

Solar Neutrinos: Past, Present, Future¹

John N. Bahcall, Institute for Advanced Study, Princeton, NJ, USA

In 1964, Ray Davis and I proposed that solar neutrinos could be used in a practical experiment "...to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars." We wanted to test quantitatively the idea that the Sun shines by burning four protons into an α -particle, two positive electrons, two neutrinos and some energy that is given up as heat to the Sun.

Seven beautiful experiments have by now detected solar neutrinos and provided measurements of their fluxes and energies. The experiments, all performed deep underground to avoid interference from cosmic rays or other possible background events on the Earth's surface are: Homestake (chlorine detector in a South Dakota gold-mine, Ray's original experiment), Kamiokande (Japanese-American experiment using pure water in the Japanese alps), GALLEX (gallium detector in the Gran Sasso Underground Laboratory north of Rome, German, Italian, French, Israeli, and American experiment), SAGE (gallium detector, Russian-American experiment performed underneath the highest mountain in eastern Europe), GNO (revitalized GALLEX gallium experiment led by an Italian collaboration), Super-Kamiokande (a gigantic pure water detector near original Kamiokande site, Japanese-American collaboration), and SNO (uses a thousand tons of heavy water in an active nickel mine in Sudbury, Ontario, Canada, a Canadian, American, English collaboration).

From the publication of the first experimental results by Davis in 1968 until 2001, which the first results from SNO were published, i. e., for about 33 years, there was a discrepancy between the predicted and the measured rates of solar neutrino experiments. In all cases, the measured rates were less than we predicted using the standard solar model and the standard electroweak model of particle physics. The standard predictions for the event rates in solar neutrino experiments involve detailed calculations of the rates of nuclear fusion reactions in the solar interior (thus the standard solar model) and the presumption, which follows from the standard electroweak model, that essentially nothing happens to solar neutrinos between the time they are created in the center of the Sun and the time they are detected on Earth.

¹ Summary of lecture given following receipt on November 14, 2003 of the Gold Medal of the Royal Astronomical Society. Background material can be found at: <http://www.sns.ias.edu/~jnb> .

The discrepancies between solar neutrino predictions and solar neutrino experiments gave rise to what was known widely as ‘The Solar Neutrino Problem’ or ‘The Mystery of the Missing Neutrinos.’ In practice, most physicists dismissed the discrepancies as due to the difficulties in calculating the details of nuclear fusion reactions that occur deep inside the Sun at very high temperatures and densities.

But, helioseismology provided a precise verification of our standard solar model calculations. Incredibly accurate measurements of periodic motions on the surface of the Sun allowed the sound speed to be inferred throughout the solar interior. The measured sound speeds agreed to better than 0.1% rms with the values calculated from the standard solar model. This spectacular agreement allowed some of us astrophysicists to argue in 1966 that the ‘solar neutrino problem’ must be a problem with the standard electroweak model of particle physics not with our standard model of the Sun. However, as you can easily imagine, arguments based upon unfamiliar observations of solar surface phenomena were not sufficient to convince most physicists that predictions of the standard solar model about neutrino production in the interior of the Sun were more accurate than inferences from the minimal standard electroweak model. After all, the standard electroweak model had been precisely tested and verified in many hundreds of experiments in laboratories throughout the world.

The situation changed dramatically on June 18, 2001. The SNO experimental collaboration combined their new results on heavy water with the earlier measurements of the Super-Kamiokande measurements on ordinary water. The combined experimental results showed unequivocally that the total number of rare high-energy ^8B solar neutrinos reaching the Earth was in excellent agreement with the number predicted by the standard solar model. Further measurements by the SNO collaboration in 2002 and 2003 strengthened and made more precise the agreement between standard solar model predictions and solar neutrino observations.

The ‘mystery of the missing neutrinos’ has been solved. The uncounted neutrinos were not missing at all. On the way from the Earth from the center of the Sun, most of the electron-type neutrinos created in the Sun were changed into (‘oscillated into’) muon-type or tau-type neutrinos that are much more difficult to detect.

