SOLAR NEUTRINOS

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The Sun is a main-sequence star at a stage of stable hydrogen burning. It produces an intense flux of electron neutrinos as a consequence of nuclear fusion reactions which generate solar energy, and whose combined effect is

$$4p + 2e^- \rightarrow {}^4\mathrm{He} + 2\nu_e + 26.73\ \mathrm{MeV} - E_\nu\ , \tag{1}$$

where E_ν represents the energy taken away by neutrinos, with an average value being $\langle E_\nu \rangle \sim 0.6$ MeV. Each neutrino-producing reaction, the resulting flux, and contributions to the event rates in chlorine and gallium solar-neutrino experiments predicted by the recent Bahcall, Basu, and Pinsonneault standard solar model (SSM) calculation [1] are listed in Table 1. This SSM is regarded as the best with helium and heavy-element diffusion. Figure 1 shows the energy spectra of solar neutrinos from these reactions quoted from Ref. 1. Recently, the SSM has been shown to predict accurately the helioseismological sound velocities with a precision of 0.1% rms throughout essentially the entire Sun, greatly strengthening confidence in the solar model [1,2].

Observation of solar neutrinos directly addresses the SSM and, more generally, the theory of stellar structure and evolution which is the basis of the SSM. The Sun as a well-defined neutrino source also provides extremely important opportunities to investigate nontrivial neutrino properties such as nonzero mass and mixing, because of the wide range of matter density and the very long distance from the Sun to the Earth. In fact, the currently available solar-neutrino data seem to require such neutrino properties, if one tries to understand them consistently.

So far, five solar-neutrino experiments have published results. Three of them are radiochemical experiments using ^{37}Cl (Homestake in USA) or ^{71}Ga (GALLEX at Gran Sasso in Italy and SAGE at Baksan in Russia) to capture neutrinos: ${}^{37}\mathrm{Cl}\ \nu_e \rightarrow {}^{37}\mathrm{Ar}\ e^-$ (threshold 814 keV) or ${}^{71}\mathrm{Ga}\ \nu_e \rightarrow {}^{71}\mathrm{Ge}\ e^-$ (threshold 233 keV). The produced ^{37}Ar and ^{71}Ge are both radioactive

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Table 1: Neutrino-producing reactions in the Sun (the first column) and their abbreviations (second column). The neutrino fluxes and event rates in chlorine and gallium solar-neutrino experiments predicted by Bahcall, Basu, and Pinsonneault [1] are listed in the third, fourth, and fifth columns respectively.

		BAHCALL 98C [1]		
Reaction	Abbr.	Flux ($\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$)	Cl (SNU*)	Ga (SNU*)
$pp \to d\,e^+\,\nu$	*pp*	$5.94(1.00^{+0.01}_{-0.01}) \times 10^{10}$	—	69.6
$pe^-p \to d\,\nu$	*pep*	$1.39(1.00^{+0.01}_{-0.01}) \times 10^{8}$	0.2	2.8
${}^3\mathrm{He}\ p \to {}^4\mathrm{He}\ e^+\nu$	*hep*	2.10×10^{3}	0.0	0.0
${}^7\mathrm{Be}\ e^- \to {}^7\mathrm{Li}\ \nu + (\gamma)$	^{7}Be	$4.80(1.00^{+0.09}_{-0.09}) \times 10^{9}$	1.15	34.4
${}^8\mathrm{B} \to {}^8\mathrm{Be}^*\ e^+\nu$	^{8}B	$5.15(1.00^{+0.19}_{-0.14}) \times 10^{6}$	5.9	12.4
${}^{13}\mathrm{N} \to {}^{13}\mathrm{C}\ e^+\nu$	^{13}N	$6.05(1.00^{+0.19}_{-0.13}) \times 10^{8}$	0.1	3.7
${}^{15}\mathrm{O} \to {}^{15}\mathrm{N}\ e^+\nu$	^{15}O	$5.32(1.00^{+0.22}_{-0.15}) \times 10^{8}$	0.4	6.0
${}^{17}\mathrm{F} \to {}^{17}\mathrm{O}\ e^+\nu$	^{17}F	$6.48(1.00^{+0.12}_{-0.11}) \times 10^{6}$	0.0	0.1
Total			$7.7^{+1.2}_{-1.0}$	129^{+8}_{-6}

