Recent SNO results and the final SNO phase

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Abstract. The SNO experiment ran in its second phase from 2001 to 2003 with \( \approx 2000 \text{ kg} \) of salt added to the heavy water. SNO has recently published \( ^{8}\text{B} \) flux results and a charged current neutrino spectrum from the full data set of 391 days. The full first two phases of SNO have also been analyzed for periodicities in the solar neutrino signal. Starting in 2003, an array of neutron detectors was added to the SNO experiment to observe the neutral current reaction. Production data taking has been in progress since November 2004. This array will provide an independent measurement of the total flux of active neutrinos from the sun with different systematic uncertainties from the first two phases of SNO. The SNO experiment finishes data taking at the end of 2006 and the heavy water will be returned. A new liquid scintillator experiment (SNO+) to measure pep solar neutrinos and geo-neutrinos is planned to be build using the SNO detector and infrastructure.

1. SNO
SNO is a heavy water Cherenkov detector that is located at 6010 m w.e. depth in the rock of Sudbury, Ontario. The heavy water is located in a 12 m diameter acrylic vessel surrounded by 9465 photomultiplier tubes [1].

2. Salt Results
The salt phase of SNO started in 2001 with the addition of \( \approx 2000 \text{ kg} \) of NaCl to the heavy water of the Sudbury Neutrino Observatory (SNO). Cl has a 500 times larger neutron capture cross section than deuterium, thereby improving the neutron capture probability and by means of a larger event energy and distinctively different event topology enabling a distinction between the neutral current and charged current solar neutrino flux.

SNO is sensitive to solar neutrinos from the \( ^{8}\text{B} \) cycle. These neutrinos can be detected in three reactions: neutral current (NC), charged current (CC) and elastic scattering (ES).

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\begin{align*}
\text{CC : } & \nu_e + D \rightarrow p + p + e^- - 1.442 \text{ MeV} \\
\text{NC : } & \nu_x + D \rightarrow n + p + \nu_x - 2.224 \text{ MeV} \\
\text{ES : } & \nu_x + e^- \rightarrow \nu_x + e^-
\end{align*}
\]

Where \( \nu_x \) is any neutrino flavor. While the NC channel is equally sensitive to all neutrino flavors the ES is predominantly sensitive to \( \nu_e \). The neutron produced in the NC reaction is captured by \( ^{35}\text{Cl} \), this capture releases 8.6 MeV.
The three different types of interactions can statistically be separated by their different behavior in the isotropy parameter $\beta_{14}$ (defined in [2]) and $\cos \theta_{sun}$ (see figures 1, 2). The neutrino fluxes are extracted from an extended maximum likelihood fit using probability density functions for the fluxes and backgrounds [2].

The total solar neutrino flux extracted in an unconstrained fit from the salt phase data is:

$$\Phi_{uncon}^{CC} = 1.68^{+0.06}_{-0.06} \text{stat}^{+0.08}_{-0.09} \text{syst}$$
$$\Phi_{uncon}^{ES} = 2.35^{+0.22}_{-0.22} \text{stat}^{+0.15}_{-0.15} \text{syst}$$
$$\Phi_{uncon}^{NC} = 4.94^{+0.21}_{-0.21} \text{stat}^{+0.38}_{-0.34} \text{syst}$$

This is consistent with the previous results and updates the older analysis with an improved understanding of the experiments’ systematics. The data was also analyzed for day/night asymmetry and no significant effect was observed [2]. The CC spectrum is shown in Figure 3. An MSW oscillation analysis was performed including the new SNO data, flux information from Cl, Sage, GALLEX/GNO, Super-Kamiokande-1 zenith angle and Kamland 766 ty data. The result is shown in Figure 4. SNO’s CC/NC ratio is the primary constraint on $\tan^2 \theta$. The hypothesis of maximal mixing is ruled out by more than 5 sigma.

3. Periodicity Analysis
There is considerable interest in solar cycles in the neutrino data. Since the solar neutrinos originate at the core of the sun a cycle in the neutrino signal would uncover potentially new and interesting solar physics.

SNO has analyzed the complete solar neutrino data set for periodic changes in an unbinned log likelihood analysis [3]. This analysis is sensitive to amplitudes in the 10% range for a 95% confidence limit. No unknown period was observed in the data.

The earth’s eccentricity was observed with a value of $0.0143^{+0.0086}_{-0.0086}$. A claim by Sturrock et. al. of a periodic signal in the Super Kamiokande data could be excluded with $3.6\sigma$.

4. Phase III - NCD Counters
SNO has been taking production data in its third phase since November, 2004. The salt was removed and an array of $^3$He filled neutron detectors for the neutral current reaction (Neutral
Figure 3. CC spectrum extracted from the salt data. The band in the predicted $^8$B spectrum represents a 1σ detector systematic uncertainty.

Figure 4. Global fit of solar neutrino oscillation parameters.

Current Detectors - NCDs [1], [4]) has been installed.

All counters are in operation and the SNO collaboration is currently analyzing the data with blindness criteria imposed. The goal of the third phase is to provide a systematically different measurement of the solar neutrino flux. This measurement will provide a much reduced uncertainty when combined with the previous data. The data taking of SNO will end Dec 31, 2006.

5. SNO+
At the end of the data taking phase for SNO some of the current SNO collaborators are proposing to use the SNO cavity and the detector for a pep solar neutrino experiment by replacing the heavy water with liquid scintillator. This experiment, called SNO+, can contribute to the understanding of neutrino oscillation by doing a precision measurement of the pep neutrino rate in an energy region sensitive to distortions from the MSW effect or other effects such as non-standard interactions and sterile neutrinos. This experiment would be part of the new long-term international laboratory, SNOLAB [5], expected to be completed in 2007. Because of its geographical location in the Canadian shield it will also provide a measurement of geo-neutrino flux with very good sensitivity. There is also a later phase option of loading the liquid scintillator with a double beta decaying substance, for example with Neodymium. Currently the SNO+ collaboration is working on a full technical proposal with will be submitted for funding of the experiment in 2006.

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