Solar Neutrino Physics from SNO

Aksel Hallin

SNOLAB Opening

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SNO Activities and Solar Neutrino Publications 1990-2012

Construction

Water Fill
Commissioning

Pure $D_2$

Salt

Neutral Current
Detectors

Draining

Continued analysis

90 91 92 93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08 09 10 11 12

First $D_2$ Paper
$D_2$ Paper, Day-Night Paper
Salt Paper
Long Salt Paper
Long $D_2$ Paper
NCD Paper
Combined $D_2$ and $D_2$ Analysis (LETA)
3 Phase Paper, Long NCD Paper, hep Paper
SNO physics: measure neutrinos that directly probe fusion reactions in the core of the sun

![Graph showing neutrino flux and energy spectrum.](image)

- SNO sensitivity

- Neutrino Spectrum ($\pm 1\sigma$)
  - Bahcall-Serenelli 2005
  - Neutrino Energy in MeV
  - Flux (cm$^{-2}$ s$^{-1}$)
  - $^{13}$N, $^{17}$F, $^{7}$Be, $^{8}$B, hep
Science in 1990:: Bahcall's plot, neutrino oscillations

SNO made a direct measurement of the total flux of solar neutrinos. Without SNO, we have the standard solar model predictions but no model independent measurement of the total solar neutrino flux.

Other experiments made measurements of electron neutrinos, and saw the significant depletion noted here, but were unable to distinguish between effects from an incorrect solar model and effects due to neutrino oscillations.

Ray Davis and John Bahcall had observed neutrino oscillations in the 70’s; but it was a model dependent observation that was suggestive but not definitive.
SNO’s Primary Measurements: Total Flux of All Neutrinos

![Graph showing SNO Measurements of solar neutrino flux (all flavours).]
Using the oscillation framework:

If neutrinos have mass: \( |\nu_l\rangle = \sum U_{li} |\nu_i\rangle \)

For three neutrinos:

\[
U_{li} = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\]

Maki-Nakagawa-Sakata-Pontecorvo matrix

(Double \(\beta\) decay only)

Solar, Reactor
Atmospheric
CP Violating Phase
Reactor...
Majorana Phases

Range defined for \(\Delta m_{12}, \Delta m_{23}\)

where \(c_{ij} = \cos \theta_{ij}\), and \(s_{ij} = \sin \theta_{ij}\)

For two neutrino oscillation in a vacuum: (valid approximation in many cases)

\[
P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2 L}{E}\right)
\]
SNO measurements that constrain oscillations: Average survival probability, \( P \).

Day/Night differences in survival probability

**TABLE VII.** Results from the maximum likelihood fit. Note that \( \Phi_B \) is in units of \( \times 10^6 \text{ cm}^{-2}\text{s}^{-1} \). The D/N systematic uncertainties includes the effect of all nuisance parameters that were applied differently between between day and night. The MC systematic uncertainties includes the effect of varying the number of events in the Monte Carlo based on Poisson statistics. The basic systematic uncertainties include the effects of all other nuisance parameters.

<table>
<thead>
<tr>
<th>( \Phi_B )</th>
<th>Best fit</th>
<th>Stat.</th>
<th>Systematic uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Basic</td>
<td>D/N</td>
</tr>
<tr>
<td>5.25</td>
<td>±0.16</td>
<td>±0.11</td>
<td>±0.01</td>
</tr>
<tr>
<td>0.317</td>
<td>±0.016</td>
<td>+0.008</td>
<td>±0.002</td>
</tr>
<tr>
<td>0.0039</td>
<td>+0.0065</td>
<td>±0.0047</td>
<td>±0.0012</td>
</tr>
<tr>
<td>-0.0010</td>
<td>±0.0029</td>
<td>±0.0013</td>
<td>±0.002</td>
</tr>
<tr>
<td>0.046</td>
<td>±0.031</td>
<td>±0.005</td>
<td>±0.012</td>
</tr>
<tr>
<td>-0.016</td>
<td>±0.025</td>
<td>±0.003</td>
<td>±0.009</td>
</tr>
</tbody>
</table>

**FIG. 10.** RMS spread in \( P_{\nu}(E_\nu) \) and \( A_{\nu}(E_\nu) \), taking into account the parameter uncertainties and correlations. The red band represents the results from the maximum likelihood fit, and the blue band represents the results from the Bayesian fit. The red and blue solid lines, respectively, are the best fits from the maximum likelihood and Bayesian fits.
SNO’s measurement and neutrino oscillation parameters:

**SNO D2O (2001)**

![Graph](image)

**SNO 3 phase (2012)**

![Graph](image)

**FIG. 14.** Two-flavor neutrino oscillation analysis contour using only SNO data.

**FIG. 15.** Two-flavor neutrino oscillation analysis contour using both solar neutrino and KamLAND (KL) results.

**FIG. 16.** Three-flavor neutrino oscillation analysis contour using both solar neutrino and KamLAND (KL) results.

**VI.4. Three-flavor neutrino oscillation analysis**

Figure 16 shows the allowed regions of the \((\tan^2 \theta_{12}, \Delta m^2_{21})\) and \((\tan^2 \theta_{13}, \sin^2 \theta_{13})\) parameter spaces obtained from the results of all solar neutrino experiments. It also shows the result of these experiments combined with the results of the KamLAND experiment. Compared to the result in Figure 15, this clearly shows that allowing non-zero values of \(\theta_{13}\) brings the solar neutrino experimental results into better agreement with the results from the KamLAND experiment.

