An Experimentalist’s Overview of Solar Neutrinos

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Abstract.
Four decades of solar neutrino research have demonstrated that solar models do a remarkable job of predicting the neutrino fluxes from the Sun, to the extent that solar neutrinos can now serve as a calibrated neutrino source for experiments to understand neutrino oscillations and mixing. In this review article I will highlight the most significant experimental results, with emphasis on the latest model-independent measurements from the Sudbury Neutrino Observatory. The solar neutrino fluxes are seen to be generally well-determined experimentally, with no indications of time variability, while future experiments will elucidate the lower energy part of the neutrino spectrum, especially pep and CNO neutrinos.

1. The Standard Solar Model
The Sun is a prolific source of $\nu_e$’s with energies in the $\sim$0.1-20 MeV range, produced by the fusion reaction

$$4p + 2e^- \rightarrow ^4\text{He} + 2\nu_e + 26.731 \text{ MeV}.$$ (1)

Solar fusion proceeds through a chain of sub-reactions called the pp chain, consisting of several steps [1]. Each neutrino-producing reaction in the pp chain produces a characteristic neutrino energy spectrum that depends only on the underlying nuclear physics, while the rates of the reactions must be calculated through detailed astrophysical models of the Sun. Experimentally the pp, $^8$B, and $^7$Be reactions are the most important neutrino-producing steps of the pp chain. A very small fraction of the Sun’s energy is produced through the alternate CNO chain.

Figure 2 illustrates the solar neutrino energy spectra. At energies above 2 MeV only $^8$B neutrinos have been directly detected by water Cherenkov experiments, while the hep reaction, which extends slightly higher in energy but is 1000 times smaller in flux, eludes detection still. Radiochemical experiments count the integral number of neutrinos from all reactions above their energy thresholds without resolving the separate contributions of each reaction. To date only the gallium experiments have sensitivity to pp neutrinos produced in the initiating reaction in the pp chain, with a rate calculable to a couple of percent just from the Sun’s luminosity. Recently the Borexino experiment has succeeded in the first real-time measurements of $^7$Be neutrinos, which are produced in a monoenergetic line just below 1 MeV [3].

2. Pre-SNO results
The pioneering solar neutrino experiment was Ray Davis’s chlorine experiment in the Homestake mine near Lead, South Dakota [4]. This experiment measured solar neutrinos by observing
\[ p + p \rightarrow ^2H + e^+ + \nu_e \]
\[ p + e^- + p \rightarrow ^2H + \nu_e \]
\[ ^2H + p \rightarrow ^3\text{He} + \gamma \]
\[ ^3\text{He} \rightarrow ^4\text{He} + 2p \]
\[ ^3\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu_e \]
\[ ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \]
\[ ^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e \]
\[ ^7\text{Li} + p \rightarrow ^4\text{He} \]
\[ ^7\text{Be} + p \rightarrow ^8\text{B} + \gamma \]
\[ ^8\text{B} \rightarrow ^8\text{Be}^* + e^+ + \nu_e \]
\[ ^8\text{Be}^* \rightarrow ^2^4\text{He} \]

**Figure 1.** The pp reaction chain. The three most important neutrino-producing reactions are highlighted in color.

**Figure 2.** Energy spectra of solar neutrinos separated by reaction type, reproduced from reference [2].

the rate of Ar atom production through the reaction \( \nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^- \). By placing 600 tons of tetrachloroethylene deep underground (to shield it from surface radiation), and using
radiochemistry techniques to periodically extract and count the number of argon atoms in the tank, Davis inferred a solar neutrino flux that was just \( \sim 1/3 \) of that predicted by solar model calculations \([4, 2]\).

