Results and Prospects From The Sudbury Neutrino Observatory

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Outline

1. SNO and the Solar Neutrino Problem
2. Neutral Current and Day-Night Results
3. Needs More Salt …
4. Anti-neutrino Limits (Preliminary)
5. Future Prospects
The Sun is an intense source of MeV neutrinos!

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

**Solar Neutrinos**

Shape of Spectra Determined By Nuclear Physics.

Solar Models Only Affect Normalization.
Two Classes of Experiment (so far)

- **Radiochemical**
  - $\nu_e$ interactions convert target nuclei
  - Radioactive products extracted and counted after exposure time

- **Water Cerenkov**
  - Real-time detection of scattered atomic $e^-$s
  - Mixed CC and NC sensitivity

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Detection Reaction</th>
<th>Threshold</th>
<th>Primary Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homestake</td>
<td>$\nu_e + ^{37}\text{Cl} \rightarrow e^- + ^{37}\text{Ar}$</td>
<td>0.8 MeV</td>
<td>$^7\text{Be}, ^8\text{B}$</td>
</tr>
<tr>
<td>Kamiokande</td>
<td>$\nu_e, (\mu, \tau) + e \rightarrow \nu_e, (\mu, \tau) + e$</td>
<td>7.3 MeV</td>
<td>$^8\text{B}$</td>
</tr>
<tr>
<td>SAGE, GALLEX/GNO</td>
<td>$\nu_e + ^{71}\text{Ga} \rightarrow e^+ + ^{71}\text{Ge}$</td>
<td>0.23 MeV</td>
<td>$pp, ^7\text{Be}, ^8\text{B}$</td>
</tr>
<tr>
<td>Super-K</td>
<td>$\nu_e, (\mu, \tau) + e \rightarrow \nu_e, (\mu, \tau) + e$</td>
<td>5 MeV</td>
<td>$^8\text{B}$</td>
</tr>
</tbody>
</table>
Assume mixing between flavor and mass eigenstates, like for quarks:

$$|\nu_e\rangle = \cos \theta |\nu_1\rangle + \sin \theta |\nu_2\rangle$$
$$|\nu_\mu\rangle = - \sin \theta |\nu_1\rangle + \cos \theta |\nu_2\rangle$$

Then $\nu_e$'s can oscillate to $\nu_\mu$'s, depending on energy, distance travelled.

Oscillation can be enhanced by matter effects in Sun or Earth:

<table>
<thead>
<tr>
<th>AT SOLAR NEUTRINO ENERGIES:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_x$</td>
</tr>
<tr>
<td>$e^-$</td>
</tr>
</tbody>
</table>

All neutrino flavors | Only electron neutrinos

Can produce day-night asymmetries.

Allowed mixing parameters (pre-SNO)
Fogli et al. (hep-ph/0106247)
The SNO Collaboration

Canada
University of British Columbia
Carleton University
University of Guelph
Laurentian University
Queen’s University
TRIUMF

United States
Brookhaven National Lab.
Lawrence Berkeley National Lab.
Los Alamos National Lab.
University of Pennsylvania
University of Texas–Austin
University of Washington

U.K.
University of Oxford
RAL/Sussex
Sudbury Neutrino Observatory

- 2092 m to Surface
- 18 m Diameter Support Structure for 9500 PMTs, 60% coverage
- 1000 Tonnes D₂O
- 12 m Diameter Acrylic Vessel
- 1700 Tonnes Inner Shielding H₂O
- 5300 Tonnes Outer Shield H₂O
- Urylon Liner and Radon Seal
Event Display–Neutrino Event
Solar $\nu$ Interactions in SNO

**Elastic Scattering (ES)**  
$\nu_x + e^- \rightarrow \nu_x + e^-$
- Directional sensitivity ($e^-$ forward peaked)
- Cross-section for $\nu_e$ is $6.5 \times$ larger than for $\nu_{\mu\tau}$

