Solar Neutrinos

Neutrinos are produced in nuclear reactions inside the Sun, as well as in laboratory nuclear reactions. The first direct tests of how the Sun produces its luminosity (observed most conspicuously on Earth as sunlight) have been carried out by observing solar neutrinos. The results of these experiments confirm the theory of how the Sun shines and stars evolve. However, persistent quantitative disagreements between calculations and observations suggest that either some of the experiments involve larger-than-expected errors or the standard physical theory of neutrinos requires modification.

Nuclear fusion in the Sun. The Sun shines because of fusion reactions similar to those envisioned for terrestrial fusion reactors. The basic solar process, called the proton-proton chain, is the fusion of four protons to form an alpha particle, two positrons (e^+), and two neutrinos (ν); that is, $4p \rightarrow \ \alpha \ + 2e^+ + \ 2\nu_e$ (see **table**). The rate for the initiating proton-proton (PP) reaction is predicted accurately (±1%) by the standard solar model. Unfortunately, the neutrinos from this reaction are below the energy thresholds for the first two experiments to detect solar neutrinos, with chlorine-37 (^{37}Cl) and with ultra pure water (H_2O). However, two experiments, one in Russia and one in Italy, which use gallium-71 (^{71}Ga), have successfully detected neutrinos from the PP reaction.

The proton-electron-proton (PEP) reaction, which is the same as the familiar PP reaction except for having the electron in the initial state, is detectable in the ^{37}Cl experiment. The ratio of PEP to PP neutrinos is approximately independent of which solar model is used for the solar predictions. Two other reactions in the proton-proton chain are of special interest. The capture of electrons by ^{7}Be produces detectable neutrinos in the ^{37}Cl experiment. The ^{8}B decay was expected to be the main source of neutrinos for the ^{37}Cl experiment because of their relatively high energy (14 MeV), although it is a rare reaction in the Sun. The ^{8}B neutrinos are the only substantial contributions to the ultrapure water experiment. There are also some less important neutrino-producing reactions from the carbon-nitrogen-oxygen (CNO) cycle, which will not be discussed here in detail since this cycle is believed to play a rather small role in the energy-production budget of the Sun. *See* CARBON-NITROGEN-OXYGEN CYCLES; NUCLEAR FUSION; NUCLEAR REACTION; PROTON-PROTON CHAIN.

Experimental tests. The first solar neutrino detector was based on the reaction $\nu_{\text{solar}} + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$, which is the inverse of the electron-capture decay of argon-37 (^{37}Ar). This reaction was chosen for the first experiment because of its unique combination of physical and chemical characteristics, which are favorable for building a large-scale solar neutrino detector. Neutrino capture to form ^{37}Ar in the ground state also has a relatively low energy threshold (0.81 MeV) and a high sensitivity, nuclear properties that are important for observing neutrinos from ^{7}Be, ^{13}N, and ^{15}O decay and the PEP reaction.

Like all solar neutrino experiments, the ^{37}Cl detector was built deep underground to avoid cosmic-ray interactions in the detector that simulate the effects of neutrinos. The final detector system consists of an approximately 100,000-gallon (400,000-liter) tank of perchloroethylene, a pair of pumps to circulate helium through the liquid, and a small building to house the extraction equipment, all in the deep Homestake gold mine in South Dakota, 5000 ft (1500 m) below the surface.

A set of experimental runs were carried out in the ^{37}Cl experiment during the 1970s and 1980s, and have continued into the 1990s. They have shown that the ^{37}Ar production rate in the tank is 0.48 ± 0.04 ^{37}Ar atoms per day. Even though the tank is nearly a mile (1.6 km) underground, a small amount of ^{37}Ar is produced by cosmic rays. The background rate has been estimated to be of order 0.1 ^{37}Ar atoms per day.

Subtracting the cosmic-ray background, a positive signal of (2.3 ± 0.3) solar neutrino units (SNU) is inferred; 1 SNU = 10^{-36} capture per target particle per second.

The predicted capture rates for the ^{37}Cl experiment (in SNU) for one solar model are as follows: PP reaction: 0; ^{8}B beta decay: 5.9; PEP reaction: 0.2; ^{7}Be electron capture: 1.2; ^{13}N decay: 0.1; and ^{15}O decay: 0.4. The total theoretical prediction is about 8 SNU. Many investigations have been undertaken of the best values to use for various parameters. The calculated event rate is relatively insensitive to the input parameters, although the total predicted rate may well differ from 8 SNU by 1 or 2 SNU.