When scrutiny of both the Davis experiment and the solar model calculations failed to uncover any clear errors, other experiments were built to measure solar neutrinos in other ways. The Kamiokande and Super-Kamiokande water Cherenkov experiments have measured elastic scattering of electrons by \(^{8}\text{B}\) solar neutrinos, using the directionality of the scattered electrons to confirm that the neutrinos in fact are coming from the Sun \([5]\). The measured elastic scattering rate is just \( \sim 47\% \) of the solar model prediction. The SAGE and GNO/GALLEX experiments have employed a different radiochemical technique to observe the \( \nu_e + ^{71}\text{Ge} \rightarrow ^{71}\text{Ge} + e^- \) reaction, which is primarily sensitive to \( pp \) neutrinos, and have measured a rate that is \( \sim 55\% \) of the solar model prediction \([6]\).

Multiple experiments using different techniques have therefore confirmed a deficit of solar \( \nu_e \)'s relative to the model predictions. Although interpretation of the data is complicated by the fact that each kind of experiment is sensitive to neutrinos of different energies produced by different reactions in the \( pp \) fusion chain, in fact there is apparently no self-consistent way to modify the solar model predictions that will bring the astrophysical predictions into agreement with the experimental results. This situation suggested that the explanation of the solar neutrino problem may not lie in novel astrophysics, but rather might indicate a problem with our understanding of neutrinos.

3. Results from the Sudbury Neutrino Observatory

The Sudbury Neutrino Observatory (SNO) has provided conclusive evidence that solar neutrinos change flavour by directly counting the rate of all active neutrino flavours, not just the \( \nu_e \) rate to which the other experiments were primarily sensitive.

SNO was a water Cherenkov detector that used 1000 tonnes of \( \text{D}_2\text{O} \) as the target material \([8]\). Solar neutrinos interact with the heavy water by three different interactions:

\[
\begin{align*}
(CC) & \quad \nu_e + d \rightarrow p + p + e^- \\
(NC) & \quad \nu_x + d \rightarrow p + n + \nu_x \\
(ES) & \quad \nu_x + e^- \rightarrow \nu_x + e^-
\end{align*}
\]

Here \( \nu_x \) is any active neutrino species. The reaction thresholds are such that SNO is only sensitive to \( ^{8}\text{B}\) solar neutrinos.\(^1\) The charged current (CC) interaction measures the flux of \( \nu_e \)'s coming from the Sun, while the neutral current (NC) reaction measures the flux of all active flavours. The elastic scattering (ES) reaction is primarily sensitive to \( \nu_e \), but \( \nu_\mu \) or \( \nu_\tau \) also elastically scatter electrons with \( \sim 1/6\)th the cross section of \( \nu_e \).

SNO ran in three separate configurations. In the first neutrons were detected by observing the \( \gamma \)-ray emitted when they capture on deuterons. In the 2nd phase 0.2% \( \text{NaCl} \) was added to the \( \text{D}_2\text{O} \) and \( \gamma \)-rays from neutron capture on \(^{35}\text{Cl} \) were included. In the final phase the salt was removed and replaced by an array of \(^{3}\text{He}\) proportional counters. These counters detected neutrons independently of the Cherenkov signal used to measure CC and ES reaction rates.

SNO’s most sensitive analysis is a low-energy threshold analysis of the Phase I and Phase II data \([9]\). In this analysis a simultaneous fit of signals and low-energy backgrounds is used to extract not just rates, but also to fit for a parameterized oscillation survival probability. For the favored Large Mixing Angle oscillation solution, the survival probability is well approximated by a 2nd order polynomial and a day-night asymmetry in the probability that can vary linearly with neutrino energy. This fit yields a value for the \(^{8}\text{B}\) flux of \( \nu_e \) that is

\(^1\) The tiny flux of higher-energy neutrinos from the \( \text{ hep} \) chain may be neglected here.
$5.046^{+0.159}_{-0.152} (\text{stat})^{+0.107}_{-0.123} (\text{syst})$ neutrinos/cm$^2$/s, which is in excellent agreement with solar model predictions. Figure 3 shows the fitted day and night $\nu_e$ survival probabilities.

