nu)$ (MeV) | Reaction(s)                                                                 |
|-----------------|----------------------|-----------------------------------------------------------------------------|
| SNO             | 6.4                  | $\nu_e + ^2\text{H} \rightarrow p + p + e^-$                                |
|                 | 2.2                  | $\nu + ^2\text{H} \rightarrow n + p + \nu$                                |
|                 | 5                    | $\nu + e^- \rightarrow \nu + e^-$                                          |
| Super-Kamiokande | 5                    | $\nu + e^- \rightarrow \nu + e^-$                                          |
| ICARUS          | $\sim 10$            | $\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^*$               |
|                 | 5                    | $\nu + e^- \rightarrow \nu + e^-$                                          |
| BOREXINO        | 0.4                  | $\nu(^7\text{Be}) + e^- \rightarrow \nu(^7\text{Be}) + e^-$                |
| HELLAZ          | 0.1                  | $\nu + e^- \rightarrow \nu + e^-$                                          |

SNO). In one year, each experiment will record more than three times the total number of neutrino events that have been counted to date in all solar neutrino experiments since the chlorine experiment began operating a quarter of a century ago. With this greater statistical accuracy, solar neutrino physics will become a more precise subject.

The experiments are listed in order of their expected completion dates: SNO (1996 [24]), Superkamiokande (1996; see Ref. [25, 26], BOREXINO ($\geq 1996$; [27]), ICARUS (1998; see Ref. [28]), and HELLAZ (proposed, not yet approved [29]). Table 2 lists the neutrino threshold energy for each reaction mode and the individual reactions that will be observed. I have not listed other promising experimental proposals because it is not yet clear which of these possibilities will receive funding. In particular, a prototype detector of $pp$ neutrinos making use of the properties of superfluid helium has been tested successfully and appears to be feasible [30, 31]. It is clear, however, that the experiments listed in Table 2 will be insufficient to uniquely solve for all of the fundamental neutrino parameters. Other experiments are required to establish uniqueness in the inferences and to provide
a measure of redundancy to assure ourselves that systematic experimental uncertainties have not misled us.

The SNO experiment has two capabilities for testing, independent of solar models, the inference that physics beyond the standard model is required. They are: 1) SNO will measure the energy spectrum of electron-flavor neutrinos above 5 MeV in the charged current reaction (neutrino absorption by deuterium) and 2) SNO will measure the total neutrino flux independent of flavor in the neutral current reaction (neutrino disintegration of deuterium).

As emphasized earlier, the shape of the $\nu_\ell$ neutrino energy spectrum is independent of solar-model uncertainties. A measurement of the neutrino energy spectrum could establish that physics beyond the standard electroweak model is required.

The comparison of the neutrino fluxes measured via neutrino absorption on deuterium and by neutrino disintegration of deuterium will test the equality of the charged and the neutral currents. If the total neutrino flux is not equal to the electron neutrino flux, this would be direct evidence for neutrino flavor changing. The charged and neutral currents must be equal unless some neutrinos change their flavor after they are created in the solar core. Unfortunately, no energy information will be available for the neutral current detection. Also, the neutral and charged-current fluxes would be equal even if some of the original electron-type neutrinos changed into sterile neutrinos.

Like SNO, ICARUS can measure the shape of the $\nu_\ell$ neutrino energy spectrum via neutrino absorption. Moreover, ICARUS has a unique “smoking-gun” signal for neutrino absorption, the $\gamma$ decay of the excited state of $^{40}\text{K}$.

There will be welcome redundancy if all experiments operate as planned. Three experiments (Superkamiokande, SNO, and ICARUS) will measure for $\nu_\ell$ the $\nu_e - e$ scattering rate and the recoil electron energy spectrum; the electron recoil spectrum reflects the incoming neutrino energy spectrum. The fact that the Superkamiokande experiment contains more than 30 times the fiducial volume for solar neutrino experiments as the highly-productive Kamiokande experiment is an indication of the amount of improvement that may be expected in the next generation of solar neutrino experiments compared to those performed to date.

The BOREXINO and HELLAZ experiments are essential in order to distinguish between different new-physics possibilities. These experiments are the only ones currently under development that will measure the energy of individual events with energies less than 5 MeV. The threshold for BOREXINO is 0.4 MeV and for HELLAZ is 0.1 MeV. These experiments must be performed in order to determine the neutrino survival probability at low energies. The BOREXINO and HELLAZ experiments also have another highly desirable feature; they will both measure the $\nu_e$ flux at a specific energy, the energy (0.86 MeV) of the $^7\text{Be}$ neutrino
line. The theoretical predictions are more specific, and therefore the measurements are more diagnostic, when the neutrino flux at a specific energy is observed.

The HELLAZ experiment is unique among the experiments being developed; it is the only experiment being developed to observe individual events from the basic $pp$ reaction (maximum energy $0.4$ MeV). In addition, HELLAZ has the energy resolution to potentially measure the predicted $^{32}$ $1.29$ keV shift between the average energy of the solar $^7$Be line and the laboratory energy of the line. A measurement of this energy shift, which is due to thermal effects in the center of the sun, is equivalent to a direct measurement of the central temperature of the sun.

## 9 Conclusions

The field of solar neutrino research is flourishing. The four operating experiments have confirmed that the sun shines via nuclear fusion reactions that produce MeV neutrinos (see Eq. (1)). There are differences between the predictions and the observations (see Figure 1), but these differences are within the usual range of astronomical uncertainties (generally a factor of two or three). The agreement between theory and observation is, from the astronomical point of view, remarkably good because the calculated neutrino fluxes depend sensitively upon the interior conditions.

Nevertheless, all four experiments disagree with the corresponding theoretical predictions based upon the simplest version of the standard electroweak theory. These disagreements are larger than the estimated uncertainties. The luminosity boundary condition and the helioseismological measurements are especially important in guaranteeing the robustness of the theoretical predictions (see discussion in 4). Monte Carlo experiments that make use of 1000 implementations of the standard solar model indicate that the chlorine and the Kamiokande II (water-Cerenkov) experiments cannot be reconciled without an energy-dependent change in the $8$ solar neutrino spectrum relative to the laboratory spectrum (see Figure 2-Figure 4). New physics is required to explain an energy-dependent change in the shape of the neutrino spectrum. The gallium experiments, GALLEX and SAGE, strengthen the conclusion that new physics is required.

New experiments, SNO, Superkamiokande, and ICARUS, will test the conclusion that new physics is required independent of uncertainties due to solar models. These experiments can determine the shape of the $8$ solar neutrino energy spectrum and whether or not electron-flavor neutrinos have oscillated into some other flavor neutrinos.

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Figure Captions

Figure 1. Comparison of measured rates [4, 5, 6, 7, 8, 9, 10, 11, 12] and standard-model predictions [13] for four solar-neutrino experiments.

Figure 2. 1000 solar models vs experiments [16]. The number of precisely calculated solar models that predict different solar neutrino event rates are shown for the chlorine experiment [4]. 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 bar includes only statistical errors (1σ).

Figure 3. 1000 solar models vs experiments [16]. The number of precisely calculated solar models that predict different solar neutrino event rates are shown for the Kamiokande experiment [5, 6]. 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. 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 bar includes only statistical errors (1σ).

Figure 4. 1000 artificially modified fluxes [16]. The 8B 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 [5, 6].
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