The Resolution to the Solar Neutrino Problem: Model-Independent Evidence for Neutrino Flavor Change at SNO

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Recent Discoveries in Neutrino Physics

Underground experiments have changed our understanding of neutrinos

- **Neutrinos are not massless** (mass is small: $m_{\nu_e} < 0.0000059 \ m_e$)

- **Evidence for neutrino flavor conversion** $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$

- **Combination of experimental results show that neutrinos oscillate**

Different experiments detect transformation of neutrino flavors

- **Atmospheric + Solar $\nu$ (Super-K)**
- **Solar (SNO)**
- **Accelerator $\nu$ (LSND)**
- **Reactor (KamLAND)**
Neutrino Astrophysics

Solar Neutrino Flux Measurements

1960’s
• Ray Davis’ Chlorine detector
• First Solar Model calculations

For 30 years
CC and ES measurements of solar ν

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Year</th>
<th>Detection Reaction</th>
<th>Ratio Exp/BP2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorine (127 t)</td>
<td>1970-1995</td>
<td>$^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^-$</td>
<td>0.34 ± 0.03</td>
</tr>
<tr>
<td>Kamiokande (680t)</td>
<td>1986-1995</td>
<td>$\nu_x + e^- \rightarrow \nu_x + e^-$</td>
<td>0.54 ± 0.08</td>
</tr>
<tr>
<td>SAGE (23 t)</td>
<td>1990-</td>
<td>$^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$</td>
<td>0.55 ± 0.05</td>
</tr>
<tr>
<td>Gallex + GNO (12 t)</td>
<td>1991-1995</td>
<td>$^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$</td>
<td>0.57 ± 0.05</td>
</tr>
<tr>
<td>SuperK (22kt)</td>
<td>1996-</td>
<td>$\nu_x + e^- \rightarrow \nu_x + e^-$</td>
<td>0.45 ± -0.017 -0.015</td>
</tr>
</tbody>
</table>

(CC) $^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^-$

(ES) $\nu_x + e^- \rightarrow \nu_x + e^-$

→ Data are incompatible with standard and non-standard solar models
What is the Solution?

• Are experiments in error?
  But all experiments show similar effect.

• Is astrophysics wrong?
  Perhaps, but even with all fluxes as free parameters, cannot reproduce the data.

  Data are incompatible with standard and non-standard solar models!
  KMH, Robertson PRL 77:3270 (1996)

• New neutrino physics such as oscillations?
  Cl-Ar and Ga detectors are only sensitiv to $\nu_e$, it would appear that the flux was low.

→ Need solar model independent measurement.
→ Need experiment that measures $\nu_e$ and $\nu_x$ separately.
Sudbury Neutrino Observatory

2092 m to Surface (6010 m w.e.)

PMT Support Structure, 17.8 m
9456 20 cm PMTs
~55% coverage within 7 m

Acrylic Vessel, 12 m diameter

1000 Tonnes D$_2$O
1700 Tonnes H$_2$O, Inner Shield
5300 Tonnes H$_2$O, Outer Shield
Urylon Liner and Radon Seal
The SNO Detector during Construction
Neutrino Interactions on Deuterium

**Charged-Current**
\[ \nu_e \rightarrow n + p \rightarrow \text{Cerenkov electron} \]
- Neutrino
- Deuteron
- Protons

**Neutral-Current**
\[ \nu \rightarrow n \rightarrow n + p \rightarrow n + n + \gamma \]
- Neutrino
- Deuteron
- Neutron
- Proton
- Triton \( E_\gamma = 6.25 \text{ MeV} \)

**Elastic Scattering**
\[ \nu_x \rightarrow e + \nu \rightarrow \text{Cerenkov electron} \]
- Neutrino
- Electron
- Neutrino
Neutrino Detection in SNO