**Figure 3.** Fitted day (a) and night (b) oscillation probabilities, along with the day-night asymmetry formed from them (c). The colored bands show the total uncertainty as a function of energy while the dashed line shows the prediction of the best-fit LMA point [9].
Fits of SNO’s $^3$He proportional counter data from Phase III give a consistent value for the $^8$B flux of $5.54^{+0.33}_{-0.31}(\text{stat})^{+0.36}_{-0.34}(\text{syst})$ neutrinos/cm$^2$/s, which although having larger uncertainties shares almost no systematics in common with other SNO analyses [10].

4. Time variability of the solar neutrino flux

Some researchers have reported periodic variations in the measured solar neutrino fluxes [11, 12, 13, 14, 15, 16, 17, 18]. Other analyses of these same data, including analyses by the experimental collaborations themselves, have failed to find such evidence [19, 20]. The reported periods have been claimed to be related to the solar rotational period. Because solar rotation should not produce variations in the solar nuclear fusion rate, non-standard neutrino properties have been proposed as an explanation. Periodicities in the solar neutrino flux, if confirmed, could provide evidence for new neutrino physics beyond the commonly accepted picture of matter-enhanced oscillation of massive neutrinos.

The SNO experiment has searched for evidence of time variability at periods ranging from 10 years down to 10 minutes [21, 22]. The sensitivity to high-frequency periodicities ($f > 1$/day) is unique to SNO, which combined real-time detection with negligible backgrounds. SNO has found no indications for any time variability of the $^8$B flux at any timescale, including in the frequency window in which $g$-mode oscillations of the solar core might be expected to occur. At present there is no conclusive evidence for time variability of the solar neutrino fluxes from any experiment.

5. Real-time low energy measurements

Liquid scintillator detectors offer some unique advantages for solar neutrino research. A scintillator detector possesses a very low (sub-MeV) energy threshold, giving sensitivity to the lower energy solar neutrinos with real-time detection capability. Unfortunately scintillator detectors do not possess directional sensitivity, and only detect elastic scattering of solar neutrinos. Unlike SNO they do not have any ability to distinguish between neutrino flavors, but can access neutrinos at very low energies. They consequently face extremely stringent radiopurity requirements.

The Borexino experiment has successfully used the scintillation technique to detect the monoenergetic $^7$Be neutrino line at 0.862 MeV. Borexino finds that the rate of $^7$Be neutrinos is $0.52^{+0.07}_{-0.06}$ of the solar model prediction, in line with expectations from the Large Mixing Angle oscillation prediction. No day-night asymmetry is seen in the $^7$Be rate, consistent with expectations [3].

The SNO+ experiment will reuse the SNO infrastructure, replacing the heavy water with a liquid scintillator target [23]. With its great depth SNO+ will be well-shielded against cosmogenic backgrounds such as $^{11}$C. This should allow SNO+ to observe the pep neutrino line. The pep neutrinos are particularly interesting because this reaction is one of the initiating reactions of the pp chain, and so its rate is predicted precisely by the overall solar luminosity. Along with their favorable energy, intermediate between the MSW-dominated and vacuum-dominated regions of the oscillation, this will provide a good test of neutrino oscillation predictions and sensitivity to new physics such as non-standard neutrino interactions. SNO+ will also have sensitivity to neutrinos from the CNO cycle.

6. Conclusions

Understanding of neutrino production in the Sun has advanced to the point that almost all of the most significant reactions in the pp chain have been measured experimentally with varying degrees of precision. The $^8$B flux itself is now measured to $\sim 3\%$, a constraint that forms the basis of the world’s best determination of the neutrino mixing angle $\theta_{12}$. On the whole standard solar
models do a remarkable job of predicting the observed neutrino fluxes once matter-enhanced neutrino oscillations are accounted for. Future efforts will focus primarily on real-time low energy measurements of the pep reaction and CNO cycle.

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