

Solar models and solar neutrinos

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Abstract

I provide a summary of the current theoretical knowledge of solar neutrino fluxes as derived from precise solar models.

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1 Introduction

I summarize in this talk the present state of solar model research as the subject relates to solar neutrino investigations. This is not a review talk. I will focus on the latest developments. [In a few places, I will add comments within square brackets on results that have been obtained since the symposium took place.]

To establish the appropriate context for our discussion, I note that measurements of the sound speed inside the Sun (via a technique called helioseismology, which is similar to terrestrial seismology) agree with solar model predictions to a root-mean-square accuracy of better than 0.1%. This excellent agreement between the measured and predicted sound speeds established as early as 1996 that the solution of the "solar neutrino problem" lay in new particle physics, not new astrophysics [1].

There are two specific reasons for continuing to study the solar neutrino fluxes that are predicted by precise solar models. First, the model predictions must be refined (uncertainties reduced) in order to use optimally the neutrino observations to provide information about the interior of the Sun and about some of the parameters used in solar and stellar models. Second, the theoretical knowledge of the neutrino fluxes can be used, in combination with solar neutrino experiments, to refine neutrino parameters such as Δm_{21}^2 and $\tan^2 \theta_{12}$ (see, e.g., [2]).

More generally, we want to use solar models and solar observations as a laboratory for testing and improving the theory of stellar evolution, the theory of how stars shine and evolve. The Sun is the nearest star to Earth and we have much more information about the Sun than about any other star. We can use the comparison between the predictions of precise solar models and the observations of solar properties to explore and refine the theory of stellar evolution. Almost every branch of astronomy and astrophysics uses stellar evolution theory, in one way or another, to interpret observations of distant stars and the elements they produce.

Recent measurements of the surface chemical composition of the Sun have posed a new 'solar problem', a problem that does not have significant implications for neutrinos but may be of importance for the theory of stellar evolution and perhaps for other branches of astronomy. My own work has been focused recently on this aspect of solar models and I will comment briefly on the subject toward the end of my talk.

I begin in Section 2 by summarizing the standard solar model predictions of solar neutrino fluxes. I also summarize the uncertainties in the predicted fluxes. For the first two and a half decades of the solar neutrino problem, the most critical theoretical issue was to establish that the uncertainties in the predictions were less than the discrepancies between the solar model predictions and the solar neutrino measurements. This goal was achieved somewhere between 1982 and 1966, depending upon the degree of skepticism toward astronomical calculations and measurements of the person making the judgment. Actually, for decades most physicists and a surprisingly large number of astronomers believed that inaccurate solar model calculations rather than neutrino properties were responsible for the solar neutrino problem. This situation changed dramatically with the publication of the first SNO experimental results in June, 2001, when it became clear to all that the solution of the solar neutrino problem was new physics rather than inadequate astronomy.

In Section 3, I comment briefly on the implications of recent measurements of the surface chemical

Table I: Predicted solar neutrino fluxes from solar models. The table presents the predicted fluxes, in units of $10^{10}(pp)$, $10^9(^7\text{Be})$, $10^8(pep, ^{13}\text{N}, ^{15}\text{O})$, $10^6(^8\text{B}, ^{17}\text{F})$, and $10^3(hep)$ $\text{cm}^{-2}\text{s}^{-1}$. Columns 2-4 show BP04, BP04+, and the previous best model BP00 [4]. Columns 5-7 present the calculated fluxes for solar models that differ from BP00 by an improvement in one set of input data: nuclear fusion cross sections (column 5), equation of state for the solar interior (column 6), and surface chemical composition for the Sun (column 7). Column 8 uses the same input data as for BP04 except for a recent report of the $^{14}\text{N} + \text{p}$ fusion cross section. References to the improved input data are given in the text. The last two rows ignore neutrino oscillations and present for the chlorine and gallium solar neutrino experiments the capture rates in SNU (1 SNU equals 10^{-36} events per target atom per sec). Due to oscillations, the measured rates are smaller: 2.6 ± 0.2 and 69 ± 4 , respectively. The neutrino absorption cross sections and their uncertainties are given in Ref. [5].

