Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory (SNO)

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Outline

1. Introduction — the Solar Neutrino Problem (SNP)

2. Solving the SNP at the Sudbury Neutrino Observatory

3. Physics Implications

4. Summary
The standard solar model is a detailed computer model of the solar evolution. It involves various nuclear reactions, primarily the pp chain. The reactions include:

- \( \text{p} + \text{p} \rightarrow \text{d} + \nu_e \)
- \( \text{d} + \text{p} \rightarrow \text{3He} + \text{e}^- + \nu_e \)
- \( \text{3He} + \text{3He} \rightarrow \text{He}^4 + 2\text{p} \)
- \( \text{3He} + \text{n} \rightarrow \text{He}^7 + \text{e}^- \)
- \( \text{He}^7 + \nu_e \rightarrow \text{He}^8 + \text{e}^- \)

Overall, the reactions can be summarized as:

\[ \text{pp} \rightarrow \text{4He} + 2\text{e}^- + 2\gamma + 26.7 \text{MeV} \]
Solar neutrino experiments (pre-SNO)

GALLEX: \[ f_{\text{Ga}}(n,e) = 0.58 \pm 0.05 \]
SAGE: \[ f_{\text{Ga}}(n,e) = 0.60 \pm 0.05 \]
Homestake: \[ f_{\text{Cl}}(n,e) = 0.34 \pm 0.03 \]
Super-K: \[ f_{\text{SK}}(n,x) = 0.451 - 0.015 + 0.017 \]

Threshold (MeV) | Reaction | Target | Experiment
--- | --- | --- | ---
5.5 | \( ^{71} \text{Ga} + n \rightarrow ^{71} \text{Ge} + e^+ + \nu \) | 60 tons metallic Ga | SAGE
5.5 | \( ^{71} \text{Ga} + n \rightarrow ^{71} \text{Ge} + e^+ + \nu \) | 61.5 tons of C2Cl4 | Homestake
7.5 | \( ^{37} \text{Cl} + n \rightarrow ^{37} \text{Ar} + e^+ + \nu \) | 61.5 tons of C2Cl4 | Homestake
3.23 | \( ^{30} \text{Ca} + n \rightarrow ^{30} \text{Cl} + e^- + \nu \) | 30.3 tons CaCl2-HCl | Kamiokande
0.233 | \( ^{71} \text{Ga} + n \rightarrow ^{71} \text{Ge} + e^- + \nu \) | 60 tons metallic Ga | SAGE
8.14 | \( ^{37} \text{Cl} + n \rightarrow ^{37} \text{Ar} + e^- + \nu \) | 61.5 tons of C2Cl4 | Homestake

Either solar models are incomplete/incorrect or flavor-changing oscillation.
Neutrino Oscillation (2 Flavors)

Equation of motion in vacuum:

\[ i \dot{\nu}_m = \frac{1}{2} E_{\nu_m} M_{\nu_m} \]

where

\[ M_{\nu_m} = m_1^2 - m_2^2 \]

Equation of motion in vacuum:

\[ i \dot{\nu}_W = \frac{1}{2} E_{\nu_W} M_{\nu_W} \]

where

\[ M_{\nu_W} = m_2^2 - m_1^2 \]

Mass states (\( n_M \))

Weak states (\( n_W \)) (participate in weak interactions)

\[ \nu_e n_{\nu_m} \]

\[ \cos q \sin q - \sin q \cos q \]

\[ \nu_1 \nu_2 \]
Solar neutrinos has long baseline L (1 A.U.) and low E (> ~18 MeV) can probe $\Delta m^2$ down to $10^{-12}$ eV$^2$. Different L/E probes can probe different regions in the $(\Delta m^2, \tan^2 \theta)$ parameter space.
Sudbury Neutrino Observatory

1700 tonnes of inner shielding H₂O
17.8m dia. PMT Support Structure

9456 20-cm dia. PMTs
56% coverage

12.01m dia. acrylic vessel

1006 tonnes D₂O

5300 tonnes of outer shielding H₂O

2 km to surface

NIM A449, 127 (2000)
Detecting $\nu$ in SNO

- **ES**
  - Low Statistics
  - \( S_f = f(\nu_e) + 0.154 f(\nu_{\mu} + \nu_{\tau}) \)
  - Strong directionality: \( \theta = 18^\circ \) (7e = 10 MeV)
  - Weak directionality: \( 1 \le 0.340 \cos q \)

