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

$$4p + 2e^- \rightarrow {}^4\text{He} \; + 2\nu_e + 26.73 \text{ MeV} - E_\nu \; , \qquad (1)$$

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 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 the SSM calculation by Bahcall and Ulrich [2]. 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 the confidence in the solar model [3].

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, four solar-neutrino experiments published the results. In addition, a new solar-neutrino experiment (Super-Kamiokande) started observation in 1996. 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: ${}^{37}\text{Cl}\;\nu_e \rightarrow {}^{37}\text{Ar}\;e^-$ (threshold 814 keV) or ${}^{71}\text{Ga}\;\nu_e \rightarrow {}^{71}\text{Ge}\;e^-$ (threshold 233 keV). The

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 expreiments predicted by Bahcall and Pinsonneault [1] are listed in the third, fourth, and fifth columns respectively.

		BAHCALL 95B [1]		
Reaction	Abbr.	Flux (cm^{-2} s^{-1})	Cl (SNU*)	Ga (SNU*)
$pp \to d\,e^+\,\nu$	pp	$5.91(1.00^{+0.01}_{-0.01}) \times 10^{10}$	—	69.7
$pe^-p \to d\,\nu$	pep	$1.40(1.00^{+0.01}_{-0.02}) \times 10^{8}$	0.22	3.0
^{3}He $p \to {}^4$He $e^+\nu$	hep	1.21×10^3		
^{7}Be $e^- \to {}^7$Li $\nu + (\gamma)$	^{7}Be	$5.15(1.00^{+0.06}_{-0.07}) \times 10^{9}$	1.24	37.7
^{8}B $\to {}^8$Be* $e^+\nu$	^{8}B	$6.62(1.00^{+0.14}_{-0.17}) \times 10^{6}$	7.36	16.1
^{13}N $\to {}^{13}$C $e^+\nu$	^{13}N	$6.18(1.00^{+0.17}_{-0.20}) \times 10^{8}$	0.11	3.8
^{15}O $\to {}^{15}$N $e^+\nu$	^{15}O	$5.45(1.00^{+0.19}_{-0.22}) \times 10^{8}$	0.37	6.3
^{17}F $\to {}^{17}$O $e^+\nu$	^{17}F	$6.48(1.00^{+0.15}_{-0.19}) \times 10^{6}$		
Total			$9.3^{+1.2}_{-1.4}$	137^{+8}_{-7}

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

produced ^{37}Ar and ^{71}Ge are both radioactive 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 6.5 MeV at present in Super-Kamiokande) the experiments

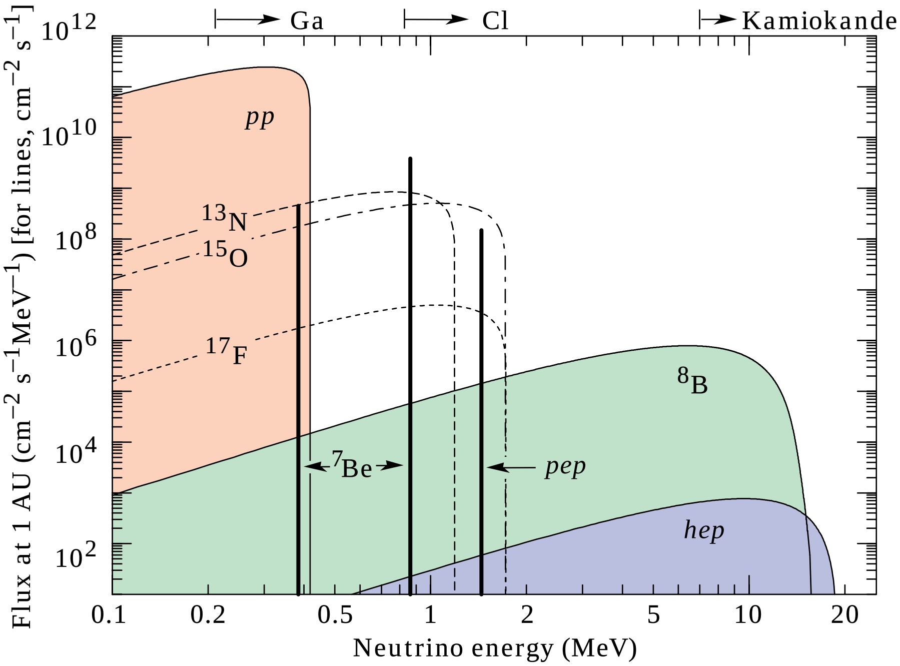

Figure 1: The solar neutrino spectrum predicted by the standard solar model. The neutrino fluxes from continuum sources are given in units of number $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{MeV}^{-1}$ at one astronomical unit, and the line fluxes are given in number $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Spectra for the *pp* chain are shown by solid lines, and those for the CNO chain by dotted or dashed lines. (Courtesy of J.N. Bahcall, 1995.)

observe pure ^{8}B solar neutrinos (*hep* neutrinos contribute negligibly).

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 day time and nighttime. The Kamiokande-II experiment came to an end at the beginning of 1995, and a 50-kton second-generation solar-neutrino detector Super-Kamiokande started observation in April, 1996.

