Present Status and Results from the SNO Experiment

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• The SNO Detector and solar $\nu$'s
• Results from the pure D$_2$O Phase
• Calibration for Salt (second) Phase
  Energy, Event Isotropy, Backgrounds
• Signal Analysis in the Salt Phase (MC)
• Projected sensitivity to mixing parameters
• Conclusion and Outlook
SNO CC vs NC implies flavor change, which can then explain other experimental results.

- SAGE+GALLEX/GNO: 0.58
- Homestake: 0.33
- Kamiokande+SuperK: 0.46
- SNO CC (June 2001): 0.35
- SNO NC (April 2002): ~1
The SNO Detector


17.8m dia. PMT Support Structure
9456 PMTs, 56% coverage

12.01m dia. acrylic vessel

1700 tonnes of inner shielding H₂O

5300 tonnes of outer shielding H₂O

Host: INCO Ltd., Creighton #9 mine
Coordinates: 46°28'30"N 81°12'04"W
Depth: 2092 m (~6010 m.w.e., ~70 μ day⁻¹)
Neutrino Reactions in SNO

**CC**

\[ \nu_e + d \rightarrow p + p + e^- \]

- Q = 1.445 MeV
- good measurement of \( \nu_e \) energy spectrum
- some directional info \( \propto (1 - 1/3 \cos \theta) \)
- \( \nu_e \) only

**NC**

\[ \nu_x + d \rightarrow p + n + \nu_x \]

- Q = 2.22 MeV
- measures total \( ^8B \) \( \nu \) flux from the Sun
- equal cross section for all \( \nu \) types

**ES**

\[ \nu_x + e^- \rightarrow \nu_x + e^- \]

- low statistics
- mainly sensitive to \( \nu_e \), some \( \nu_\mu \) and \( \nu_\tau \)
- strong directional sensitivity
Solar Neutrino Physics with SNO

What can we learn from measuring the NC interaction rate and the Day/Night variations of the $^8$B Flux?

- Total $^8$B $\nu$ flux (NC)
  $\nu_e$ flux (CC)
  $CC_{SNO}/NC_{SNO}$ → Test of neutrino flavor change

- Total flux of solar $^8$B neutrinos
  → Test of solar models

- Diurnal time dependence
  → Test of neutrino oscillations

- Electron neutrino energy spectrum
  → Distortions in $^8$B spectrum?
### SNO’s response to neutron events (solar NC signal)

<table>
<thead>
<tr>
<th>Phase I (pure D2O):</th>
<th>Phase II (dissolved salt):</th>
<th>Phase III (3He n counters):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron capture on D</td>
<td>Neutron capture on Cl</td>
<td>$n + ^3\text{He} \rightarrow p + t$</td>
</tr>
<tr>
<td>Single 6.25 MeV $\gamma$</td>
<td>Multiple $\gamma$ s, 8.6 MeV</td>
<td>Independent channel</td>
</tr>
<tr>
<td>Statistical separation</td>
<td>Statistical separation</td>
<td>NC uncorrelated to CC</td>
</tr>
<tr>
<td>(Energy, radius)</td>
<td>(Isotropy)</td>
<td></td>
</tr>
<tr>
<td>High CC-NC correlation</td>
<td>Better CC-NC separation</td>
<td></td>
</tr>
</tbody>
</table>

**Past**  **Present**  **Future**
Statistical Signal Separation (D2O phase analysis)

- Signal PDFs used for statistical separation

$$F_{CC}(r, E, \cos \theta_{sun})$$
$$F_{ES}(r, E, \cos \theta_{sun})$$
$$F_{NC}(r, E, \cos \theta_{sun})$$

SNO response in event radius, energy and direction to solar neutrinos through CC, ES, and NC reactions

Maximum Likelihood fit for $\nu$ fluxes
Shape Constrained Signal Extraction Results (Pure D2O phase)

<table>
<thead>
<tr>
<th>#EVENTS</th>
<th>CC</th>
<th>ES</th>
<th>NC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>1967.7</strong> +61.9 +60.9</td>
<td><strong>263.6</strong> +26.4 +25.6</td>
<td><strong>576.5</strong> +49.5 +48.9</td>
</tr>
</tbody>
</table>