Source	BP04	BP04+	BP00	Nucl	EOS	Comp	^{14}N
<i>pp</i>	$5.94(1 \pm 0.01)$	5.99	5.95	5.94	5.95	6.00	5.98
<i>pep</i>	$1.40(1 \pm 0.02)$	1.42	1.40	1.40	1.40	1.42	1.42
<i>hep</i>	$7.88(1 \pm 0.16)$	8.04	9.24	7.88	9.23	9.44	7.93
^7Be	$4.86(1 \pm 0.12)$	4.65	4.77	4.84	4.79	4.56	4.86
^8B	$5.82(1 \pm 0.23)$	5.28	5.05	5.79	5.08	4.62	5.77
^{13}N	$5.71(1^{+0.37}_{-0.35})$	4.06	5.48	5.69	5.51	3.88	3.23
^{15}O	$5.03(1^{+0.43}_{-0.39})$	3.54	4.80	5.01	4.82	3.36	2.54
^{17}F	$5.91(1^{+0.44}_{-0.44})$	3.97	5.63	5.88	5.66	3.77	5.85
Cl	$8.5^{+1.8}_{-1.8}$	7.7	7.6	8.5	7.6	6.9	8.2
Ga	131^{+12}_{-10}	126	128	130	129	123	127

composition of the Sun. I conclude in Section 4 with a discussion of the role of neutrinos as dark matter, a subject treated at this symposium by Max Tegmark more extensively and from a different perspective.

2 Solar model fluxes

I base the discussion in this section on the results reported in the recent paper [3]. Full numerical details of the solar models, BP04 and BP00 that are discussed below are presented, together with earlier solar models in this series, at the Web site: <http://www.sns.ias.edu/~jnb>. In particular, the primordial hydrogen and helium mass fractions for the BP04 model discussed below are, respectively, $X_0 = 0.7078$ and $Y_0 = 0.2734$, while the current surface abundances are $X_S = 0.7397$ and $Y_S = 0.2434$.

2.1 Fluxes from different solar models

Table I, taken from Ref. [3], gives the calculated solar neutrino fluxes for a series of solar models calculated with different plausible assumptions about the input parameters. The range of fluxes shown for these models illustrates the systematic uncertainties in calculating solar neutrino fluxes. The second (third) column, labeled BP04 (BP04+), of Table I presents the current best solar model calculations for the neutrino fluxes. The uncertainties in the calculated neutrino fluxes are given in column 2. The model BP04 utilizes the older heavy element abundances on the surface of the Sun as summarized in the paper by Grevesse and Sauval (1998) [6]. The BP04+ model uses recently determined heavy element abundances [7], which are discussed in more detail in Section 3.