Solar neutrinos have also been observed with the aid of electrons that the neutrinos scatter in a 770 short-ton (700-metric-ton) detector of pure water located in the Kamioka metal mine about 200 mi (300 km) west to Tokyo in the Japanese Alps. These results are of great importance since they provide direct evidence that the observed neutrinos originate in the Sun; the electrons are scattered by neutrinos in the forward direction between the Earth and the Sun. Moreover, the neutrino events are registered at the exact time they are detected, making possible a sensitive search for possible time dependencies. The measurement of the Kamiokande collaboration yielded the result given by the equation below

$$\frac{\text{Observed}}{\text{Predicted}} = 0.54 \pm 0.07.$$

The indicated error is a 1-standard-deviation combined statistical and systematic uncertainty. The predicted event rate in the equation stands for the best estimate of the number of events calculated to occur according to the standard model of the Sun and the standard model of how neutrinos behave. The Kamioka result refers only to high energy neutrinos from ^{8}B decay.

The SuperKamiokande detector is a much larger version of the original Kamiokande detector and is located in the same mine. The active detector in the SuperKamiokande experiment contains 32,000 tons of pure water and 11,200 specially designed tubes for observing electrons scattered by neutrinos. This new super-detector finds a rate

$$\frac{\text{Observed}_{\text{SuperK}}}{\text{Predicted}} = 0.47 \pm 0.02.$$

The new rate is in good agreement with the previous measurement but is more precise.

Since the Japanese water experiments (Kamiokande and SuperKamiokande) and the chlorine experiment are both primarily sensitive to the same ^{8}B neutrinos, it is difficult to understand why the discrepancy between observation and calculation is so much greater for the chlorine than for the water experiments. The most likely interpretation is that some new physical process happens to neutrinos that affects the lower-energy neutrinos observed in the chlorine experiment more than it affects the higher-energy neutrinos observed in the Kamioka experiment. This interpretation has been strengthened by the fact that the SuperKamiokande experiment finds strong evidence that neutrinos produced by cosmic rays in the atmosphere change their type when they travel distances comparable to the earth's radius.

Experiments have also been performed with gallium detectors located underneath a mountain in the Caucus region of Russia (60 tons of gallium, SAGE experiment) and in an underground laboratory about an hour north of Rome (30 tons of gallium, GALLEX experiment). These experiments are similar to the chlorine experiment described earlier. The two gallium experiments and the chlorine experiment all use radiochemical techniques to extract a small number of radioactive nuclei produced by neutrinos from huge tanks containing enormous numbers of atoms or chlorine or gallium. Unlike the Kamiokande and SuperKamiokande experiments, the gallium and chlorine detectors do not determine specific energies for neutrinos which they detect. Instead, the radiochemical gallium and chlorine detectors specify only a minimum energy: 0.23 MeV for gallium and 0.81 MeV for chlorine.

The results from the gallium experiments reinforce the conclusion that new physics may be required. The observed rate is 73± 5 SNU, which is much less than the standard model predicted rate of about 130 SNU. Almost all of the observed rate in the gallium experiments could be attributed to the fundamental low-energy neutrinos from the PP and PEP reactions. The rate expected from these neutrinos is largely independent of astronomical uncertainties. If the PP and PEP neutrinos are being detected at the expected rate, there is practically no room in the experimental results to accommodate the neutrinos from ^{7}Be, whose number is also believed to be reliably calculated with the solar models, and the ^{8}B neutrinos, which are actually observed in the Kamioka experiment.

Possible explanations. Many explanations have been advanced for the discrepancy between the observed and the predicted event rates in the solar neutrino experiments. These explanations can be divided into three general classes: (1) the standard solar model must be significantly modified; (2) something is seriously wrong with the experiments; (3) the standard model of how neutrinos behave must be significantly modified.

No one has succeeded in modifying a solar model so that it is consistent with all of the experimental data on the sun and the laboratory measurements of the parameters used in constructing the solar models. Most recently, precise measurements of the thousands of frequencies with which the Sun pulsates on its surface (characteristic period of order 5 minute) have confirmed to an accuracy of 0.1% the predictions of the standard solar model for these pulsation frequencies. This agreement has convinced researchers that the standard solar model is an accurate description of the sun.

All of the solar neutrino experiments have been examined carefully by many different researchers. A variety of checks have been made to test whether their was a significant error or a large uncertainty in one of the experiments that might explain the different between prediction and observation. No significant previously unknown errors or uncertainties have been found. Moreover, the gallium experiments have been tested in the most direct fashion possible. Intense laboratory sources of neutrinos have been placed near the gallium detectors and the expected number of events have been observed from these artificial sources. The consensus view among scientists in the field is that the solar neutrino experiments are yielding a valid although surprising result.