Neutrino Interactions in D$_2$O and H$_2$O and their Flavor Sensitivity

**Charged-Current (CC)**

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

**\( \nu_e \) only**

Measurement of energy spectrum

**E\text{thresh} = 1.4 \text{ MeV}**

**Elastic Scattering (ES)**

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

**\( \nu_x \), but enhanced for \( \nu_e \)**

Strong directional sensitivity

**Neutral-Current (NC)**

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

**\( \nu_x \)**

Measures total $^8$B flux from Sun

**E\text{thresh} = 2.2 \text{ MeV}**
Looking for Unexpected Neutrino Flavors

Comparing total flux of solar $^8$B neutrinos vs pure $\nu_e$ flux

CC/NC ratio is a direct signature for flavor transitions

$$\frac{[CC]}{[NC]} = \frac{[\nu_e]}{[\nu_e + \nu_\mu + \nu_\tau]}$$

CC/ES could also show significant effects

$$\frac{[CC]}{[ES]} = \frac{[\nu_e]}{[\nu_e + 0.15(\nu_\mu + \nu_\tau)]}$$

Smoking Gun for Neutrino Flavor Transformation
Testing the Hypothesis of Neutrino Oscillations

Comparing the solar $\nu$ flux at Day and Night

Certain $\nu$ oscillation models predict $\nu$ regeneration in Earth

\[
\frac{[CC]_{\text{DAY}}}{[CC]_{\text{NIGHT}}} = \frac{[\nu_e]_{\text{DAY}}}{[\nu_e]_{\text{NIGHT}}} \neq 1
\]

\[
\frac{[NC]_{\text{DAY}}}{[NC]_{\text{NIGHT}}} = \frac{[\nu_e + \nu_\mu + \nu_\tau]_{\text{DAY}}}{[\nu_e + \nu_\mu + \nu_\tau]_{\text{NIGHT}}} \neq 1
\]

Smoking Guns for Neutrino Oscillations
Solar Neutrino Physics with SNO

What can we learn from measuring the $^8$B solar neutrino flux at SNO?

- Total $^8$B $\nu$ flux (NC) vs $\nu_e$ flux (CC)
  
  \[ \frac{CC_{SNO}}{NC_{SNO}} \rightarrow \text{Test of neutrino flavor change} \checkmark \]

- Total flux of solar $^8$B neutrinos
  
  \[ \rightarrow \text{Test of solar models} \checkmark \]

- Diurnal time dependence
  
  \[ \rightarrow \text{Test of neutrino oscillations} \]

- Distortions of neutrino energy spectrum
  
  \[ \rightarrow \text{Test of neutrino oscillations} \]
SNO D$_2$O Phase

Pure D$_2$O
measure CC, ES
some NC sensitivity
$n+d \rightarrow t+\gamma \ldots (E_\gamma = 6.25 \text{ MeV}, \varepsilon_n \sim 29\%)$

Data Set: Nov 2, 1999 - May 27, 2001
Neutrino Livetime: 306.4 live days
Calibrating the SNO Detector Response

Calibration Issues

• Photon generation, transport, and detection
  • different media: D$_2$O, acrylic, H$_2$O, PMT
  • attenuation, reflection, scattering

• Detector geometry
• Detector status and conditions

Calibration Techniques

• Energy response
  $^{16}$N 6.13 MeV $\gamma$, tagged
  $p,t$ 19.8 MeV $\gamma$
  neutrons 6.25 MeV $\gamma$
  $^{8}$Li $\beta$-spectrum 13 MeV endpoint
  $^{8}$B $\beta$-spectrum 15 MeV endpoint

• Optical Response
  pulsed laser at $\lambda$=337, 365, 386, 420, 500, and 620 nm, ~2 ns resolution

• Electronics
  electronic pulzers, pulsed light sources
Established with triggered $^{16}$N ($E_\gamma = 6.13$ MeV) 
Tested against $^8$Li, $^{252}$Cf, and (p,t) source