Figure 17 shows the projection of these results onto the individual oscillation parameters. This result shows that due to the different dependence between \(\tan^2 \theta_{12}\) and \(\sin^2 \theta_{13}\) for the solar neutrino experimental results...
FIG. 16. Three-flavor neutrino oscillation analysis contour using both solar neutrino and KamLAND (KL) results.
Some of the other SNO Measurements

Measured 1229 days, 514 event, 1.22+/-

Periodicity Paper: PRD72, 052010 (2005)
No variations between 1s and 10 years
Except for eccentricity of orbit

Hep neutrino measurement
Preliminary fit to all SNO data. Consistent with SSM 8e3/cm**2/s
+ Nucleon decay, antineutrinos, spallation neutrons, ...

Preliminary posterior distribution
Sudbury Neutrino Observatory

1700 tonnes Inner Shielding H₂O
1000 tonnes D₂O
5300 tonnes Outer Shield H₂O
12 m Diameter Acrylic Vessel
Support Structure for 9500 PMTs, 60% coverage
Urylon Liner and Radon Seal

Neutrino-Electron Scattering (ES)
Charged Current (CC)
Neutral Current (NC)
Three Phases of SNO: 3 NC reactions

Phase I: Just D2O: neutron capture on deuterium
- Simple detector configuration, clean measurement
- Low neutron sensitivity
- Poor discrimination between neutrons and electrons

Phase II: D2O + NaCl: neutron capture on Chlorine
- Very good neutron sensitivity
- Better neutron electron separation

Phase III: D2O + 3He Proportional Counters
- Good neutron sensitivity
- Great neutron/electron separation

Why three phases?
1. Additional information to separate NC and CC
2. Completely different systematics, allowed us to check for consistency
3. Allowed us to "repeat" the measurement
Advantages of (2-Phase) Low Threshold Analysis

Ø Breaking NC/CC Covariance

Phase I (D_2O)

“Beam Off”

Phase II (D_2O+Salt)

“Beam On”
Observables

Photomultiplier tube
- position
- time
- Charge

NCD digitized data:

Neutrons
Alphas

FIG. 3. Sample waveforms. The top plot shows a neutron waveform (black) obtained from $^{24}$Na calibration data with the best fit to the neutron hypothesis (red). The bottom plot shows an alpha waveform (black) obtained from a string filled with $^3$He with the best fit to the alpha hypothesis (red). The vertical lines represent the fit boundaries.
Reconstruction

Reconstructed event

- Vertex position
- Electron direction
- Energy
- Isotropy (reaction discriminator)
- Particle identification and counting in NCD’s

History of SNO saw a continuous progression of fitters- to improve resolution, incorporate shadowing of the NCD’s, better incorporation of correlations,
Cherenkov light and $\beta_{14}$

Charged particle, $v > c/n$

Hollow cone of emitted photons

Energy & Direction

\[ \beta_1 = \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \cos \theta_{ij} \]

\[ \beta_4 = \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{1}{64} (9 + 20 \cos 2\theta_{ij} + 35 \cos 4\theta_{ij}) \]

$\beta_{14} = \beta_1 + 4\beta_4$
NEUTRINO EVENT DISPLAYED ON SNO COMPUTER SYSTEM
Controlling and Measuring Systematic Uncertainties

1. SNO spent a large fraction of the data acquisition time calibrating- which both determined the parameters for the MC and the systematic uncertainties.
2. In most cases, measured by careful comparison of calibration data with MC at various positions, times, energies, sources.
3. The 3 single phase measurements were done with assumptions that often required increasing systematic uncertainties/thresholds.
4. The LETA analysis included a major re-evaluation of all systematic uncertainties from charge pedestals, source positions, fitter response, background measurements.
5. The 3Phase analysis included all the data, but used a high PMT–side energy threshold to stay away from backgrounds. It did include correlations between systematic effects in the various phases.
SNO Calibrations

Determine detector response (optical parameters and time offsets): Dye-pumped laser and laser diffuser system.