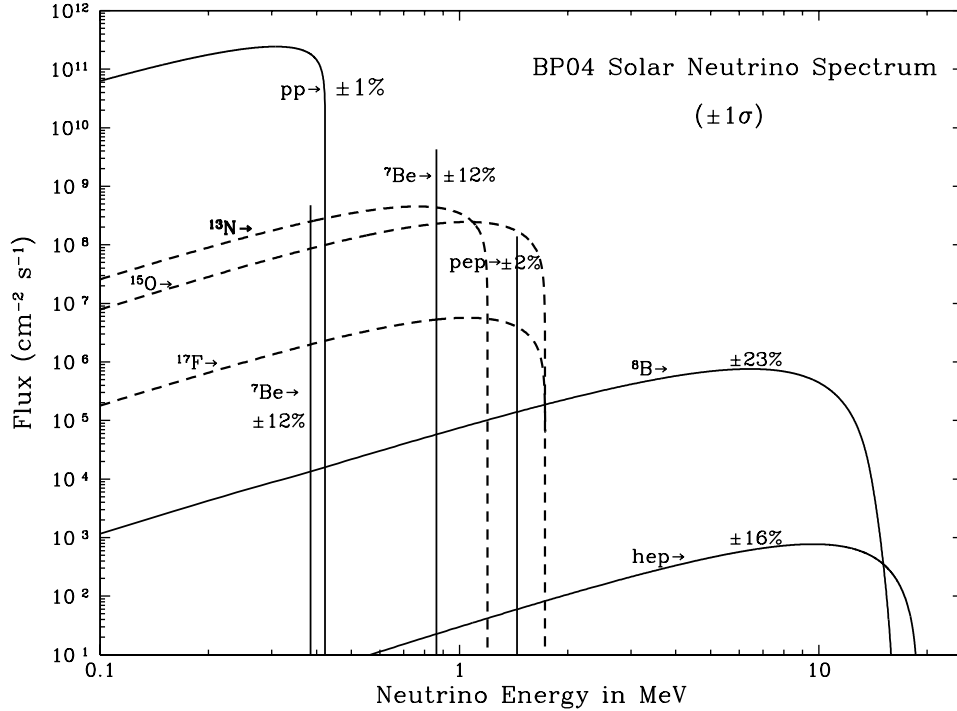


Figure 1: The predicted solar neutrino energy spectrum. The figure shows the energy spectrum of solar neutrinos predicted by the BP04 solar model [3]. For continuum sources, the neutrino fluxes are given in number per $\text{cm}^{-2}\text{sec}^{-1}\text{MeV}^{-1}$ at the Earth's surface. For line sources, the units are number per $\text{cm}^{-2}\text{sec}^{-1}$. The total theoretical uncertainties for the neutrinos in the p-p chain are taken from column 2 of Table I and are shown for each source. In order not to complicate the figure, I have omitted the very large uncertainties for the difficult-to-detect CNO neutrino fluxes (see Table I).

Figure 1 presents the neutrino energy spectrum predicted by the BP04 solar model for the most important solar neutrino sources.

The model BP04+ was calculated with the use of new input data for the equation of state, nuclear physics, and solar composition. The model BP04, the currently preferred model, is the same as BP04+ except that BP04 does not include the most recent analyses of the solar surface composition [7]. My collaborators and I prefer the model BP04 over the model BP04+ because the lower heavy element abundance used in calculating BP04+ causes the calculated sound speeds and the depth of the solar convective zone to conflict with helioseismological measurements [3, 8].

The error estimates, which are the same for the three models labeled BP04, BP04+, and ^{14}N in Table I) include the recent composition analyses. The differences between the neutrino fluxes calculated for the solar models BP04 and BP04+ are all well within the estimated uncertainties in the calculated fluxes. This is one way of seeing that the 'new solar problem' associated with the lower heavy element abundances that have been reported recently does not affect solar neutrino questions in a significant way.

Column four of Table I presents the fluxes calculated using the preferred solar model, BP00 [4], that was posted on the archives in October 2000 (prior to the first reported SNO measurement). The BP04 best-estimate neutrino fluxes and their uncertainties have not changed markedly from their BP00 values

despite refinements in input parameters. The only exception is the CNO flux uncertainties which have almost doubled due to the larger systematic uncertainty in the surface chemical composition estimated in this paper.

The columns 5-7 of Table I describe improvements in the input data relative to BP00, i.e., relative to our best standard solar model constructed in 2000. Quantities that are not discussed here are the same as for BP00. Each class of improvement is represented by a separate column, columns 5-7. The magnitude of the changes between the fluxes listed in the different columns of Table I are one measure of the sensitivity of the calculated fluxes to the input data.

Column 5 contains the fluxes computed for a solar model that is identical to BP00 except that improved values for direct measurements of the ${}^7\text{Be}(p,\gamma){}^8\text{B}$ cross section [9, 10], and the calculated p-p and hep cross sections [10]. The reactions that produce the ${}^8\text{B}$ and hep neutrinos are rare; changes in their production cross sections only affect, respectively, the ${}^8\text{B}$ and hep fluxes. The 15% increase in the calculated ${}^8\text{B}$ neutrino flux, which is primarily due to a more accurate cross section for ${}^7\text{Be}(p,\gamma){}^8\text{B}$, is the only significant change in the best-estimate fluxes.

The fluxes in Column 6 were calculated using a refined equation of state, which includes relativistic corrections and a more accurate treatment of molecules [11]. The equation of state improvements between 1996 and 2001, while significant in some regions of parameter space, change all the solar neutrino fluxes by less than 1%. Solar neutrino calculations are insensitive to the present level of uncertainties in the equation of state.

The most important changes in the astronomical data since BP00 result from new analyses of the surface chemical composition of the Sun. The input chemical composition affects the radiative opacity and hence the physical characteristics of the solar model, and to a lesser extent the nuclear reaction rates. New values for C,N,O,Ne, and Ar have been derived [7] using three-dimensional rather than one-dimensional atmospheric models, including hydrodynamical effects, and paying particular attention to uncertainties in atomic data and observational spectra. The new abundance estimates, together with the previous best-estimates for other solar surface abundances [6], imply a ratio of heavy elements to hydrogen by mass of $Z/X = 0.0176$, much less than the previous value of $Z/X = 0.0229$ [6]. Column 7 gives the fluxes calculated for this new composition mixture. The largest change in the neutrino fluxes for the p-p chain is the 9% decrease in the predicted ${}^8\text{B}$ neutrino flux. The N and O fluxes are decreased by much more, $\sim 35\%$, because they reflect directly the inferred C and O abundances. [Subsequent to the completion of the calculations described here, additional changes in the recently-determined heavy element abundances have been made and are reported in Ref. [12]. These additional changes are sufficiently small that they do not affect any of the conclusions expressed in the present review.]