![Graphs showing event distributions and efficiencies](diagram.png)
Flux Results – Pure $\text{D}_2\text{O}$ Phase

\[
\Phi_e = 1.76^{+0.05}_{-0.05} (\text{stat.})^{+0.09}_{-0.09} (\text{syst.}) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}
\]

\[
\Phi_{\mu\tau} = 3.41^{+0.45}_{-0.45} (\text{stat.})^{+0.48}_{-0.45} (\text{syst.}) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}
\]

5.3 $\sigma$ effect

Neutrinos change flavour

Constrained Fit for flavour change test

\[
\Phi_{\text{SSM}} = 5.05^{+1.01}_{-0.81}
\]

\[
\Phi_{\text{SNO}} = 5.09^{+(0.44\oplus0.46)}_{-(0.43\oplus0.43)}
\]

Without Constraint

\[
\Phi_{\text{SNO}} = 6.42^{+(1.57\oplus0.55)}_{-(1.57\oplus0.58)}
\]
Physics Interpretation – Neutrino Oscillations
SNO D2O results, pre-KAMLAND

SNO Day and Night
Energy Spectra Alone

Combining All Experimental
and Solar Model information

\[
\log(\tan^2 \theta) \quad \log(\Delta m^2 / eV^2)
\]

- 90% CL
- 95% CL
- 99% CL
- 99.73% CL

LMA
LOW
VAC
SMA

(a)

(b)
Salt Phase Dataset (Analysis being completed now)

- Salt added to detector
- May 27, 2001 to October 10, 2002
- 503 days
- ~280 neutrino live-days (57.4%)
- improved NC statistics
- improved CC-NC separation from isotropy
- Improved measurement of external neutron backgrounds
  - improved measurement of CC/NC ratio
  - precision unconstrained result
What We Measure

PMT Measurements
- position
- charge
- time

Reconstructed Event
- event vertex
- event direction
- energy
- isotropy
SNO Detector Calibration

Monte Carlo

Cherenkov production (e^-, γ, β−γ)
Photon propagation and detection
Neutron transport and capture
Reconstruction
(position, direction, energy, isotropy)

Calibration

Pulsers
Pulsed Laser 337nm to 620 nm

^{16}N 6.13 MeV γ’s

^{3}H(p,γ)^{4}He 19.8 MeV γ’s

^{8}Li <13.0 MeV β’s

^{252}Cf neutrons

U/Th ^{214}Bi & ^{208}Tl β–γ’s

NDM03, June 9 2003
Vertex Reconstruction of $^{16}\text{N}$ Events

PMT times used to reconstruct event position

Resolution $\sim 15$ cm
Energy Calibration

Prompt time cut applied to accept only direct photons

Reduces uncertainty due to scattering

Corrections for detector optics, dead PMTs, and gain applied

No. prompt hits vs. electron energy determined from MC calculations

(SNOMAN → EGS)
Energy Scale Calibration in Salt Phase

Relative gain from 16N calibration

Energy scale drift agrees with MC prediction
Due to small increase with time in D2O photon absorption.
Response to Neutrons in Salt

Capture on $^{35}\text{Cl} \leftrightarrow ^{36}\text{Cl}$ cascade

• Multi-photon events $\Leftrightarrow$ isotropy
• Energy peaks higher

Signature of NC reaction

$$n + ^{35}\text{Cl} \rightarrow ^{36}\text{Cl} + \Sigma \gamma \quad (E\Sigma\gamma = 8.6 \text{ MeV})$$
Encapsulated $^{252}$Cf Fission Source

$^{252}$Cf decays by $\alpha$ emission or spontaneous fission.

Every fission produces $3.7676 \pm 0.0047^*$ neutrons on average.

These neutrons capture on $^{35}$Cl and we observe the resulting gamma cascade, with the energy distribution as shown.

$\gamma$’s accompanying the fission and $\beta$’s emitted by daughter products are removed using a timing cut.

The Cf source is deployed in the detector encapsulated in an acrylic cylinder (height 2.5cm, radius 2.5cm).