**Charged Current (CC)**  
$\nu_e + d \rightarrow p + p + e^-$
- Some directional information ($1 - \frac{1}{3} \cos \theta_{e\nu}$)
- Good $E_\nu$ sensitivity ($\nu_e$ spectrum)

**Neutral Current (NC)**  
$\nu_x + d \rightarrow n + p + \nu_x$
- Total flux of active neutrinos above 2.2 MeV
- Detect neutrons by $n + d \rightarrow t + 6.25$ MeV $\gamma$
Each signal has characteristic energy, radial, and angular distributions.
Deriving Flavor Content from Reaction Rates

\[ CC = \nu_e \]
\[ ES = \nu_e + 0.154 \nu_{\mu\tau} \]
\[ NC = \nu_e + \nu_{\mu\tau} \]

Measuring 2 out of 3 determines flavor content.
Measuring all three gives consistency check.
**Measured SNO Fluxes**

Assuming $^8$B energy spectrum ...

### Fluxes ($\times 10^6$ cm$^{-2}$ sec$^{-1}$)

- $\phi_{CC} = 1.76 \pm 0.06_{0.05}$ (stat.) $\pm 0.09$ (sys.)
- $\phi_{ES} = 2.39 \pm 0.24_{0.23}$ (stat.) $\pm 0.12$ (sys.)
- $\phi_{NC} = 5.09 \pm 0.44_{0.43}$ (stat.) $\pm 0.46_{0.43}$ (sys.)

**$\phi_{CC} < \phi_{ES} < \phi_{NC}$**

NC flux in agreement with SSM prediction!
\[ \phi_e = 1.76 \pm 0.06 \pm 0.09 \times 10^6 \text{ cm}^{-2} \text{ sec}^{-1} \]

\[ \phi_{\mu\tau} = 3.41 \pm 0.45^{+0.48}_{-0.45} \times 10^6 \text{ cm}^{-2} \text{ sec}^{-1} \]

\[ \phi_{\mu\tau} > 0 \text{ at } 5.3\sigma \text{ level!} \]
Day-Night Asymmetries

Day-night rate asymmetry is signature of matter effects:

\[ A = \frac{N - D}{\frac{1}{2}(N + D)} \]

Measure both \( A_e \) and \( A_{tot} \):

- MSW matter effect: \( 0 < A_e < 20\% \)
- If only active \( \nu \)'s, \( A_{tot} = 0 \)

Letting \( A_{tot} \) float:

\[ A_e = +12.8\% \pm 6.2\% \pm 1.4\% \]
\[ A_{tot} = -24.2\% \pm 16.1\% \pm 2.4\% \]

Demanding \( A_{tot} \equiv 0 \):

\[ A_e = +7.0\% \pm 4.9\% \pm 1.2\% \]

All results assume undistorted \( ^{8}\text{B} \) spectrum.
Fit to all solar $\nu$ data strongly favors LMA solution
LOW, vacuum oscillations ruled out at $\sim 99\%$ C.L.
For LMA, maximal mixing excluded at $3\sigma$ level

- Equivalent to
  \[ m(\nu_1) < m(\nu_2) \]
- Indirect evidence for matter effects
Limitations of the SNO Results

- Assumes $^8$B spectral shape in signal extraction
  - Required to separate CC/NC effectively
  - OK for null hypothesis test, but couples oscillation parameters and flux measurements
  - Need to break CC/NC covariances in bin-by-bin manner
- Significant CC/NC correlations (statistical and systematic)
- Cannot distinguish $\nu_{\mu\tau}$ from $\bar{\nu}_{\mu\tau}$
- Statistics-limited for many physics topics
  - day-night, spectrum, seasonal variations ...
In June 2001 added 0.2% NaCl to D$_2$O to increase neutron capture (on $^{35}$Cl)

Capture efficiency increased by $\times 2.6$

$\sim 2–4$ gammas totalling 8.6 MeV

Emitted radiation increases from 6.25 MeV to 8.6 MeV

Multiple $\gamma$'s emitted—separate CC, NC events using event topology, isotropy
Notable change in neutron capture radial profile.
Better sensitivity to neutrons produced near AV.
Neutrons produce multi-particle decay → more isotropic
Electrons produce single Cherenkov rings

Comparison of isotropy for calibration neutron data and MC.