The CNO nuclear reaction rates are less well determined than the rates for the more important (in the Sun) p-p reactions [13]. The rate for ${}^{14}\text{N}(p,\gamma){}^{15}\text{O}$ is poorly known, but is important for calculating CNO neutrino fluxes. Extrapolating to the low energies relevant for solar fusion introduces a large uncertainty. Column 8 gives the neutrino fluxes calculated with input data identical to BP04 except for the cross section factor $S_0({}^{14}\text{N} + p) = 1.77 \pm 0.2 \text{ keV b}$ that is about half the current best-estimate; this value assumes a

Table II: Principal sources of uncertainties in calculating solar neutrino fluxes. Columns 2-5 present the fractional uncertainties in the neutrino fluxes from laboratory measurements of, respectively, the ${}^3\text{He}$ - ${}^3\text{He}$, ${}^3\text{He}$ - ${}^4\text{He}$, p - ${}^7\text{Be}$, and p - ${}^{14}\text{N}$ nuclear fusion reactions. The last four columns, 6-9, give, respectively, the fractional uncertainties due to the calculated radiative opacity, the calculated rate of element diffusion, the measured solar luminosity, and the measured heavy element to hydrogen ratio.

Source	3-3	3-4	1-7	1-14	Opac	Diff	L_{\odot}	Z/X
pp	0.002	0.005	0.000	0.002	0.003	0.003	0.003	0.010
pep	0.003	0.007	0.000	0.002	0.005	0.004	0.003	0.020
hep	0.024	0.007	0.000	0.001	0.011	0.007	0.000	0.026
${}^7\text{Be}$	0.023	0.080	0.000	0.000	0.028	0.018	0.014	0.080
${}^8\text{B}$	0.021	0.075	0.038	0.001	0.052	0.040	0.028	0.200
${}^{13}\text{N}$	0.001	0.004	0.000	0.118	0.033	0.051	0.021	0.332
${}^{15}\text{O}$	0.001	0.004	0.000	0.143	0.041	0.055	0.024	0.375
${}^{17}\text{F}$	0.001	0.004	0.000	0.001	0.043	0.057	0.026	0.391

particular R-matrix fit to the experimental data [14]. The recent LUNA measurement [15] of the cross section factor $S_0({}^{14}\text{N} + \text{p})$ provides a firm experimental basis for the assumed smaller value of the cross section factor. The p-p cycle fluxes are changed by only $\sim 1\%$, but the ${}^{13}\text{N}$ and ${}^{15}\text{O}$ neutrino fluxes are reduced by 40% – 50% relative to the BP04 predictions. CNO nuclear reactions contribute 1.6% of the solar luminosity in the BP04 model and only 0.8% in the model with a reduced $S_0({}^{14}\text{N} + \text{p})$.

2.2 Flux uncertainties

Table II, also taken from Ref. [3], shows the individual contributions to the flux uncertainties. These uncertainties are useful in deciding how accurately we need to determine a given input parameter in order to improve the overall accuracy of the calculated neutrino fluxes. Moreover, the theoretical flux uncertainties continue to play a significant role in some determinations of neutrino parameters from solar neutrino experiments (see, e.g., Ref. [16]).

Columns 2-5 present the fractional uncertainties from the nuclear reactions whose measurement errors are most important for calculating neutrino fluxes. Unless stated otherwise, the uncertainties in the nuclear fusion cross sections are taken from Ref. [13].

The measured rate of the ${}^3\text{He}$ - ${}^3\text{He}$ reaction, which changed by a factor of 4 after the first solar model calculation of the solar neutrino flux [17], and the measured rate of the ${}^7\text{Be} + \text{p}$ reaction, which for most of this series has been the dominant uncertainty in predicting the ${}^8\text{B}$ neutrino flux, are by now very well determined. If the current published systematic uncertainties for the ${}^3\text{He}$ - ${}^3\text{He}$ and ${}^7\text{Be} + \text{p}$ reactions are correct, then the uncertainties in these reactions no longer contribute in a crucial way to the calculated theoretical uncertainties (see column 2 and column 4 of Table II). This felicitous situation is the result of an enormous effort extending over four decades, and represents a great collective triumph, for the nuclear physics community.