Event Isotropy Calibration in Salt Phase

16N calibration source

252Cf source

See next talk J. Dunmore
Neutron Response

Factor of ~3-4 increase in stats
- larger capture cross-section
- energy response peaks higher

Systematics Include:
- energy scale and resolution
- vertex reconstruction
- source position
- $^{252}\text{Cf}$ source strength
- burst selection
- background

Total $\Rightarrow$ Few Percent Level
In-Situ Background Measurement in Salt Phase

Separation of Background using Isotropy Distributions

- Ti (Th Chain)
- Na
- Bi (U Chain)

$\beta_{14}$
Fitting external source neutron backgrounds in salt

Monte-Carlo simulation

\[ \rho = \left( \frac{r}{600} \right)^3 \]

Maximum likelihood fit to extract external source neutron background events

Increased n capture efficiency on Cl allows separation of internal and external (background) sources of neutrons
Neutrino Flux Analysis for Salt Phase

Variables: \( E, R^3, \cos\theta_{\text{sun}}, \beta_{14} \)

- Unconstrained
- NC E higher
- NC E higher

Statistical Signal Separation

<table>
<thead>
<tr>
<th>Signal</th>
<th>Bkg</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC, NC, ES</td>
<td>( \Phi_e, \Phi_{\mu\tau} )</td>
</tr>
<tr>
<td>Cerenkov Photodis.</td>
<td></td>
</tr>
<tr>
<td>Fit</td>
<td>Fix</td>
</tr>
</tbody>
</table>

Extended ML Fit

- Fluxes
- Systematic Uncertainties
- Directionality Unchanged
- Isotropy Separation

\( \beta_{14} \)

\( R^3 \)

\( \cos\theta_{\text{sun}} \)
Statistical Signal Separation Using Angular Information

![Graphs showing Isotropy Distribution and Energy Spectrum from Monte Carlo simulations.](Image)
Fit Result Uncertainties (Monte-Carlo)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>E, R, $\theta_{\text{sun}}$</td>
<td>3.4%</td>
<td>8.6%</td>
<td>10%</td>
</tr>
<tr>
<td>E, R, $\theta_{\text{sun}}$, $\text{Iso}$</td>
<td>4.2%</td>
<td>6.3%</td>
<td>10%</td>
</tr>
<tr>
<td>E, R, $\theta_{\text{sun}}$, $\text{Iso}$</td>
<td>3.3%</td>
<td>4.6%</td>
<td>10%</td>
</tr>
<tr>
<td>$R$, $\theta_{\text{sun}}$, $\text{Iso}$</td>
<td>3.8%</td>
<td>5.3%</td>
<td>10%</td>
</tr>
</tbody>
</table>

D2O results

Simulated Salt Phase Results

Published D2O energy-unconstrained stat. Error was 24%

Simulations assume 1 yr of data with central values and cuts from D2O phase results.
Projected Sensitivity to Mixing Parameters

Projected sensitivity from SNO salt phase

Assuming D$_2$O phase NC result

Combined Solar + KAMLAND data

Projected limit on maximal 1-2 mixing

Figure adapted from Holanda and Smirnov, hep-ph/0212270
Summary

From pure D$_2$O Phase (Phase I):
- Flavour Transformation
- Neutrinos Massive
- SSM agreement
  
  Combined $\nu$ Results:
  - MSW Model -> LMA Favoured Region  
    (now confirmed by KamLAND)

From Salt Phase (Phase II): (expect this)
- Increased NC statistics – Additional Isotropy Separation
- Precision Fluxes without *Shape Constraint*
- Improved CC/NC Measurement
- Model independent NC measurement
  
  Limit on $\theta_{12}$, and on maximal mixing
  
  Currently finalizing systematics and analysis for salt phase dataset

Next Phase (Phase III): NCDs soon
  
  Independent NC channel
The SNO Collaboration

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Low Energy Calibration with $^{24}\text{Na}$

- A side benefit of NaCl addition is the ability to use $^{24}\text{Na}$ as a low energy calibration source.

  $^{23}\text{Na} + n \rightarrow ^{24}\text{Na}$

- $n$ from a strong $\gamma$ source via photodisintegration. The source is then removed and the $^{24}\text{Na}$ decays away with $T_{1/2} = 15$ hours.

- The major advantage is that this source is containerless, removing concerns about shielding or container geometry.