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 most recent published results on the average capture rates or flux from these 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 95B [1] and DAR 96 [9] 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. The BAHCALL 95B [1] model and the TURCK-CHIEZE 93B [10] model differ primarily in that BAHCALL 95B [1] includes element diffusion. DAR 96 [9] model differs significantly from the BAHCALL 95B [1] model mostly due to the use of nonstandard reaction rates, the different treatments of diffusion and the equation of state.

There was a controversy whether the ^{37}Cl capture rate showed possible time variation, anticorrelated with the sunspot numbers which represent the 11-year solar-activity cycle. However, Walther recently argued that the claimed significant anticorrelation is due to a statistical fallacy [7]. Also, eight years

Table 2: Recent results from the four 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			
(DAVIS 89)[4]	2.33 ± 0.25	—	—
GALLEX			
(HAMPEL 96)[5]	—	$69.7 \pm 6.7^{+3.9}_{-4.5}$	—
SAGE			
(ABDURASHI...94)[6]	—	73^{+18+5}_{-16-7}	—
Kamiokande			
(FUKUKDA 96)[8]	—	—	$2.80 \pm 0.19 \pm 0.33$
(DAR 96)[9]	4.1 ± 1.2	115 ± 6	2.49
(BAHCALL 95B)[1]	$9.3^{+1.2}_{-1.4}$	137^{+8}_{-7}	$6.6(1.00^{+0.14}_{-0.17})$
(TURCK-CHIEZE 93B)[10]	6.4 ± 1.4	123 ± 7	4.4 ± 1.1
(BAHCALL 92)[11]	$8.0 \pm 3.0^{\dagger}$	$132^{+21\dagger}_{-17}$	$5.69(1.00 \pm 0.43)^{\dagger}$
(BAHCALL 88)[2]	$7.9 \pm 2.6^{\dagger}$	$132^{+20\dagger}_{-17}$	$5.8(1.00 \pm 0.37)^{\dagger}$
(TURCK-CHIEZE 88)[12]	5.8 ± 1.3	125 ± 5	$3.8(1.00 \pm 0.29)$
(FILIPPONE 83)[13]	5.6	—	—
(BAHCALL 82)[14]	$7.6 \pm 3.3^{\dagger}$	$106^{+13\dagger}_{-8}$	5.6
(FILIPPONE 82)[15]	7.0 ± 3.0	111 ± 13	4.8
(FOWLER 82)[16]	6.9 ± 1.0	—	—
(BAHCALL 80)[17]	7.3	—	—

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

† "3σ" errors.

of Kamiokande-II solar-neutrino observations covering an entire period of solar cycle 22 [8] does not show evidence for a statistically significant correlation or anticorrelation between the solar-neutrino flux and sunspot number.

All results from the present solar-neutrino experiments indicate significantly less flux than expected from the SSM calculations except DAR 96 [9]. The DAR 96 [9] model predicts the ^{8}B solar-neutrino flux which is consistent with the Kamiokande-II result, 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. 18–20)

- 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 existing data and ended up with similar results. For example, Hata and Langacker [19] analyzed the solar-neutrino data as of 1996 in terms of two-flavor oscillations, including the preliminary result from Super-Kamiokande [21] on the average ^{8}B solar-neutrino flux which is consistent with the Kamiokande-II result. They obtained viable solutions for the BAHCALL 95B [1] SSM: the small-mixing solution ($\Delta m^2 \sim 5 \times 10^{-6}$ eV^2 and $\sin^2 2\theta \sim 8 \times 10^{-3}$) and the large-mixing solution ($\Delta m^2 \sim 1.6 \times 10^{-5}$ eV^2 and $\sin^2 2\theta \sim 0.6$). Vacuum oscillations also provide solutions ($\Delta m^2 = (5\text{–}8) \times 10^{-11}$ eV^2 and $\sin^2 2\theta = 0.65 - 1$).

Assuming that the solution to the solar-neutrino problem be provided by some nontrivial neutrino properties, how can one discriminate various scenarios? The measurements of energy spectrum of the solar neutrinos and the day-night flux difference, and the measurement of solar-neutrino flux by utilizing neutral-current reactions are key issues. The MSW small-mixing solution causes the energy-spectrum distortion, while the MSW large-angle solution causes the day-night flux difference. If the flux measured by neutral-current reactions is consistent with the SSM prediction, and larger than that measured by charged-current reactions, it is a clear indication of neutrino oscillations.

Two high-statistics solar-neutrino experiments, Sudbury Neutrino Observatory (SNO) and Super-Kamiokande are expected to provide such results within a few years. Super-Kamiokande is sensitive to the solar-neutrino spectrum through measurement of recoil electron energy. SNO, which is expected to be completed in 1998, will use 1,000 tons of heavy water (D_2O) to measure solar neutrinos through both inverse beta decay ($\nu_e d \to e^- pp$) and neutral current interactions ($\nu_x d \to \nu_x pn$). In addition, νe scattering events will also be measured. The Borexino experiment with 300 tons of ultrapure liquid scintillator is approved for the Gran Sasso. The primary purpose of this experiment is the measurement of the ^{7}Be solar neutrino flux, whose possible deficit is now a key question, by lowering the detection threshold for the recoil electrons to 250 keV. Also, the vacuum-oscillations cause seasonal variation of the ^{7}Be solar neutrino flux. It is hoped that these new experiments will finally provide the key to solving the different solar-neutrino problems raised by the first-generation experiments.

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