At the present time, the most important nuclear physics uncertainty in calculating solar neutrino fluxes is the rate of the ${}^3\text{He}$ - ${}^4\text{He}$ reaction (see column 3 of Table II). The systematic uncertainty in the rate of

$^3\text{He}(^4\text{He}, \gamma)^7\text{Be}$ reaction (see Ref. [13]) causes an 8% uncertainty in the prediction of both the ^7Be and the ^8B solar neutrino fluxes. It is scandalous that there has not been any progress in the past 15 years in measuring this rate more accurately. [A very recent precise measurement has been reported for this reaction at center-of-mass energies above 400 keV [18], but so far there have not been any other measurements that could test the accuracy of this result.]

For $^{14}\text{N}(\text{p}, \gamma)^{15}\text{O}$, we have continued to use in Table II the uncertainty given in Ref. [13], although the recent reevaluation in Ref. [14] suggests that the uncertainty could be somewhat larger (see column 7 of Table I).

The dominant uncertainty, 15.1% (1σ), for the hep neutrino flux results from the difficult theoretical calculation of the low energy cross section factor for this reaction [19].

The uncertainties due to the calculated radiative opacity and element diffusion, as well as the measured solar luminosity (columns 6-8 of Table II), are all moderate, non-negligible but not dominant. For the ^8B and CNO neutrino fluxes, the uncertainties that are due to the radiative opacity, diffusion coefficient, and solar luminosity are all in the range 2% to 6%.

The surface composition of the Sun is the most problematic and important source of uncertainties. Systematic errors dominate: the effects of line blending, departures from local thermodynamic equilibrium, and details of the model of the solar atmosphere. In the absence of detailed information to the contrary, it is assumed that the uncertainty in all important element abundances is approximately the same. The 3σ range of Z/X is defined as the spread over all modern determinations (see Refs. [4, 17, 20]), which implies that at present $\Delta(Z/X)/(Z/X) = 0.15$ (1σ), 2.5 times larger than the uncertainty adopted in discussing the predictions of the model BP00 [4]. The most recent uncertainty quoted for oxygen, the most abundant heavy element in the Sun, is similar: 12% [7].

Heavier elements like Fe affect the radiative opacity and hence the neutrino fluxes more strongly than the relatively light elements [4]. This is the reason why the difference between the fluxes calculated with BP04 and BP04+ (or between BP00 and Comp, see Table I) is less than would be expected for the 26% decrease in Z/X . The abundances that have changed significantly since BP00 (C, N, O, Ne, Ar) are all for lighter volatile elements for which meteoritic data are not available.

The dominant uncertainty listed in Table II for the ^8B and CNO neutrinos is the chemical composition, represented by Z/X (see column 9). The uncertainty ranges from 20% for the ^8B neutrino flux to $\sim 35\%$ for the CNO neutrino fluxes. Since the publication of BP00, the best published estimate for Z/X decreased by 4.3σ (BP00 uncertainty) and the estimated uncertainty due to Z/X increased for ^8B (^{15}O) neutrinos by a factor of 2.5 (2.8). Over the past three decades, the changes have almost always been toward a smaller Z/X . The monotonicity is surprising since different sources of improvements have caused successive changes. Nevertheless, since the changes are monotonic, the uncertainty estimated from the historical record is large.

The total ^8B neutrino flux measured by the neutral current mode of the SNO experiment [21] is

$$\phi(^8\text{B}, \text{SNO}) = 0.90\phi(^8\text{B}, \text{BP04 solar model}) [1.0 \pm 0.09 \pm 0.23] , \quad (1)$$

where the first uncertainty listed in equation (1) is the 1σ measurement error and the second (larger)

uncertainty is the estimated 1σ uncertainty in the solar model calculation (taken from Table II). If all the data from solar neutrino and reactor experiments are combined together (see figure 2 below), the above relation becomes [16]

$$\phi(^8\text{B}, \text{SNO}) = 0.87\phi(^8\text{B}, \text{BP04 solar model}) [1.0 \pm 0.05 \pm 0.23] . \quad (2)$$

The calculated ^8B neutrino flux [3] agrees with the measured flux to better than 1σ . The theoretical uncertainty is much larger than the uncertainty in the measurements. The dominant theoretical uncertainty for the ^8B neutrino flux is due to uncertainties in the measured surface heavy element abundances of the Sun.