Isotropy can provide statistical separation of neutrons and electrons, and reduce dependence on energy spectra.
Can produce “model-independent” NC flux
D$_2$O results used energy spectrum to separate CC from NC events.

For salt results, add in isotropy as additional separation parameter.

Two ways to do analysis:

- Assume $^8$B spectral shape (best statistical separation)
- Assume nothing about shape (least model dependence)

*All salt results are Monte Carlo*
KamLAND will provide precision $\Delta m^2$ measurement, but weak $\theta_{12}$ constraint

(Plot from Nunokawa, Teves, Funchal, hep-ph/0212202)

Precision solar measurements, especially SNO $CC/NC$ ratio and day-night, constrain $\Delta m^2$ but especially $\theta_{12}$

(de Holanda & Smirnov, hep-ph/0212270)
Electron Antineutrino Search

- Solar oscillations believed for theoretical reasons to be $\nu_e \rightarrow \nu_{\mu\tau}$
- However, $\nu_e \rightarrow \bar{\nu}_{\mu\tau}$ is not ruled out
- What about $\nu_e \rightarrow \bar{\nu}_e$?

Spin Flavor Precession

1. Give $\nu$’s small magnetic moment ($< 10^{-10} \mu_B$)
2. Coupling of $\mu_\nu$ with strong solar B field produces
   $$\nu_e \rightarrow \bar{\nu}_{\mu\tau}$$
3. Standard neutrino oscillations (with or without MSW) can then produce:
   $$\bar{\nu}_{\mu\tau} \rightarrow \bar{\nu}_e$$

Does the Sun put out any $\bar{\nu}_e$’s?
SNO has a unique triple-coincidence signal for $\bar{\nu}_e$'s:

$$\bar{\nu}_e + d \rightarrow e^+ + n + n$$

Three detection channels:

<table>
<thead>
<tr>
<th>Detection Efficiency (prelim.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 – fold $e^+ + n + n$</td>
</tr>
<tr>
<td>(1.1 ± 0.02±0.12)%</td>
</tr>
<tr>
<td>2 – fold $e^+ + n$</td>
</tr>
<tr>
<td>(10.27 ± 0.05±0.94)%</td>
</tr>
<tr>
<td>2 – fold $n + n$</td>
</tr>
<tr>
<td>(1.1 ± 0.02±0.10)%</td>
</tr>
</tbody>
</table>

Coincidence signal provides almost background-free measurement.

“Two-neutron” channel sensitive down to $E_\nu = 4.03$ MeV
Searching for $\bar{\nu}_e$'s

Selection Cuts:

- $T_{eff} > 5$ MeV
- $R < 550$ cm
- Coincidence window: 150 msec (neutron capture time: 42 msec)
- Spallation cuts:
  - Events following muons
  - Events with NHIT $> 150$ and anything within 0.5 sec afterwards (removes most atmospheric $\nu$'s)

Livetime: 305.9 days

Candidate events (preliminary):

- 1 three-fold coincidence
- 2 two-fold coincidences

But if we lower energy to 4.5 MeV:

- Two-folds become 1 three-fold and 1 four-fold
- Four-fold rejected because $P(4\text{-fold from } \bar{\nu}_e) \ll P(4\text{-fold from inelastic NC})$

No further coincidences seen at 4.0 MeV
### Backgrounds for $\bar{\nu}_e$'s (Preliminary)

