ν Oscillations in the `Solar Sector’ and the Sudbury Neutrino Observatory

Aspen Winter 2005: The Highest Energy Physics

- Testing the New Neutrino Model
- Upcoming Results
- Future Physics
- SNO Phase III Status

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After Six Solar $\nu$ Experiments

- 3 Gallium (Radiochemical)
- 1 Chlorine (Radiochemical)
- Kamiokande + Super-Kamiokande (Water Cerenkov)
\( \nu \) Reactions in SNO

**CC**
\[ \nu_e + d \Rightarrow p + p + e^- \]
- Good measurement of \( \nu_e \) energy spectrum
- Weak directional sensitivity \( \propto 1 - 1/3 \cos(\theta) \)

**NC**
\[ \nu_x + d \Rightarrow p + n + \nu_x \]
- Measure total \(^8\text{B} \nu\) flux from the sun.
- Equal cross section for all \( \nu \) types

**ES**
\[ \nu_x + e^- \Rightarrow \nu_x + e^- \]
- Mainly sensitive to \( \nu_e \), some sensitivity to \( \nu_\mu \) and \( \nu_\tau \)
- Strong directional sensitivity

**Charged Current/Elastic Scattering**

**Neutral Current** — Capture in D or Cl
The Three Phases

• **Phase I: Pure D$_2$O**
  • Simple detector configuration, clean measurement
  • Low neutron sensitivity
  • Poor discrimination between neutrons and electrons

• **Phase II: D$_2$O + NaCl**
  • Very good neutron sensitivity
  • Better neutron electron separation

• **Phase III: D$_2$O + $^3$He Proportional Counters**
  • Good neutron sensitivity
  • Great neutron/electron separation
Phase I + First Phase II Results

- SNO Compared to Other Solar Expts.

But the new neutrino model makes other predictions besides fluxes...
Matter (MSW) Effects

**AT SOLAR NEUTRINO ENERGIES:**

\[
\begin{array}{c c c c c c c}
\nu_x & \nu_x & \nu_e & e^- \\
Z^0 & e^- & e^- & W^+ & e^- & \nu_e \\
\end{array}
\]

All neutrino flavors \quad Only electron neutrinos

\[\sigma(\nu_{\mu,\tau}) = 0.155\sigma(\nu_e)\]

Rise in Survival Probability at low \(E_\nu\)

Generally speaking, neutrino oscillations in matter provide a resonant interferometer to detect very small effects.
Spectral Shape/Earth Regeneration

Spectral Shape/Earth Regeneration

Day/Night Asymmetry? (\(A_{CC}\) or \(A_{NC}\))?

\(A_{NC}\) Unconstrained:

\[ A_{CC} = 14.0\% \pm 6.3\%^{+1.5\%}_{-1.4\%} \]

\(A_{NC} = 0:\)

\[ A_{E} = 7.0\% \pm 4.9\%^{+1.3\%}_{-1.2\%} \]
Spectral Shape/Earth Regeneration

- **SNO** CC reaction has good energy response

Neutrino absorption by deuteron

![Neutrino absorption diagram](image)

![Graphs](image)
Solar Sector (1,2) Mixing Parameters

SNO alone, no Solar Model Fluxes

Maximal mixing ruled out at ~ 3 σ

All Solar Experiments+Model Constraints
Notes On `Solar Sector’
Parameters ($\Delta m^2_{12}, \sin^2 2\theta_{12}$)

Parameters measured by solar experiments require matter (MSW) effect:

\[
\begin{array}{c|c|c|c}
\nu_x & \nu_x & \nu_e & e^- \\
\hline
\nu_e & e^- & e^- & \nu_e \\
\hline
\end{array}
\]

All neutrino flavors  Only electron neutrinos

but specific signatures of MSW effect are as yet unobserved (`unlucky’ parameters).
Testing the New Neutrino Model

Is our model of neutrino mixing and oscillation complete, or are there other mechanisms at work?

Given KamLAND measurements, model predicts solar parameters

<table>
<thead>
<tr>
<th></th>
<th>Reactor</th>
<th>Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ (MeV)</td>
<td>2-10</td>
<td>0.1-15</td>
</tr>
<tr>
<td>$L$ (km)</td>
<td>150</td>
<td>1.5 x 10^8</td>
</tr>
<tr>
<td>MSW</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Anti-$\nu_e$</td>
<td>$\nu_e$</td>
</tr>
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</table>

Only (?) Standard Model predicts these 2 experimental regimes see the same effect

KamLAND Collaboration, hep-ex/0406035, 11/1/2004
Maximal mixing ruled out at 5.4 $\sigma$
Testing the New Neutrino Model

Resonant neutrino `interferometry' allows us to look for even very small new interactions, which will look like an `MSW’-like effect

Sterile neutrinos will disappear from $\nu_e$ spectrum but not reappear in NC rate

So how do we do further tests?
SNO Phase I: Extracting Signals

Can use derived observables ($R^3$, $\cos \theta_{\odot}$, and $E$) to produce pdfs.