- **NC**
  - Measure total $\beta$ flux from the sun
  - Measurement of $\nu_e$ energy spectrum

- **CC**
  - Measurement of $\nu_e$ energy spectrum

- **ES**
  - Strong directionality: \( \theta = 18^\circ \) (7e = 10 MeV)
  - Weak directionality: \( 1 \le 0.340 \cos q \)
Cherenkov Signals in SNO (Pure D₂O)

Energy

Number of Hit PMTs

Counts/yr/hit PMT

~ 9 PMT Hits/MeV

NC D₂O (E(38))
CC (E(38))
ES (E(38))

ν/ν in D₂O and H₂O
Alan Poon, SLAC Experimental Seminar (May 16, 2002)

Smoking Guns for Flavor Changing Oscillation

Oscillation to active flavor if:

Measure:

April 2002: Day and Night fluxes [nucl-ex/0204009]

April 2002: Day and Night fluxes [nucl-ex/0204008]

June 2001: SNOCC ($\nu_e$) < SKES ($\nu_x$) (3.3 s) [PRL 87, 071301]

NightCC (ES) - DayCC (ES) [nucl-ex/0204009]

Oscillation to active flavor if:
Recap \[T_0 > 6.75 \text{ MeV}\]

Result 1: $n e \xrightarrow{\nu} n m, t$

- Excludes: pure sterile at 3.1
- Excludes: \[3.3 \text{ s} \]

Result 2: Solar model predictions are verified
What else can NC tell us?

1. Neutrino disappearance and appearance in one experiment:
   - Direct measurement of the total active $^8$B flux
   - No ambiguity in combining results from experiments

2. Lowest $E_n$ threshold (2.2 MeV) for real time experiments
   - No energy spectral information

\[ n_x + d \rightarrow n + p + n_x \]
Solar Neutrino Analysis (NC+CC+ES)

- **Energy**
  - Threshold: \( E_{\text{th}} > 5 \text{ MeV} \)
  - Background
  - NC
  - CC
  - ES
  - Monte Carlo

- **Fiducial Volume**: \( R > 550 \text{ cm} \)
- **Energy**: \( E_{\text{th}} > 5 \text{ MeV} \)

**NC and Day-Night Analysis in Pure D^2O**
NC Data Analysis

- Energy Cut + Fiducial Volume Cut
- Signal Decomposition: CC, NC, ES
- Neutron response
- Reconstruction (vertex + directional)
- Reconstruction (vertex)
- Energy response
- Low Energy Background Analysis

Data

- Energy response
- Neutron

Signal Decomposition:
- CC, NC, ES
- Fiducial Volume Cut + Energy Cut
- Reconstruction efficiency + Instrumental Bkg Cut
- Low Energy Background
- Similar to high E threshold CC analysis

Neal Poon, SLAC Experimental Seminar (May 16, 2002)
Data Reduction

Nov 2, 1999 to May 28, 2001
306.4 live days \( \text{Day}=128.5 \text{ days, Night}=177.9 \text{ days} \)

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<th>Events</th>
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<td><strong>Candidate Event Set</strong></td>
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</table>

[c.f. High energy CC paper: 240.9 live days, 1169 candidate events]
Data Reduction Cuts

Residual Instrumental Bkg. contamination:

- CC: 1.43 ± 0.21 ± 0.39%
- ES: 1.46 ± 0.19 ± 0.41%
- NC: 2.28 ± 0.23 ± 0.41%

Pass 0 Cuts

- Instrumental background removal using:
  - PMT time distribution
  - PMT charge distribution
  - Veto PMT tag
  - Event time correlation

Residual instrumental bkg. contamination:

- "Cherenkov Likelihood" — Event time correlation
- Veto PMT tag
- PMT charge distribution
- PMT time distribution

Residual instrumental bkg. contamination:

- > 3 events (95% CL)

Light arrival timing

Light isotropy measure

Light isotropy measure

Light arrival timing
Energy Response

- Calibration:
  - PMT & Optics
  - Normalized to 16N
  - PMT & Optics

- Linearity check with PT

Linearity = ±0.23% @ E=19.1 MeV

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<td>DE/E</td>
<td>±1.21%</td>
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### Reconstruction

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<th>$\pm 2.8%$</th>
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**Vertex: 8Li at different locations**

