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 and the resulting flux predicted by the two recent standard solar model (SSM) calculations [1,2] are listed in Table 1. Figure 1 shows the energy spectra of solar neutrinos from these reactions quoted from the SSM calculation by Bahcall and Ulrich [3]. All SSM calculations give essentially the same results for the same input parameters and physics. The Bahcall and Pinsonneault model [1] and the Turck-Chièze and Lopes model [2] listed in Table 1 differ primarily in that Bahcall and Pinsonneault include helium diffusion [4].

Table 1: Neutrino-producing reactions in the Sun (the first column) and their abbreviations (second column). The neutrino fluxes predicted by Bahcall and Pinsonneault (B-P) [1] and by Turck-Chièze and Lopes (T-C-L) [2] are listed in the third and fourth columns, respectively. The errors associated with the B-P calculation are "theoretical" 3 standard deviations according to the authors.

Reaction	Abbr.	B-P	T-C-L
$pp \rightarrow d\, e^+\, \nu$	pp	$6.00(1 \pm 0.02)$E10	6.02E10
$pe^-p \rightarrow d\, \nu$	pep	$1.43(1 \pm 0.04)$E8	1.3E8
${}^3\mathrm{He}\, p \rightarrow {}^4\ \mathrm{He}\ e^+\nu$	hep	1.23E3	
${}^7\mathrm{Be}\ e^- \rightarrow {}^7\ \mathrm{Li}\ \nu + (\gamma)$	${}^7\mathrm{Be}$	$4.89(1 \pm 0.18)$E9	4.33E9
${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^*\ e^+\nu$	${}^8\mathrm{B}$	$5.69(1 \pm 0.43)$E6	4.43E6
${}^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C}\ e^+\nu$	${}^{13}\mathrm{N}$	$4.92(1 \pm 0.51)$E8	3.83E8
${}^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N}\ e^+\nu$	${}^{15}\mathrm{O}$	$4.26(1 \pm 0.58)$E8	3.15E8
${}^{17}\mathrm{F} \rightarrow {}^{17}\mathrm{O}\ e^+\nu$	${}^{17}\mathrm{F}$	$5.39(1 \pm 0.48)$E6	

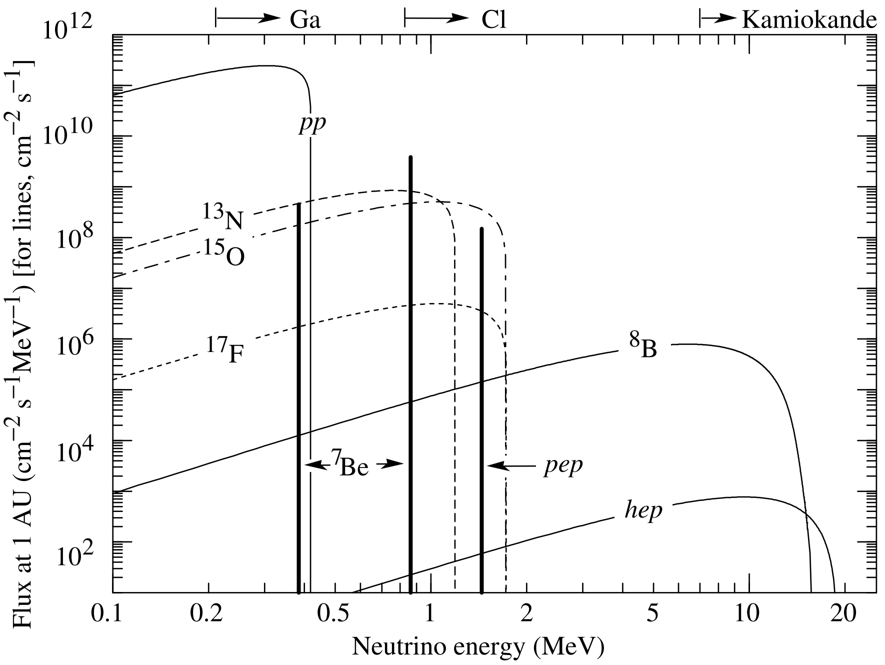

Figure 1: The solar neutrino spectrum predicted by the standard solar model. The neutrino fluxes from continuum sources are given in units of number cm^{-2}s^{-1}MeV^{-1} at one astronomical unit, and the line fluxes are given in number cm^{-2}s^{-1}. Spectra for the *pp* chain are shown by solid lines,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

Observations 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.