Absolute Quantum efficiency (16N source in center)

Neutron capture efficiency (252Cf, AmBe) sources throughout volume

Position, direction and energy uncertainties “Isotropy” (16N and 252Cf)
\( \beta \)'s from 8Li
\( \gamma \)'s from 16N and \( t(p, \gamma)4He \)

SNO Energy Calibrations

Energy calibrated to \( \sim 1.5 \% \)
Throughout detector volume

Optical calibration at 5 wavelengths with "Laserball"

\( 6.13 \text{ MeV} \)

\( 19.8 \text{ MeV} \)

252Cf neutrons

\( 0.5\% \text{ LETA} \)
Background Reduction

LETA energy estimator includes both 'prompt' and 'late' light

12% more hits ≈ 6% narrowing of resolution
~60% reduction of internal backgrounds

LETA Cuts help reduce external backgrounds by ~80%

Example:
High charge early in time
Systematic Uncertainties

- Nearly all systematic uncertainties from calibration data-MC
- Upgrades to MC simulation yielded many reductions
- Residual offsets used as corrections w/ additional uncertainties
- All uncertainties verified with multiple calibration sources
Systematic Uncertainties—Energy Scale

Volume-weighted uncertainties:
Old: Phase I = ±1.2%  Phase II = ±1.1%
New: Phase I = ±0.6%  Phase II = ±0.5% (about half Phase-correlated)

16N calibration source: 6.13 MeV γ

Tested with: Independent 16N data, n capture events, Rn `spike' events...
Central runs remove source positioning offsets, MC upgrades reduce shifts.

Fiducial volume uncertainties:

Old: Phase I ~ ±3%  Phase II ~ ±3%
New: Phase I ~ ±1%  Phase II ~ ±0.6%

Tested with: neutron captures, 8Li, outside-signal-box vs
Low Energy Threshold Analysis

Systematic Uncertainties—Isotropy ($\beta_{14}$)

MC simulation upgrades provide biggest source of improvement tests with muon 'followers', Am-Be source, Rn spike

$\beta_{14}$ Scale uncertainties:

Old: Phase I ---,  Phase II = $\pm 0.85\%$ electrons, $\pm 0.48\%$ neutrons

New: Phase I $\pm 0.42\%$,  Phase II = $\pm 0.24\%$ electrons, $+0.38\%-0.22\%$ neutrons
$\emptyset$ PMT $\beta-\gamma$ PDFs

Not enough CPUs to simulate sample of events \text{ Use data instead}

```
\begin{align*}
NPF &= \varepsilon_1(1-\varepsilon_2)Nb \\
NFP &= (1-\varepsilon_1)\varepsilon_2Nb \\
NFF &= (1-\varepsilon_1)(1-\varepsilon_2)Nb \\
NPP &= \varepsilon_1\varepsilon_2Nb + Ns \\
NPMT &= NPP - Ns \\
&= NFP * NPF / NFF
\end{align*}
```

(so fixing pedestals gave us a handle on these bkds...)
Pulse Shape Analysis in NCDs (3 Phase)

FIG. 4. Distribution of particle identification parameters for neutron events (boxes, where the area represents the number of events) and alpha events (red marks). The line represents the boundary for cuts. PID cut 1 applies to parameters $p_a$ and $p_b$, and PID cut 2 applies to parameters $p_c$ and $p_d$ for events that failed PID cut 1.

FIG. 9. The fitted $E_{\text{NCD}}$ spectrum after the particle identification cut. The thick black line is the best fit. The blue and red lines are the best fitted neutron and alpha spectra, respectively.

FIG. 5. $E_{\text{NCD}}$ spectrum before (brown) and after (red) the particle identification cut. From left to right the plots are for $^{24}\text{Na}$ calibration data (neutrons), data from strings filled with $^4\text{He}$ (alphas), and data from strings filled with $^3\text{He}$. 

$1115 \pm 79$ neutrons
Signal Extraction: a multiparameter fit of the data to pdf’s describing the various signals and backgrounds; including correlations between phases, and a variety of systematic parameters. In 3 phase analysis, almost 60 parameters.
Three Phase Fit

FIG. 11. Projection of the $T_{\text{eff}}$, $\rho$, $\cos \theta_C$, and $\beta_{14}$ for the Phase I data. Day events hollow circles and dashed lines. Night events filled circle and solid lines. Note that the sharp break in the data in the top panel at 5 MeV arises from change of bin width.

FIG. 12. Projection of the $T_{\text{eff}}$, $\rho$, $\cos \theta_C$, and $\beta_{14}$ for the Phase II data. Day events hollow circles and dashed lines. Night events filled circle and solid lines. Note that the sharp break in the data in the top panel at 5 MeV arises from change of bin width.

FIG. 13. Projection of the $T_{\text{eff}}$, $\rho$, and $\cos \theta_C$ for the data from Phase III. Day events hollow circles and dashed lines. Night events filled circle and solid lines.
Analysis techniques used by SNO

Blind analysis

Independent analyses (at least two for every publication)

Extended ML minimization against Monte Carlo and analytic pdf’s of varying dimensionality.

Parameterizing and floating systematic functions

And many, many arguments! Some of which were fun... at least afterwards.
SNO has published it’s final solar neutrino analyses.

A handful of remaining papers, such as the hep paper, the antineutrino paper and neutron backgrounds from cosmic rays atSNO depth will be finalized soon.
People of SNO