[For decades, the composition uncertainty has been calculated by considering the uncertainty in the total heavy element abundance by mass, Z , or the uncertainty in the total heavy element to hydrogen ratio, Z/X . In an article now in preparation, Bahcall and Serenelli 2005, we have made a more refined calculation of the abundance uncertainties by evaluating separately the abundance uncertainty of each heavy element. The final result for the total uncertainty to be used in equation (1) and equation (2) is ± 0.16 instead of ± 0.23 .]

The p-p solar neutrino flux has been measured by combining the results from all the relevant solar neutrino and reactor experiments, together with the imposition of the luminosity constraint [22]. The result is [23]

$$\phi(\text{p} - \text{p}, \text{all neutrino experiments}) = 1.01\phi(\text{p} - \text{p}, \text{BP04 solar model}) [1.0 \pm 0.02 \pm 0.01] , \quad (3)$$

where the first uncertainty listed in equation (3) is the 1σ measurement error and the second (smaller) uncertainty is the estimated 1σ uncertainty in the solar model calculation (taken from Table II).

3 Recent developments regarding the solar surface composition

In the last several years, determinations of the solar surface abundances of heavy elements have become more refined and detailed [7, 12, 24]. These recent determinations yield significantly lower values than were previously adopted (e.g., by Grevesse and Sauval 1998 [6]) for the abundances of the volatile heavy elements: C, N, O, Ne, and Ar. However, these recent abundance determinations also lead to solar models that disagree with helioseismological measurements ([3, 8]).

Standard solar models constructed with the newly-determined heavy element abundances predict incorrectly the solar sound speeds, the depth of the solar convective zone, and the surface helium abundance (see especially Ref. [8]). The discrepancies occur in the temperature region below the solar convective zone, $2 \times 10^6 \text{K}$ to $4.5 \times 10^6 \text{K}$ [8]. In this temperature domain, the volatile heavy elements, C, N, O, Ne, and Ar, are partially ionized and their abundances significantly affect the radiative opacities. Fortunately, neutrinos are produced in the deep solar interior not in this outer region, $0.45R_\odot$ to $0.72R_\odot$, where the discrepancies with helioseismology exist. This is the reason why the new abundances do not affect significantly the calculated neutrino fluxes, i.e., the reason why the models BP04 and BP04+ in Table I yield similar neutrino fluxes.

What is wrong? I don't know. One possibility we have considered is that the standard radiative opacity needs to be increased (by about 11%) near the base of the convective zone. However, detailed and refined

Total Rates: Standard Model vs. Experiment Bahcall–Pinsonneault 2004

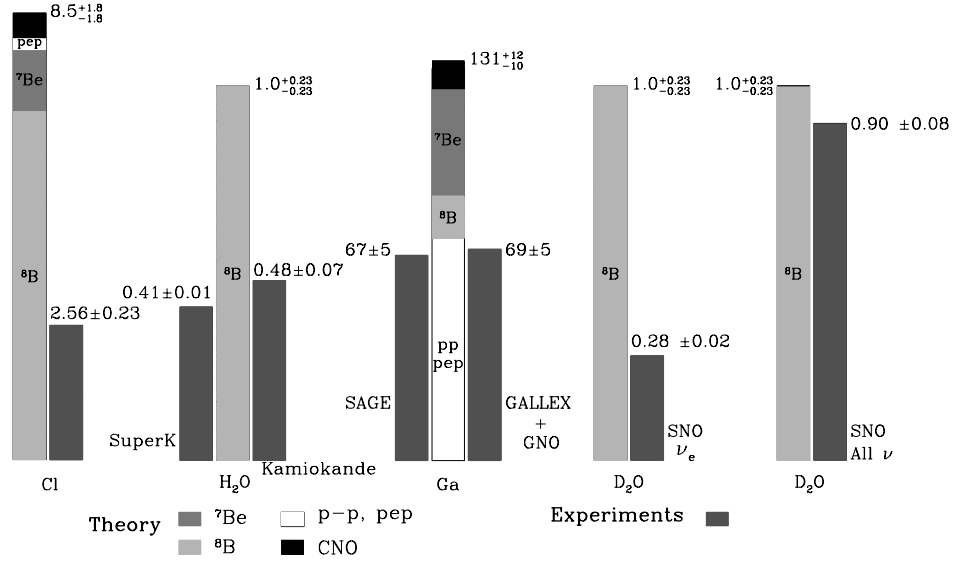


Figure 2: Theory versus experiment. The figure compares the predictions of the standard solar model plus the standard model of electroweak interactions with the measured rates in all solar neutrino experiments. The solar neutrino experimental results are discussed in talks by Y. Suzuki and A. McDonald in this proceeding.