- $^{24}\text{Na}$ source helps validate performance of Monte Carlo at low energies.
How Will the Salt Be Removed?

The current run plan is to obtain 9 - 12 months of livetime prior to salt removal.

- Salt will be removed using a reverse osmosis unit, which will produce a concentrated brine.
- The target is for ~1ppm salt in the D₂O after multiple passes through the unit.
- At this level salt will not significantly affect neutron capture in the heavy water region.

Once the salt has been removed, SNO plans to continue with a short pure D₂O run before entering the third phase of neutral current detection, when an array of 96 ³He proportional counters will be installed into the detector.
Radioactivity and Background from Salted $D_2O$

Internal Radioactivity creates neutron background to the Neutral Current signal. The following table gives SNO’s aim for purity and the measured values of radioactivity in the $D_2O$ and in the salt:

<table>
<thead>
<tr>
<th></th>
<th>Goal (yields ~1 n/day)</th>
<th>Pure $D_2O$ (measured)</th>
<th>Salt $D_2O$ (preliminary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}Th$</td>
<td>$&lt; 3.7E-15$ g /g salt $D_2O$</td>
<td>$1.6E-15$ g /g $D_2O$</td>
<td>$~ 3E-15$ g /g salt $D_2O$</td>
</tr>
<tr>
<td>$^{238}U$</td>
<td>$&lt; 4.5E-14$ g /g salt $D_2O$</td>
<td>$1.8E-14$ g /g $D_2O$</td>
<td>$~ 2E-14$ g /g salt $D_2O$</td>
</tr>
</tbody>
</table>

• Before the salt was added to the $D_2O$, it was purified by flow over MnOx and HTiO which reduced its Th and U concentrations by a factor of $~100$.

• The radioactivity in the salt is not expected to significantly increase the background to the NC signal.

*** Contributed by P. Jagam and B. Cleveland ***
**Detection**

**Electrons** emit Čerenkov light, which is detected by the PMTs.

**Neutrons** are captured on $^{35}$Cl nuclei, which then emit a number of $\gamma$'s

$\begin{align*}
n + {35}\text{Cl} & \rightarrow {36}\text{Cl}^* \\
{36}\text{Cl}^* & \rightarrow \gamma \text{'s} \quad (\Sigma_\gamma = 8.6 \text{ MeV})
\end{align*}$

or on deuterium nuclei, as in the pure D$_2$O phase: $n + d \rightarrow t + 6.25\text{MeV} \text{ (single } \gamma\text{)}$

The $\gamma$'s produce electrons through Compton scattering, or, less commonly, pair production or photoelectric absorption.
Sources Include:
- Detector State Stability
- 16N Runs
- Optical Model
- Radial/Asymmetry Studies
- Timing

Total Uncertainty ~1-2%

Preliminary Data – June 2001 scan
Data – May 2002 scan
Data – January 2003 scan
MC – May 2002 scan
Calibration Radon Spike in SNO Detector

Rn injected into D2O region
The NaCl brine in the underground buffer tank was activated by neutrons from the rock wall. We observed the decay of $^{24}$Na after the brine is injected in the SNO detector.
Key signatures for $\nu$ oscillations

Measure total flux of solar neutrinos vs. the pure $\nu_e$ flux

$$\frac{\Phi_{cc}}{\Phi_{es}} = \frac{\nu_e}{\nu_e + 0.154(\nu_\mu + \nu_\tau)}$$  

Evidence for $\nu$ flavor change  

$$\frac{\Phi_{cc}}{\Phi_{nc}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$  

Potential signal for $\nu$ oscillations  

$\Phi_{\text{day}}$ vs $\Phi_{\text{night}}$  

June 2001  

April 2002
Background Measurements in Salt Phase

Containerless source

$^{24}\text{Na}$

2.75 MeV

1.37 MeV

$^{24}\text{Mg}$

$t_1/2=14.95\text{h}$

- A hot Th source is used to photodisintegrate the deuteron. The resulting neutrons activate the $^{23}\text{Na}$ nuclei in the salt.

- Used to test the low energy response of the detector, and to calibrate the light isotropy parameters used in the low energy background in-situ analysis.

- Used to trace the water flow pattern in the ex-situ assay of radioactive backgrounds.