* 1 SNU (Solar Neutrino Unit) = 10^{-36} captures per atom per second.

nuclei, with half lives ($\tau_{1/2}$) of 34.8 days and 11.43 days, respectively. After an exposure of the detector for two to three times $\tau_{1/2}$, the reaction products are extracted and introduced into a low-background proportional counter, and are counted for a sufficiently long period to determine the exponentially decaying signal and a constant background. In the chlorine experiment, the dominant contribution comes from ^{8}B neutrinos, but ^{7}Be, *pep*, ^{13}N, and ^{15}O neutrinos also contribute. At present, the most abundant *pp* neutrinos can be detected only in gallium experiments. Even so, almost half of the capture rate in the gallium experiments is due to other solar neutrinos.

The other experiments are real-time experiments utilizing νe scattering in a large water-Čerenkov detector (Kamiokande and Super-Kamiokande in Japan). These experiments take advantage of the directional correlation between the incoming neutrino and the recoil electron. This feature greatly helps the clear separation of the solar-neutrino signal from the background. Due to the high thresholds (7 MeV in Kamiokande and 5.5 MeV at present in Super-Kamiokande) the experiments

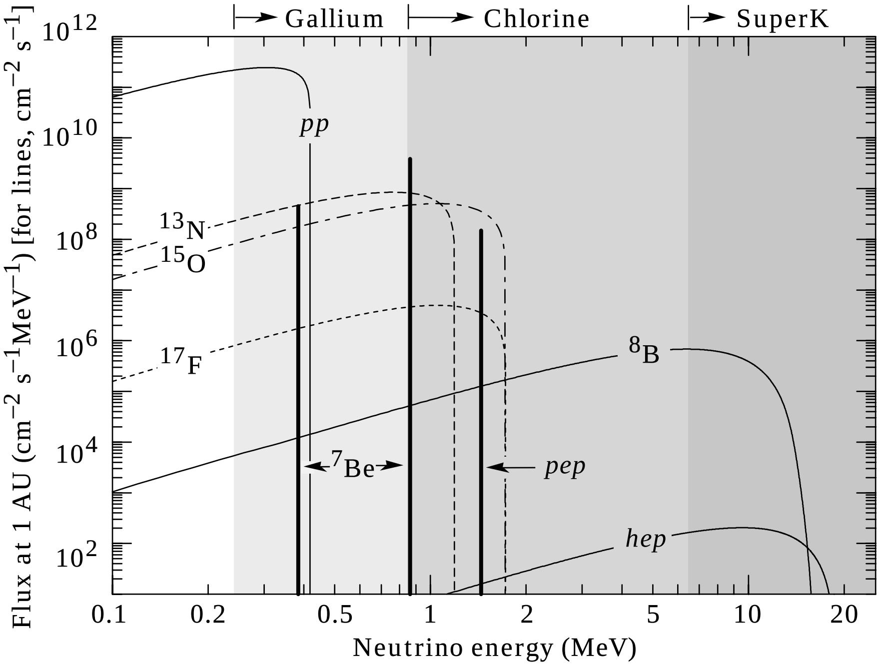

Figure 1: The solar neutrino spectrum predicted by the standard solar model. The neutrino fluxes from continuum sources are given in units of number cm^{-2}s^{-1}MeV^{-1} at one astronomical unit, and the line fluxes are given in number cm^{-2}s^{-1}. Spectra for the *pp* chain, shown by the solid curves, are courtesy of J.N. Bahcall (1999), and reflect updates in BAHCALL 98C. Spectra for the CNO chain are shown by the dotted curves, and are courtesty of J.N. Bahcall (1995).

observe pure ^{8}B solar neutrinos because *hep* neutrinos contribute negligibly according to the SSM. (However, the recent Super-Kamiokande results on the recoil-electron energy spectrum at > 13 MeV raised some discussion on the possibility of an enhanced *hep* neutrino contribution [3,4].)