The only remaining possibility, third in the list above, is that the theory of how the neutrino behaves must be changed. New experiments are underway that will test this conclusion.

Further experiments. Fortunately, testable distinctions can be made. A new experiment called SNO (Sudbury Neutrino Observatory) uses 1000 tons of precious heavy water in the Inco nickel mine in Sudbury, Ontario, Canada. This experiment began operating in the spring of 1999 and will ultimately measure the ratio of the number of neutrinos of the electron type (associated with electrons) to the number of number of neutrinos of all types (associated with electrons, muons, and tau particles). Standard neutrino physics predicts that all solar neutrinos are electron type, i. e., that the ratio of electron neutrinos to total neutrinos is one. Most new-physics explanations of solar neutrino experiments predict a ratio of electron-type neutrinos to all neutrino types that is much less than one.

The SuperKamiokande and the SNO experiments will also search for other evidence of non-standard neutrino behavior, including a counting rate that is different during the night and during the day. According to some of the most attractive new-physics explanations of solar neutrino experiments the Sun appears brighter at night in neutrinos than during the day. Another diagnostic measurement that is being made by the SuperKamiokande and SNO experiments is to determine the relative number of solar neutrinos of different energies that reach the Earth. A mistake in the solar model could change the total number of neutrinos that are observed but not the relative number of neutrinos of different energies that are produced. On the other hand, modifications of the standard model of neutrinos can cause the observed number of neutrinos of different energies to change from the expected proportions to some different ratios. *See* NEUTRINO; STANDARD MODEL; STELLAR EVOLUTION; SUN. **John N. Bahcall**

Bibliography. B. T. Cleveland et al., Measurement of the Solar Electron Neutrino Flux with the Homestake Chlorine Detector *ApJ* 496:505-526 1998; Y. Fukuda, Final Solar neutrino results at Kamiokande, Phys. Rev. Lett. 77: 1683-1686, 1996; Y. Fukuda, Measurements of the Solar Neutrino Flux from SuperKamiokande's First 300 Days, Phys. Rev. Lett. 81: 1158-1162 (1998); J. N. Abdurashitov et al., Measurement of the solar neutrino capture rate with gallium metal (the Soviet-American Gallium Solar Neutrino Experiment, SAGE), *Phys. Rev. C, October, in press*, astro-ph/9907113(http://xxx.lanl.gov), 1999; W. Hampel et al., GALLEX solar neutrino observations: results for GALLEX IV, Phys. Letters B447: 127-133, 1999; J. N. Bahcall, *Neutrino Astrophysics*, 1989; J. N. Bahcall and R. Davis, Jr., Solar neutrinos: A scientific puzzle, *Science*, 191: 264-267, 1976; J. N. Bahcall, S. Basu, and M. H. Pinsonneault, How uncertain are solar neutrino predictions?, Phys. Letters B433: 1-8, 1998. J. N. Bahcall, P. I. Krastev, and A. Yu. Smirnov, Where do we stand with solar neutrino oscillations?, Phys. Rev. D, 58, 096016, 1-22, 1998.

Principal reactions of the proton-proton chain in the Sun

Number	Reaction	Percentage of solar terminations*	Maximum neutrino energy, MeV
1 (PP reaction)	$p + p \rightarrow {}^{2}\text{H} + e^{+} + \nu$ or	99.75	0.420
2 (PEP reaction)	$p + e^{-} + p \rightarrow {}^{2}\text{H} + \nu$	0.3	1.44 (monoenergetic)
3	${}^{2}\text{H} + p \rightarrow {}^{3}\text{He} + \nu$	100	
4	${}^{3}\text{He} + {}^{3}\text{He} \rightarrow {}^{4}\text{He} + 2p$ or	85	
5	${}^{3}\text{He} + {}^{4}\text{He} \rightarrow {}^{7}\text{Be} + \nu$	15	
6	${}^{7}\text{Be} + e^{-} \rightarrow {}^{7}\text{Li} + \nu$	—	0.861 (90%), 0.383 (10%) (both monoenergetic)
7	${}^{7}\text{Li} + p \rightarrow 2\ {}^{4}\text{He}$ or	—	
8	${}^{7}\text{Be} + p \rightarrow {}^{8}\text{B} + \nu$	0.02	
9	${}^{8}\text{Be} \rightarrow {}^{8}\text{Be}^{*} + e^{+} + \nu$	—	14
10	${}^{8}\text{Be}^{*} \rightarrow 2\ {}^{4}\text{He}$	—	

*Percentage of solar terminations of the proton-proton chain in which this reaction occurs