recalculations of the radiative opacity by the Opacity Project collaboration disfavor [25, 26] the suggestion [8, 27] that the origin of the discrepancy might be the adopted opacities rather than the adopted heavy element abundances. Another possibility that astronomers discuss privately is that something is systematically wrong with the new abundance determinations. After all, the old standard abundances lead to solar models that are in excellent agreement everywhere with the helioseismological measurements. However, no one has identified a serious problem with the new abundance measurements. But, it would certainly be healthy for the field if more than one group were to undertake a thorough reevaluation of the surface heavy element abundances of the Sun.

As we continue to measure more precisely the properties of the Sun and to compare the results with theoretical solar models, we continue to learn new things. Nature seems to surprise us each time. The present conflict engendered by the new heavy element abundance determinations may have significant implications for other parts of stellar physics. After all, if we can't get the abundances or the opacity or something else significant correct for the Sun, about which we know much more than any other star, how can we have confidence in our quantitative inferences for other less well studied star?

4 Neutrinos as dark matter

Neutrinos are the first cosmological dark matter to be discovered. I cannot resist making a few remarks on this subject, because of the importance of dark matter to both physics and astronomy.

Solar and atmospheric neutrino experiments show that neutrinos have mass but these oscillations experiments only determine the differences between masses, not the absolute values. If we make the plausible but unproven assumption that the lowest neutrino mass, m_1 , is much less than the square root of $\Delta m_{\text{solar}}^2$, then we can conclude that the mass of cosmological neutrino background is dominated by the mass of the heaviest neutrino. This heaviest neutrino mass is then determined by $\Delta m_{\text{atmospheric}}^2$. With this assumption the cosmological mass density in neutrinos is only [28, 29, 30]

$$\Omega_\nu = (0.0009 \pm 0.0001), \quad m_1 \ll \sqrt{(\Delta m_{\text{solar}}^2)}. \quad (4)$$

Although the mass density given in Equation (4) is small, it is of the same order of magnitude as the observed mass density in stars and gas.

The major uncertainty in determining by neutrino experiments the value of Ω_ν is the unknown value of the lowest neutrino mass. It is possible that neutrino masses are nearly degenerate and cluster around the highest mass scale allowed by direct beta-decay experiments. If, for example, all neutrino masses are close to 1 eV, then $\Omega_\nu(1 \text{ eV}) \sim 0.03$, which would be cosmologically significant, but would not explain the bulk of the dark matter.

More sensitive neutrino beta-decay experiments and neutrinoless double beta-decay experiments offer the best opportunities for determining the mass of the lowest mass neutrino and hence establishing the value of Ω_ν from purely laboratory measurements.

For most of the period of 1968-2001, between the first suggestion of a solar neutrino problem and its final resolution as indicating neutrino oscillations, the great majority of physicists believed that solar neutrino experiments indicated the need for improvements in the solar model, not in the standard model of particle physics. In part, this was a matter of aesthetics; the standard model of particle physics was beautiful and experimentally successful. Why mess up this beautiful theory with an ugly neutrino mass? By contrast with the elegant laboratory experiments that confirmed the standard electroweak model, the interior of the appeared Sun remote and complicated. Also, the belief in inadequate astrophysics rather than incomplete physics was, I believe, partially a result of a lack of familiarity with the accuracy of the solar model calculations. For some of the physicists that believed in solar neutrino oscillations for particle physics reasons (see the discussion by Pierre Ramond in this volume), the most attractive possibility was that neutrino masses accounted for the missing dark matter. One could argue persuasively, using Ockham's razor, that this was the only 'natural' value. Unfortunately, as has happened so often in the history of weak interaction physics, our aesthetic principles were violated. The neutrino has a mass, but the neutrino mass does not account for nearly all of the dark matter if we adopt the most plausible mass hierarchy (see equation 4).

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