Solar neutrino experiments show that physics beyond the minimal standard electroweak model is occurring. The inferences regarding new physics are confirmed and refined by the KamLAND reactor anti-neutrino experiment. All of the solar and reactor neutrino results are well described by simple models of neutrinos oscillating

or changing their types. Neutrinos come in three different flavors-electron, muon, or tau-depending upon whether they are associated with electron, muon, or tau leptons. Fitting the models to the all the relevant neutrino data, now 96 independent data points, leads to relatively accurate determinations for two parameters of neutrino oscillations: Δm^2 , $\tan^2\Theta$. These two quantities characterize a mass scale for neutrinos (Δm^2) and the extent to which individual neutrino mass states are linear combinations of different neutrino flavor states ($\tan^2\Theta$, which tells us how 'mixed up' neutrinos are).

The combined solar and reactor neutrino experiments together determine to high accuracy the rates of two nuclear fusion reactions that occur in the solar interior. The first of these reactions is the very rare solar fusion process ${}^7\text{Be}(p, \gamma){}^8\text{B}$. This fusion reaction occurs, according to the standard solar model, only about twice in every 10^4 times that the Sun burns four protons into an α -particle. The total flux of the rare high-energy solar neutrinos produced by the β -decay of ${}^8\text{B}$ is 1 ± 0.04 (1 sigma) in units of the flux predicted by the standard solar model. The dominant low energy solar neutrino flux (p-p ν 's, with a flux approximately 10^4 larger than the ${}^8\text{B}$ neutrino flux) is produced by the fundamental nuclear reaction $p(p, e^+ + \nu){}^2\text{H}$. The p-p neutrino flux is determined to be 1.02 ± 0.02 , also in units of the flux predicted by the standard solar model (1 sigma).

The measured values of the solar neutrino fluxes agree to better than one standard deviation with the best-estimate predictions of the standard solar model. The experimental error in the measurement of the rare ${}^8\text{B}$ neutrinos is less than the error in the theoretical prediction of the standard solar model, so the agreement is accidentally good. I think that we can calculate the flux of the p-p neutrinos to $\pm 1\%$, so there is a strong motivation to measure this fundamental p-p flux to higher accuracy. In addition, the second most abundant neutrino flux, the ${}^7\text{Be}$ neutrino flux produced by the reaction ${}^7\text{Be}(e, \nu){}^7\text{Li}$, is very poorly measured at present and must be determined accurately to test if the solar models predict well the ratio of the two most important ways of completing the burning of hydrogen to helium. The p-p and ${}^7\text{Be}$ solar neutrino experiments that are under development provide a strong incentive for us to refine and to make certain our calculations are correct to measurable accuracy.

I want to close with a remark about the ${}^8\text{B}$ solar neutrino flux, the first solar neutrino flux to be measured. The calculated flux of the high-energy ${}^8\text{B}$ neutrinos depends approximately on the 25th power of the central temperature of the Sun, i. e., is proportional to T^{25} . In order to calculate this neutrino flux correctly, one must determine precisely a large number of plasma physics, nuclear physics, astrophysical,

and astronomical quantities. Many input quantities must be measured (e. g., low energy cross sections for nuclear reactions or the abundances of heavy elements on the surface of the Sun) and other input quantities must be calculated (e. g., the cross sections for nuclear reactions that occur via the weak interactions and the stellar opacity). Over the last forty years, thousands of dedicated researchers working at institutions distributed throughout the world have made measurements or calculations that have helped to refine the predictions of the standard solar model. Many hundreds of other very talented physicists, chemists, and engineers have collaborated to make precise measurements of elusive solar neutrinos. This is truly a community effort. Together we have shown that the predictions of the standard solar model are, unlikely as that may have seemed three or four decades ago, more accurate than the relevant neutrino predictions of the minimal standard electroweak model.