#### Direct $\bar{\nu}_e$ Backgrounds (prelim.):

<table>
<thead>
<tr>
<th>Source</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric</td>
<td>$\leq 0.072$</td>
</tr>
<tr>
<td>Reactor</td>
<td>$\leq 0.15$</td>
</tr>
<tr>
<td>Terrestrial radio-isotopes</td>
<td>0</td>
</tr>
<tr>
<td>Relic supernovae</td>
<td>$\leq 5.2 \times 10^{-3}$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$\leq 0.23$</td>
</tr>
</tbody>
</table>

#### Non-$\bar{\nu}_e$ Coincidence Backgrounds (prelim.):

<table>
<thead>
<tr>
<th>Source</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inelastic NC from atmos. $\nu$'s</td>
<td>$\leq 1$</td>
</tr>
<tr>
<td>Spallation neutrons</td>
<td>$\leq 0.23$</td>
</tr>
<tr>
<td>Accidentals</td>
<td>0.10</td>
</tr>
<tr>
<td>Intrinsic</td>
<td></td>
</tr>
<tr>
<td>$^{214}\text{Bi} \beta - \gamma$</td>
<td>$7.6 \times 10^{-5}$</td>
</tr>
<tr>
<td>$^{210}\text{Tl} \beta - \gamma$</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>$^{208}\text{Tl} \beta - \gamma$</td>
<td>$8.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{238}\text{U}$ spontaneous fission</td>
<td>0.14</td>
</tr>
<tr>
<td>$\gamma \rightarrow$ scattered $e^- +$ new $n$</td>
<td>$&lt; 8 \times 10^{-4}$</td>
</tr>
<tr>
<td>$n$ cap. $\rightarrow$ multiple $\gamma \rightarrow$ $n$'s</td>
<td>$&lt; 0.05$</td>
</tr>
<tr>
<td>Fast $n \rightarrow (n, 2n)$</td>
<td>$&lt; 1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{13}\text{C}(\alpha, n e^+ e^-)^{16}\text{O}$</td>
<td>$&lt; 1.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>Instrumental contam.</td>
<td>$&lt; 0.027$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$&lt; 1.57$</td>
</tr>
</tbody>
</table>

**Total background $< 1.8$ events**
Solar $\bar{\nu}_e$ Limit (Preliminary)

Kamiokande (1991) \hspace{1cm} < 3.03 \times 10^5 \text{ cm}^{-2} \text{ sec}^{-1} \hspace{1cm} 99\% \text{ CL}

LSD (1996) \hspace{1cm} < 1 \times 10^{-5} \text{ cm}^2 \text{ sec}^{-1} \hspace{1cm} 90\% \text{ CL}

Super-Kamiokande (2000) \hspace{1cm} < 1.8 \times 10^5 \text{ cm}^{-2} \text{ sec}^{-1} \hspace{1cm} 95\% \text{ CL}

Super-Kamiokande (2002) \hspace{1cm} < 4.04 \times 10^4 \text{ cm}^{-2} \text{ sec}^{-1} \hspace{1cm} 90\% \text{ CL}

SNO (2003, preliminary) \hspace{1cm} < 5.15 \times 10^4 \text{ cm}^{-2} \text{ sec}^{-1} \hspace{1cm} 90\% \text{ CL}

Preliminary SNO limit is $< 1.0\%$ of SSM $^8\text{B}$ flux.

SNO limit is comparable to SK limit, but uses different, independent technique.

Salt data will provide $\times 3$ gain in sensitivity.
In Fall 2003 SNO will begin installation of $^3\text{He}$ proportional counters. Measures NC rate by independent method. Event-by-event neutron ID breaks charged current, neutral current covariances.
Conclusions

- Direct evidence for neutrino flavor transformation at the $5.3\sigma$ level.
- Solar $\nu$ data strongly favors LMA solution — see KamLAND talk
- Salt data will improve statistics, reduce model dependence
- Preliminary solar antineutrino limit: $< 1^{\circ}0 \times$ SSM
- Plethora of other topics: anti-$\nu$’s, supernovae, atmospheric $\nu$’s, baryon decay
Calibrating Neutron Response