In May, 1999, a new realtime solar-neutrino experiment, SNO (Sudbury Neutrino Observatory) started observation. This experiment uses 1000 tons of heavy water (D_2O) to measure solar neutrinos through both inverse β decay ($\nu_e d \rightarrow e^- pp$)

and neutral-current interactions ($\nu_x d \rightarrow \nu_x pn$). In addition, νe scattering events will be measured.

Solar neutrinos were first observed in the Homestake chlorine experiment in the late 1960's. From the very beginning, it was recognized that the observed capture rate was significantly smaller than the SSM prediction provided nothing happens to the electron neutrinos after they are created in the solar interior. This deficit has been called "the solar-neutrino problem."

The Kamiokande-II Collaboration started observing the ^{8}B solar neutrinos at the beginning of 1987. Because of the strong directional correlation of νe scattering, this result gave the first direct evidence that the Sun emits neutrinos (no directional information is available in radiochemical solar-neutrino experiments.) The observed solar-neutrino flux was also significantly less than the SSM prediction. In addition, Kamiokande-II obtained the energy spectrum of recoil electrons and the fluxes separately measured in the daytime and nighttime. The Kamiokande-II experiment came to an end at the beginning of 1995.

GALLEX presented the first evidence of *pp* solar-neutrino observation in 1992. Here also, the observed capture rate is significantly less than the SSM prediction. SAGE, after the initial confusion which is ascribed to statistics by the group, observed a similar capture rate to that of GALLEX. Both GALLEX and SAGE groups tested the overall detector response with intense man-made ^{51}Cr neutrino sources, and observed good agreement between the measured ^{71}Ge production rate and that predicted from the source activity, demonstrating the reliability of these experiments. The GALLEX Collaboration formally finished observations in early 1997. Since April, 1998, a newly defined collaboration, GNO (Gallium Neutrino Observatory) resumed the observations.

Super-Kamiokande is a 50-kton second-generation solar-neutrino detector, which is characterized by a significantly larger counting rate than the first-generation experiments. This experiment started observation in April 1996. The average solar-neutrino flux is smaller than, but consistent with, the

Kamiokande-II result. However, the flux measured in the nighttime shows an excess over that measured in the daytime [5,6], though the significance is not yet high. Super-Kamiokande also observed the recoil-electron energy spectrum [7]. Its shape showed an excess at the high-energy end (> 13 MeV) compared to the SSM expectation, though its statistical significance is not very high. More recent results indicate that the high-energy excess is reduced with the accumulation of statistics.

The most recent published results on the average capture rates or flux from solar-neutrino experiments are listed in Table 2 and compared to the results from SSM calculations which are taken from “Lepton Particle Listings (E) Solar ν Experiments” in this edition of “Review of Particle Physics.” In these calculations, BAHCALL 98C [1], BRUN 98 [12], BAHCALL 95B [14], and DAR 96 [13] take into account helium and heavy-element diffusion, but other calculations do not. SSM calculations give essentially the same results for the same input parameters and physics. This statement applies to the most recent BAHCALL 98C [1] and BRUN 98 [12] models. The BAHCALL 98C model [1] differs from the BAHCALL 95B model [14] in that BAHCALL 98C [1] uses the nuclear fusion rates systematically reevaluated and recommended by Adelberger *et al.* [24], and other best available input data. The $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ cross section adopted by Adelberger *et al.* [24] is 15% lower than the value used by BAHCALL 95B [14]. This is the principal reason why the ^{8}B neutrino flux and the ^{37}Cl and ^{71}Ga capture rates calculated by the BAHCALL 98C model [1] are lower than those calculated by the BAHCALL 95B model [14]. The BAHCALL 95B [14] model and the TURCK-CHIEZE 93B [15] model differ primarily in that BAHCALL 95B [14] includes element diffusion. The DAR 96 [13] model differs significantly from the BAHCALL 95B [14] model mostly due to the use of nonstandard reaction rates, different treatments of diffusion, and the equation of state.