$\Delta E = 1.21\%$

$^8$Li
13 MeV endpoint
(n,\(\alpha\)) on $^{11}$B

p,t
$E = 19.8$ MeV
from $^3$H(p,\(\gamma\))^4He

$^{252}$Cf
$E = 6.25$ MeV
from n capture

Sources at Center
Components in the Raw SNO Data

**Neutrino Events**
- Charged-current (CC)
- Neutral-current (NC)
- Elastic scattering (ES)

**Low-Energy Backgrounds**
- Internal photodisintegration from U, Th in D$_2$O
- PMT $\beta$-$\gamma$
- Backgrounds from PMT support structure and cavity

**High Energy Backgrounds**
- Backgrounds from PSUP and cavity
- Muon-induced spallation

**Instrumental Effects**
- PMT flashers, bubblers
- Wet-end high voltage breakdown
- Hot cards etc.
Data Flow & Instrumental Background Cuts

Data Flow

<table>
<thead>
<tr>
<th>Analysis Step</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Event Triggers</strong></td>
<td>450,188,649</td>
</tr>
<tr>
<td>Neutrino Data Triggers</td>
<td>191,312,560</td>
</tr>
<tr>
<td>NHIT ≥30 (Analysis Threshold)</td>
<td>10,088,842</td>
</tr>
<tr>
<td>Instrumental Background</td>
<td>7,805,238</td>
</tr>
<tr>
<td>High Level Cuts</td>
<td>3,418,439</td>
</tr>
<tr>
<td>Fiducial Volume Cut</td>
<td>67,343</td>
</tr>
<tr>
<td>Energy Threshold</td>
<td>3440</td>
</tr>
<tr>
<td>Muon Followers</td>
<td>2981</td>
</tr>
<tr>
<td>Invisibles</td>
<td>2928</td>
</tr>
<tr>
<td><strong>Candidate Event Set</strong></td>
<td>2928</td>
</tr>
</tbody>
</table>

Instrumental Background Removal

- Charge
- Timing
- PMT hit Geometry
- Event Rate
- PMT Veto Tubes

Cerenkov Nature of Events

- prompt light
- single particle event

Instrumental removal:

Two independent methods

Signal loss:

0.4±0.3% within $R_{fit}\leq550$ cm from $^{16}$N, $^{8}$Li, and the laser ball

Contamination:

limits from bifurcated analyses and hand-scanning
Candidate Neutrino Event
Characteristic Detector Distributions of Candidate Event Set

Energy

Radial

Solar Angle
Neutrino Signals in D$_2$O Data

Signal Extraction with CC Shape Constraint

<table>
<thead>
<tr>
<th>Type</th>
<th>Value (MeV)</th>
<th>Error (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>1967.7</td>
<td>+61.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+60.9</td>
</tr>
<tr>
<td>NC</td>
<td>576.5</td>
<td>+49.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+48.9</td>
</tr>
<tr>
<td>ES</td>
<td>263.6</td>
<td>+26.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+25.6</td>
</tr>
</tbody>
</table>

Hypothesis Test of Flavor Change

→ Assume no distortion in the $^8$B energy spectrum and no MSW distortions of CC

Total Number of Events: 2928

Neutron Bkgd: 78 $^{+12/-12}$
Cherenkov Bkgd: 45 $^{+18/-12}$
Solving the Solar Neutrino Problem: Test of Neutrino Flavor Change & Test of Solar Models

**SNO Flux Results**

- 8B from CC\textsubscript{SNO}+ES\textsubscript{SK} (2001)
- ES\textsubscript{SNO} (2001)
- CC\textsubscript{SNO} (2001)
- NC\textsubscript{SNO} (2002)
- ES\textsubscript{SNO} (2002)
- CC\textsubscript{SNO} (2002)

- 2/3 of initial solar $\nu_e$ are observed at SNO to be $\nu_\mu$, $\nu_\tau$
- Standard Solar Model predictions for total $^8$B flux in excellent agreement!
  $\rightarrow$ Null hypothesis (no flavor change) ruled out at 5.3 $\sigma$ level
  $\rightarrow$ Model-independent evidence for neutrino flavor change
2/3 of initial solar $\nu_e$ are observed at SNO to be $\nu_{\mu,\tau}$

Standard Solar Model predictions for total $^8B$ flux in excellent agreement!

$$\Phi_{^8B\text{SSM}} = 5.05 \pm 1.01 \pm 0.81$$

$$\Phi_{^8B\text{NC}_{\text{SNO}}} = 5.09 \pm 0.44 \pm 0.46 \pm 0.43$$
Model-Independence of Flux Result

Testing the theoretical inputs

In effective field theory weak axial two body current $L_{1,A}$ is dominant uncertainty of every low energy weak interaction deuteron breakup process.