Need to measure neutron capture efficiency as function of radius

$^{252}\text{Cf}$ source produces thermal neutrons through fission (average multiplicity of 3.8)

Three techniques for determining response:

- Analytic calculation using cross sections, isotopic abundances
- Directly count neutron captures from absolutely calibrated source
- Use multiplicity distribution, Poisson statistics to get capture efficiency

Average capture efficiency for NC events:

$29.9\% \pm 1.1\%$
## Dominant Systematic Errors

<table>
<thead>
<tr>
<th>Source</th>
<th>CC Uncert. (percent)</th>
<th>NC Uncert. (percent)</th>
<th>$\phi_{\mu\tau}$ Uncert. (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy scale †</td>
<td>-4.2,+4.3</td>
<td>-6.2,+6.1</td>
<td>-10.4,+10.3</td>
</tr>
<tr>
<td>Energy resolution †</td>
<td>-0.9,+0.0</td>
<td>-0.0,+4.4</td>
<td>-0.0,+6.8</td>
</tr>
<tr>
<td>Vertex accuracy</td>
<td>-2.8,+2.9</td>
<td>±1.8</td>
<td>±1.4</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>-0.2,+0.2</td>
<td>-0.3,+0.3</td>
<td>-0.3,+0.3</td>
</tr>
<tr>
<td>Internal source pd †</td>
<td>±0.0</td>
<td>-1.5,+1.6</td>
<td>-2.0,+2.2</td>
</tr>
<tr>
<td>External source pd</td>
<td>±0.1</td>
<td>-1.0,+1.0</td>
<td>±1.4</td>
</tr>
<tr>
<td>D$_2$O Cherenkov †</td>
<td>-0.1,+0.2</td>
<td>-2.6,+1.2</td>
<td>-3.7,+1.7</td>
</tr>
<tr>
<td>AV Cherenkov</td>
<td>±0.0</td>
<td>-0.2,+0.2</td>
<td>-0.3,+0.3</td>
</tr>
<tr>
<td>PMT Cherenkov †</td>
<td>±0.1</td>
<td>-2.1,+1.6</td>
<td>-3.0,+2.2</td>
</tr>
<tr>
<td>Neutron capture</td>
<td>±0.0</td>
<td>-4.0,+3.6</td>
<td>-5.8,+5.2</td>
</tr>
<tr>
<td>Experimental uncertainty</td>
<td>-5.2,+5.2</td>
<td>-8.5,+9.1</td>
<td>-13.2,+14.1</td>
</tr>
<tr>
<td>Cross section</td>
<td>±1.8</td>
<td>±1.3</td>
<td>±1.4</td>
</tr>
</tbody>
</table>
The $pp$ Chain

$p + p \rightarrow ^2\text{H} + e^+ + \nu_e$

$\gamma$ (pp)

99.6%

$p + e^- + p \rightarrow ^2\text{H} + \nu_e$

(lep)

0.4%

$^2\text{H} + p \rightarrow ^3\text{He} + \gamma$

85%

15%

$^2\text{H} + p \rightarrow ^4\text{He} + 2p$

$^3\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu_e$

(hep)

$^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma$

99.9%

0.1%

$^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e$

($^7\text{Be}$)

$^7\text{Li} + p \rightarrow ^4\text{He}$

$^7\text{Be} + p \rightarrow ^8\text{B} + \gamma$

$^8\text{B} \rightarrow ^8\text{Be}^* + e^+ + \nu_e$

($^8\text{B}$)

$^8\text{Be}^* \rightarrow ^4\text{He}$
The Solar Neutrino Problem

- **BAD:** All experiments show a flux deficit of 30-60%.
- **WORSE:** Flux suppression is energy dependent.
  - Standard Solar Model Predictions:
    - Gallium
    - Chlorine
    - SuperKamiokande
  - Measurements:
  - Looks like complete absence of $^7$Be neutrinos.