All results from the present solar-neutrino experiments indicate significantly less flux than expected from SSM calculations except those of DAR 96 [13]. The DAR 96 [13] model predicts the ^{8}B solar-neutrino flux which is consistent with the

Table 2: Recent results from the five solar-neutrino experiments and a comparison with theoretical solar-model predictions. Solar model calculations are also presented. The evolution of these results over the years gives some feeling for their robustness as the models have become more sophisticated and complete.

	^{37}Cl→^{37}Ar (SNU)	^{71}Ga→^{71}Ge (SNU)	^{8}B ν flux (10^6cm^{-2}s^{-1})
Homestake			
(CLEVELAND 98)[8]	$2.56 \pm 0.16 \pm 0.16$	—	—
GALLEX			
(HAMPEL 99)[9]	—	$77.5 \pm 6.2^{+4.3}_{-4.7}$	—
SAGE			
(ABDURASHI. . .99B)[10]	—	$67.2^{+7.2+3.5}_{-7.0-3.0}$	—
Kamiokande			
(FUKUKDA 96)[11]	—	—	$2.80 \pm 0.19 \pm 0.33$
Super-Kamiokande			
(FUKUKDA 99)[5]	—	—	$2.436^{+0.053+0.085}_{-0.047-0.071}$
(BAHCALL 98C)[1]	$7.7^{+1.2}_{-1.0}$	129^{+8}_{-6}	$5.15(1.00^{+0.19}_{-0.14})$
(BRUN 98)[12]	7.18	127.2	4.82
(DAR 96)[13]	4.1 ± 1.2	115 ± 6	2.49
(BAHCALL 95B)[14]	$9.3^{+1.2}_{-1.4}$	137^{+8}_{-7}	$6.6(1.00^{+0.14}_{-0.17})$
(TURCK-CHIEZE 93B)[15]	6.4 ± 1.4	123 ± 7	4.4 ± 1.1
(BAHCALL 92)[16]	$8.0 \pm 3.0^{\dagger}$	$132^{+21\dagger}_{-17}$	$5.69(1.00 \pm 0.43)^{\dagger}$
(BAHCALL 88)[17]	$7.9 \pm 2.6^{\dagger}$	$132^{+20\dagger}_{-17}$	$5.8(1.00 \pm 0.37)^{\dagger}$
(TURCK-CHIEZE 88)[18]	5.8 ± 1.3	125 ± 5	$3.8(1.00 \pm 0.29)$
(FILIPPONE 83)[19]	5.6	—	—
(BAHCALL 82)[20]	$7.6 \pm 3.3^{\dagger}$	$106^{+13\dagger}_{-8}$	5.6
(FILIPPONE 82)[21]	7.0 ± 3.0	111 ± 13	4.8
(FOWLER 82)[22]	6.9 ± 1.0	—	—
(BAHCALL 80)[23]	7.3	—	—

* 1 SNU (Solar Neutrino Unit) = 10^{-36} captures per atom per second.

† "3σ" errors.

Kamiokande-II and Super-Kamiokande results, but even this model predicts ^{37}Cl and ^{71}Ga capture rates significantly larger than the Homestake, GALLEX, and SAGE results.

Is there any possible consistent explanation of all the results of solar-neutrino observations in the framework of the standard solar model? This is difficult because the Homestake result and the Kamiokande result, taken at face value, are mutually inconsistent if one assumes standard neutrino spectra. That is, with the reduction factor of the ^{8}B solar-neutrino flux as determined from the Kamiokande result, the Homestake ^{37}Cl capture rate would be oversaturated, and there would be no room to accommodate the ^{7}Be solar neutrinos. This makes astrophysical solutions untenable because ^{8}B nuclei are produced from ^{7}Be nuclei in the Sun.

Several authors made more elaborate analyses using the constraint of observed solar luminosity, and found (see for example, Refs. 25–28)

- that both the comparison of the Kamiokande and gallium results and the comparison of the gallium and chlorine results also indicate strong suppression of the ^{7}Be solar-neutrino flux, and
- that not only the SSM but also nonstandard solar models are incompatible with the observed data.