Use $R^{\text{SNO}}_{\text{CC}}$, $R^{\text{SNO}}_{\text{NC}}$, $R^{\text{SK}}_{\text{ES}}$ to constrain weak axial two body current $L_{1,A}$.

<table>
<thead>
<tr>
<th>Processes</th>
<th>$L_{1,A}$ ($fm^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC, NC, ES</td>
<td>4.0 ± 6.3</td>
</tr>
<tr>
<td>Reactor $\bar{\nu}$-d</td>
<td>3.6 ± 4.6</td>
</tr>
<tr>
<td>Tritium decay</td>
<td>4.2 ± 0.1</td>
</tr>
<tr>
<td>Helioseismology</td>
<td>4.8 ± 5.9</td>
</tr>
</tbody>
</table>

$L_{1,A} = 4.0 \pm 4.7$ (stat.) ± 4.5 (syst.) fm$^3$

$\phi_{\nu x} = (6.4 \pm 1.4 \pm 0.6) \times 10^6$ cm$^{-2}$ s$^{-1}$

Theoretical inputs to SNO's determination of the CC and NC fluxes can be

- self-calibrated from $R^{\text{SNO}}_{\text{CC}}$, $R^{\text{SNO}}_{\text{NC}}$
- calibrated from $R^{\text{SK}}_{\text{ES}}$
- calibrated by reactor data

Ref: Chen, KMH, Robertson nucl-th/0210073
SNO Charged-Current Energy Spectrum

Testing the Hypothesis of Oscillations through Spectral Distortions

CC spectrum derived from fit \textit{without} constraint on shape of $^{8}$B spectrum

CC spectrum normalized to predicted $^{8}$B spectrum

$\rightarrow$ No evidence for shape distortions
Solar $\nu$ Flux at Day and Night

Testing the Hypothesis of Neutrino Oscillations through the Earth-Matter Effect

Certain $\nu$ oscillation models predict $\nu$ regeneration in Earth

$$\frac{[CC]_{DAY}}{[CC]_{NIGHT}} = \frac{[\nu_e]_{DAY}}{[\nu_e]_{NIGHT}} \neq 1$$

Neutrino Oscillations

Day/Night Asymmetries of $\nu$ Flux:

$$A^{SNO}_{\nu_e} = 7.0 \pm 4.9\%$$

$$A^{SK}_{\nu_e} = 5.3 \pm 3.7\%$$
Solar Neutrino Flux at Day and Night

Total Livetime: 306.4 days
Number of Events: 2928

Day: 128.5 days
Night: 177.9 days

**Day-Night Energy Spectrum**

**Day-Night Fluxes**

Signal Extraction in $\Phi_{CC}$, $\Phi_{NC}$, $\Phi_{ES}$

Day
Night

$\Phi_{Day+Night}$

$\Phi_{Day+Night}$

$\Phi_{Day+Night}$

$\Phi_{Day+Night}$

$\Phi_{Day+Night}$

$\Phi$ in units of $10^6$ cm$^{-2}$ s$^{-1}$

Karsten Heeger, LBNL
Moriond, March 16, 2003
Oscillation Interpretation of Solar Neutrino Data

Matter Enhanced Oscillations

- explains energy dependence
- effective 2-neutrino mixing
- MSW gives dramatic extension of oscillation sensitivity to potential regions in $\Delta m^2$

Chlorine  Homestake
Gallium  GALLEX/GNO
SAGE
Water  Super-Kamiokande

Solar neutrino data are consistent with the MWS hypothesis. Several possible oscillation solutions.
Solar Neutrinos in the Big Picture