Max. Likelihood fit for relative signal amplitudes
SNO Phase I Signal Fits

Undistorted $^8$B spectral shape assumed, except for bin-by-bin extraction above 7.25 MeV
SNO Phase II (Salt Phase)

- Advantages of NaCl: Event Isotropy

\( \gamma \) multiplicity means PMT hit pattern for neutron events more isotropic than for single Cerenkov electrons

\( \gamma \)\footnote{\textsuperscript{36}Cl}

\( \gamma \)\footnote{\textsuperscript{252}Cf Data}

\( \gamma \)\footnote{\textsuperscript{16}N Data}

\( \gamma \)\footnote{\textsuperscript{252}Cf Monte Carlo}

\( \gamma \)\footnote{\textsuperscript{16}N Monte Carlo}

\( \gamma \)\footnote{CC Monte Carlo}

\( \beta_{14} \)

~2–4 gammas totalling 8.6 MeV
SNO Phase II (Salt Phase)

- Advantages of NaCl: Signal Extraction

**Energy Distribution**

**Radial Distribution** ($R^3$, $R_{AV}=1$)

**Solar Direction Distribution**

**Isotropy Distribution**

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*Covariances between Isotropy and Energy actually require 2D PDFs*
SNO Phase II Signal Fits

Solar Direction

Isotropy

Now entire analysis can be done bin-by-bin.
First Phase II Results

- Flux Measurements (units $10^6$ cm$^{-2}$ s$^{-1}$)

\[
\begin{align*}
\phi_{\text{CC}}^{\text{SNO}} &= 1.59^{+0.08}_{-0.07} \text{(stat)}^{+0.06}_{-0.08} \text{(syst)} \\
\phi_{\text{ES}}^{\text{SNO}} &= 2.21^{+0.31}_{-0.26} \text{(stat)} \pm 0.10 \text{(syst)} \\
\phi_{\text{NC}}^{\text{SNO}} &= 5.21 \pm 0.27 \text{ (stat)} \pm 0.38 \text{ (syst)}
\end{align*}
\]

Still not really a spectrum
Upcoming Phase II Results

• Roughly 50% more data (391 live-days)

• First spectrum with all differential sys. uncertainties

• New Day/Night asymmetry result

• ‘Full’ details (~40 pp)

• (‘Long’ paper detailing Phase I results starting internal editing and review process ~70 pp)
**SNO Low Threshold Analysis**

Work underway to push threshold on Phase I+II data to $T > 4$ MeV

Predictions for SNO response for various MSW solns:
**Detection Principle**

\[ {}^2H + \nu_x \rightarrow p + n + \nu_x - 2.22 \text{ MeV} \quad \text{(NC)} \]

\[ \text{array of } {}^3\text{He counters} \]

40 Strings on 1-m grid

440 m total active length

\[ {}^3\text{He} + n \rightarrow p + {}^3\text{H} \]

Production data taking began Dec 2004
SNO Phase III (NCD Phase)

Physics Motivation---Energy Spectrum

- CC and NC separation in pure D2O had big covariances (>90% correlations)

- Salt phase broke covariance with isotropy, but additional neutrons dilute CC signal

<table>
<thead>
<tr>
<th>Correlation Coefficient</th>
<th>D₂O</th>
<th>Salt</th>
<th>³He</th>
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</thead>
<tbody>
<tr>
<td>CC,NC</td>
<td>-0.950</td>
<td>-0.521</td>
<td>~0</td>
</tr>
<tr>
<td>NC,ES</td>
<td>-0.297</td>
<td>-0.064</td>
<td>~0</td>
</tr>
<tr>
<td>CC,ES</td>
<td>-0.208</td>
<td>-0.156</td>
<td>~ -0.2</td>
</tr>
</tbody>
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- Third phase has best of both worlds
  - ³He (‘NCD’) counters absorb neutrons
  - Independently constrain remainder
  - And can be applied retroactively
Conclusions

• Starting to look at `precision’ tests of the new neutrino model
  • KamLAND + SNO + Super-K + BOREXINO +???

• Upcoming SNO results will contain first `precision’ SNO spectrum and new Day/Night asymmetry results

• Further work to lower SNO energy threshold, test model further

• SNO Phase III likely to highest precision low threshold $^8$B measurement