In view of the above situation, it is attractive to invoke nontrivial neutrino properties. Neutrino oscillation in matter (MSW mechanism) is particularly attractive in explaining all the experimental data on the average solar-neutrino flux consistently, without any *a priori* assumptions or fine tuning. Several authors made extensive MSW analyses using all the available data and ended up with similar results. For example, Bahcall, Krastev, and Smirnov [28] analyzed the solar-neutrino data as of 1998 in terms of two-flavor oscillations. In addition, they analyzed the case of vacuum oscillations. They obtained the following solutions for the BAHCALL 98C [1] SSM: Using only the total event rates in the five solar-neutrino experiments, there are three MSW solutions and one vacuum-oscillation solution at the 99% confidence level for oscillations into active neutrinos (ν_μ or ν_τ).

- Small mixing-angle (SMA) solution:
  $\Delta m^2 = 5.4 \times 10^{-6}$ eV^2, $\sin^2 2\theta = 6.0 \times 10^{-3}$
- Large mixing-angle (LMA) solution:
  $\Delta m^2 = 1.8 \times 10^{-5}$ eV^2, $\sin^2 2\theta = 0.76$

- LOW (low probability or low mass) solution:
  $\Delta m^2 = 7.9 \times 10^{-8}$ eV^2, $\sin^2 2\theta = 0.96$
- Vacuum (VAC) solution:
  $\Delta m^2 = 8.0 \times 10^{-11}$ eV^2, $\sin^2 2\theta = 0.75$.

In the case of oscillations into sterile neutrinos, only the SMA and VAC solutions are allowed at the 99% confidence level with the best-fit parameters similar to the ones given above.

Bahcall, Krastev, and Smirnov [28] also made global analyses using all of the available solar-neutrino data, *i.e.*, total event rates plus the Super-Kamiokande recoil-electron energy spectrum and day-night asymmetry. At the 99% confidence level, acceptable solutions are found to be SMA (oscillations into both active and sterile neutrinos) and VAC. The LMA and LOW solutions are marginally ruled out.

Assuming that the solution to the solar-neutrino problem will really be provided by neutrino oscillations, how can one discriminate various solutions? The MSW SMA solution causes an energy-spectrum distortion. In the Super-Kamiokande and SNO observations, the flux will be more suppressed at lower energies. The MSW LMA solution predicts the day-night flux difference, a hint of which is seen in the recent Super-Kamiokande results [6]. However, the LMA solution gives almost no spectrum distortion. Thus, should LMA be a correct solution, one needs to explain the high-energy excess in the recoil-electron spectrum observed by Super-Kamiokande [7], if it turns out to be a real effect, due to a very large contribution from *hep* neutrinos or from other possibilities [4]. The VAC solution is characterized by seasonal variation of the flux, which is different from the trivial variation due to the eccentricity of Earth's orbit [29,30]. Also, the VAC solution can explain the high-energy excess of the recoil-electron spectrum observed by Super-Kamiokande [30].

SNO's observations of solar-neutrino flux by neutral-current reactions will give decisive evidence for neutrino oscillations into active neutrinos, if that flux is consistent with the SSM prediction and larger than the flux measured by charged-current reactions. On the other hand, the signal for oscillations into sterile neutrinos will be the same amount of reduction of the fluxes measured by neutral- and charged-current reactions.

An important task of the second-generation solar neutrino experiments is the measurement of monochromatic ^{7}Be solar neutrinos. If the VAC solution is correct, the flux of ^{7}Be neutrinos shows larger seasonal variations than the flux of ^{8}B neutrinos. The ^{7}Be neutrino flux will be measured by a new experiment, Borexino, at Gran Sasso *via* νe scattering in 300 tons of ultra-pure liquid scintillator with a detection threshold as low as 250 keV. The Borexino detector is expected to be completed in 2001.

KamLAND, which is under construction at Kamioka and will be completed in 2001, is a multi-purpose neutrino experiment with 1000 tons of ultra-pure liquid scintillator. This experiment will also observe ^{7}Be neutrinos if the detection threshold can be lowered to a level similar to that of Borexino. However, one of the primary purposes of this experiment is the observation of oscillations of neutrinos produced by power reactors. The sensitivity region of KamLAND includes the MSW LMA solution. Thus, the LMA solution may be proved or excluded by KamLAND.