Reactor and Beamstop Neutrinos

$\nu_\mu \Rightarrow \nu_s \Rightarrow \nu_e$

Atmospheric and Reactor Neutrinos

$\nu_\mu \Rightarrow \nu_\tau$

Solar and Reactor Neutrinos

$\nu_e \Rightarrow \nu_{\mu,\tau}$

Large mixing favored

LMA solution can be tested with reactor neutrinos

Status: Summer 2002

Murayama

Karsten Heeger, LBNL

Moriond, March 16, 2003
Neutrino Mixing Matrix

### Mixing Angles

**Solar**
\[ \theta_{12} = 30.3^\circ \]

**Atmospheric**
\[ \theta_{23} = \sim 45^\circ \]

**Chooz + SK**
\[ \tan^2 \theta_{13} < 0.03 \text{ at } 90\% \text{ CL} \]

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & 1/\sqrt{2} & 1/\sqrt{2} \\
0 & -1/\sqrt{2} & 1/\sqrt{2}
\end{pmatrix} \times \begin{pmatrix}
\sim 1 & 0 & e^{-i \delta_{CP}} \sin \theta_{13} \\
0 & 1 & 0 \\
-e^{i \delta_{CP}} \sin \theta_{13} & 0 & \sim 1
\end{pmatrix} \times \begin{pmatrix}
0.85 & 0.51 & 0 \\
-0.51 & 0.85 & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

- **atmospheric \( v \)** (SK)
- **reactor and accelerator \( v \)** (Chooz)
- **solar \( v \) + KamLAND** (LMA)
Solar Neutrino Oscillation Parameters

Before KamLAND

Region favored by solar $\nu$ experiments

After KamLAND

KamLAND 95% exclusion by rate

KamLAND 95% allowed by rate+shape
Constraining Oscillation Parameters with SNO

Precision Measurement of $\theta_{12}$

Assumptions: 8% measurement of SNO NC/CC
$A_{\text{SNO CC}}^{\text{CC}} = 7 \pm 4%$
**Enhanced NC sensitivity**

\[ \varepsilon_n \sim 45\% \text{ above threshold} \]

\[ n + ^{35}\text{Cl} \rightarrow ^{36}\text{Cl}^+ + \gamma \]

**Systematic check of energy scale**

\[ E_{\Sigma \gamma} = 8.6 \text{ MeV} \]

**Statistical separation of NC and CC interactions by event isotropy**
SNO Phase III - Neutral Current Detection via $^3$He(n,p)$^3$H

**Summer 2003 - 2005?**

**Array of $^3$He counters**
- 50 Strings on 1-m grid
- 450 m total active length

**Detection Principle**

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

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

**Physics Motivation**

**Event-by-event separation.** Measure NC and CC in separate data streams.

**Different systematic uncertainties**
- than neutron capture on NaCl.

**NCD array as active poison.**
What has been learned?

- The Solar Neutrino problem was caused by new neutrino properties.
- Neutrinos have mass.
- Neutrinos have mixed flavor, and …. they oscillate.
- Unlike the quark sector the lepton sector exhibits large mixing.
- Evidence that Standard Model of Particle Physics is incomplete.

- Direct evidence of neutrino flavor conversion from SNO at > 5σ.
- First measurement of total flux of active $^8B$ neutrinos confirms Standard Solar Model predictions
- No evidence of regeneration in Earth or spectral distortions.

- Can use solar $\nu$ to study neutrino properties!
Outlook

Next steps in SNO ...

• Enhanced NC measurements in SNO (NaCl and $^3$He-filled NC detectors) will improve model-independent NC rate measurement.

• Improved NC/CC measurement will help constrain $\theta_{12}$.

• Search for direct signs of neutrino oscillation in energy spectrum.

and in solar neutrino physics ...

• Towards direct detection of $^7$Be neutrinos with Borexino and KamLAND.

• R&D on low-energy solar pp neutrino detection for more precise measurements of oscillation parameters and detailed tests of solar models.
The SNO Collaboration

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