At present, four solar-neutrino experiments are taking data. 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 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 these experiments is due to other solar neutrinos.

The fourth is a real-time experiment utilizing νe scattering in a large water-Čerenkov detector (Kamiokande in Japan). This experiment takes 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 its high threshold (7 MeV at present), Kamiokande observes pure ^{8}B solar neutrinos (*hep* neutrinos have too small a flux to be observed in the present generation of solar neutrino experiments.)

Solar neutrinos were first observed in the Homestake chlorine experiment around 1970. From the very beginning, it was recognized that the observed capture rate was significantly smaller than the SSM prediction. 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. 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 initial confusion which is ascribed to statistics by the group, observes a similar capture rate to that of GALLEX. The most recent results on the average capture rates or flux from these experiments [5–8] are compared with the recent SSM calculations [1,2] in Table 2.

Table 2: Recent results from the four solar-neutrino experiments. For Homestake [5], GALLEX [6], and SAGE [7], the data are capture rates given in SNU (Solar Neutrino Units; 1 SNU = 10^{-36} capture per atom per second). For Kamiokande [8], the datum is ^{8}B solar-neutrino flux given in units of 10^6 cm^{-2} s^{-1}. The first errors are statistical and the second errors are systematic. The SSM predictions by Bahcall and Pinsonneault (B-P) [1] and by Turck-Chièze and Lopes (T-C-L) [2] are listed in the third and fourth columns, respectively. The errors associated with the B-P calculation are "theoretical" 3 standard deviations according to the authors.

Experiment	Data	B-P	T-C-L
Homestake	$2.55 \pm 0.17 \pm 0.18$	8.0 ± 3.0	6.4
GALLEX	$79 \pm 10 \pm 6$	131.5^{+21}_{-17}	122.5
SAGE	$73^{+18}_{-16}{}^{+5}_{-7}$	131.5^{+21}_{-17}	122.5
Kamiokande	$2.89^{+0.22}_{-0.21} \pm 0.35$	5.7 ± 2.4	4.4

There was a controversy concerning whether the ^{37}Cl capture rate showed time variation, anticorrelated with the sunspot numbers which represent the 11-year solar-activity cycle. However, more than 7 years of the Kamiokande-II solar-neutrino observation 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. 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. Several authors made more elaborate analyses using the constraint of observed solar luminosity, and found that not only the SSM but also nonstandard solar models are incompatible with the observed data. Now it is a common understanding that the solar-neutrino problem is not only the deficit of the ^{8}B solar-neutrino flux, but also the deficit of ^{7}Be solar-neutrino flux. The latter problem stems from the incompatibility between the Homestake and Kamiokande results and this makes astrophysical solutions untenable. There is another solar-neutrino problem concerning the low gallium capture rate observed by GALLEX and SAGE.

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 [9] analyzed the solar-neutrino data as of mid-1993. They obtained solutions for various standard and nonstandard solar models taking the Earth effect and the Kamiokande day-night data into account. Assuming the Bahcall-Pinsonneault SSM [1], the small-mixing solution ($\Delta m^2 \sim 6 \times 10^{-6}$ eV^2 and $\sin^2 2\theta \sim 7 \times 10^{-3}$) gives an excellent fit to the data, but the large-mixing solution ($\Delta m^2 \sim 9 \times 10^{-6}$ eV^2 and $\sin^2 2\theta \sim 0.6$) is marginally allowed at 90% confidence level.

Assuming that the solution to the solar-neutrino problem be provided by some nontrivial neutrino properties, how can one discriminate various scenarios? There are at least two very important things to do experimentally. One is the measurement of energy spectrum of the solar neutrinos and the other is the measurement of the solar-neutrino flux by utilizing neutral-current reactions. Two high-statistics solar-neutrino experiments which are under construction, SuperKamiokande and Sudbury Neutrino Observatory (SNO) are expected to provide such results within a few years. A 50 kton water-Čerenkov detector, SuperKamiokande is sensitive to the solar-neutrino spectrum through measurement of recoil electron energy. SNO 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 ultra-pure liquid scintillator is approved for the Gran Sasso. The primary purpose of this experiment is the measurement of the ^{7}Be solar neutrino flux, where possible deficit is now a key question, by lowering the detection threshold for the recoil electrons to 250 keV. It is hoped that these experiments will finally provide the key to solving the solar-neutrino problem.

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