The second-generation solar-neutrino experiments, Super-Kamiokande, SNO, and Borexino, as well as KamLAND, will provide a variety of data with high statistical accuracy. It is hoped that these experiments will solve the long-standing solar-neutrino problem in coming years.

References

1. J.N. Bahcall, S. Basu, and M.H. Pinsonneault, Phys. Lett. **B433**, 1 (1998) [BAHCALL 98C].
2. J.N. Bahcall *et al.*, Phys. Rev. Lett. **78**, 171 (1997) [BAHCALL 97].
3. J.N. Bahcall and P.I. Kratsev, Phys. Lett. **B436**, 243 (1998).
4. J.N. Bahcall, P.I. Krastev, and A.Yu. Smirnov, Phys. Rev. **D60**, 093001 (1999).
5. Y. Fukuda *et al.*, Phys. Rev. Lett. **82**, 1810 (1999).
6. Y. Suzuki, talk at the *XIX Int. Symposium on Lepton and Photon Interactions at High Energies*, Stanford (August 1999).
7. Y. Fukuda *et al.*, Phys. Rev. Lett. **82**, 2430 (1999).

8. B.T. Cleveland *et al.*, Ap. J. **496**, 505 (1998) [CLEVELAND 98].
9. W. Hampel *et al.*, Phys. Lett. **B447**, 127 (1999) [HAMPEL 99];
   W. Hampel *et al.*, Phys. Lett. **B388**, 384 (1996) [HAMPEL 96].
10. J.N. Abdurashitov *et al.*, Phys. Rev. **C60**, 0055801 (1999) [ABDURASHI...99B].
11. Y. Fukuda *et al.*, Phys. Rev. Lett. **77**, 1683 (1996) [FUKUDA 96].
12. A.S. Brun, S. Turck-Chieze, and P. Morel, Astrophys. J. **506**, 913 (1998) [BRUN 98].
13. A. Dar and G. Shaviv, Astrophys. J. **468**, 933 (1996) [DAR 96].
14. J.N. Bahcall and M. H. Pinsonneault, Rev. Mod. Phys. **67**, 781 (1995) [BAHCALL 95B].
15. S. Turck-Chieze and I. Lopez, Astrophys. J. **408**, 347 (1993) [TURCK-CHIEZE 93B].
16. J.N. Bahcall and M. H. Pinsonneault, Rev. Mod. Phys. **64**, 885 (1992) [BAHCALL 92].
17. J.N. Bahcall and R.K. Ulrich, Rev. Mod. Phys. **60**, 297 (1988) [BAHCALL 88].
18. S. Turck-Chieze *et al.*, Astrophys. J. **335**, 415 (1988) [TURCK-CHIEZE 88].
19. B.W. Filippone *et al.*, Phys. Rev. Lett. **50**, 412 (1938) [FILIPPONE 83].
20. J.N. Bahcall *et al.*, Rev. Mod. Phys. **54**, 767 (1982) [BAHCALL 82].
21. B.W. Filippone and D.N. Schramm, Astrophys. J. **253**, 393 (1982) [FILIPPONE 82].
22. W.A. Fowler, AIP Conf. Proceedings 96 80 (1982) [FOWLER 82].
23. J.N. Bahcall *et al.*, Phys. Rev. Lett. **45**, 945 (1980) [BAHCALL 80].
24. E.G. Adelberger *et al.*, Rev. Mod. Phys. **70**, 1265 (1998).
25. N. Hata and P. Langacker, Phys. Rev. **D52**, 420 (1995) [HATA 95].
26. N. Hata and P. Langacker, Phys. Rev. **D56**, 6107 (1997).
27. K.M. Heeger and R.G.H. Robertson, Phys. Rev. Lett. **77**, 3720 (1996) [HEEGER 96].
28. J.N. Bahcall, P.I. Krastev, and A.Yu. Smirnov, Phys. Rev. **D58**, 096016 (1998).

29. S.L. Glashow, P.J. Kerman, and L.M. Krauss, Phys. Lett. **B445**, 412 (1999).
30. V. Barger and K. Whismant, Phys. Lett. **B456**, 54 (1999).