**Angular Resolution:** $16N$ far from source

**Reconstructed Vertex Position (cm):**

- Monte Carlo
- Data
Neutron Capture Efficiency

Measured:

\[ n \text{ capture on } d \text{ (uniform source)} \]

\[ 29.9 \pm 1.1 \% \]

\[ \text{Isotope} \quad \text{Abundance} \quad \text{Escape} \]

\begin{array}{c|c|c|c|c|c|c|c|c|c|c|c|c|c}

\hline

Isotope & Abundance & Point Source & Uniform Source & Total & Escape & 18-O & 17-O & 16-O & H & D

\hline

D & 99.9 & 97.6 & 96.0 & 99.9 & 0.03 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00

H & 0.08 & 24.0 & 29.1 & 0.08 & 0.00 & 0.05 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00

O & 99.9 & 95.9 & 95.9 & 99.9 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00

\hline

\end{array}

252Cf source data
Given a 5-MeV e– kinetic energy (T_e) analysis threshold, what is the probability of observing the Cherenkov signal from the 6.25 MeV γ in the (n,γ) reaction?

14.4 ± 0.5 %

Signal from the 6.25 MeV γ in the (n,γ) reaction. Observing the Cherenkov signal at 6 MeV threshold.

252Cf source data

MC Evaluated Neutron Energy

χ² = 0.86

Central 5.37±0.013

Run 14131 Gaussian Fit Evaluation

Neutron Detection Efficiency

SLAC Experimental Seminar (May 16, 2002)
"Photodisintegration"

\[ \text{Indistinguishable from NC} \]

**Technique:**
- Radiochemical assay
- Light isotropy study

**Cause:** Tail of resolution, or "Cherenkov Tail"

**MC Prediction:**
- Monte Carlo

**U/Th calib. source**

**Mis-reconstruction**

**Daughters in U or Th chain**

\[ + p \]

\[ + d \]

\[ + n \]

\[ \beta \text{ decays} \]

\[ \beta \text{ decays} \]

**Low Energy Background (Overview)**

**Must Know U and Th concentration in D_2O**

**Overview:**
- U or Th calib. source
- MC Prediction for 240 days of signal + internal + background

**Technique:**
- Radiochemical assay
- Monte Carlo

**Indistinguishable from NC i"
1. Ex-situ:

Radioc hemical assays of the D²O and H²O.

Extract 226Ra and 224Ra in the U and Th chain using MnOx and HTIO ion exchanger. Measure U and Th concentration by:

- MnOx: Spectroscopy on Po daughters
- HTIO: Bi-Po coincidence

Extract 222Rn in the U chain by degassing.

Measure Rn concentration by direct counting in a Lucas cell.

2. In-situ:

Light isotropy:

- ²⁰⁸Tl (Th chain) mostly + more anisotropic light pattern
- ²¹⁴Bi (U chain) mostly single

More isotropic light pattern by direct counting in a Lucas cell.

Extract 222Rn in the U chain by degassing. Measure Rn concentration by direct counting in a Lucas cell.
Calibrating the In-situ Technique

1. Activated salt water in storage tank with “hot” Th source in
   April 2008 - March 2009

2. Date from high Rn period

24Na

\[ ^{24}\text{Na} \]

\[ ^{14}\text{Na} \]
In-situ and ex-situ measurements give consistent results.

Monte Carlo

\[
\begin{array}{ccc}
\text{Count} & \text{Count} & \text{Count} \\
9.5 \pm 0.58 & 1.63 \pm 0.58 & 8 \\
17.8 \pm 3.5 & 7.8 \pm 3.5 & 7.5 \pm 3.0 \\
\end{array}
\]

\[
\begin{array}{ccc}
\text{H}_2\text{O} & \text{D}_2\text{O} & \text{H}_2\text{O} \\
(10.1 \pm 0.1) & (10.1 \pm 0.1) & (10.1 \pm 0.1) \\
5.8 \pm 2.7 & 6.5 \pm 2.6 & 7.5 \pm 2.4 \\
\end{array}
\]

\[
\begin{array}{ccc}
\text{H}_2\text{O}_2 & \text{D}_2\text{O} & \text{H}_2\text{O}_2 \\
(10.1 \pm 0.1) & (10.1 \pm 0.1) & (10.1 \pm 0.1) \\
5.8 \pm 2.7 & 6.5 \pm 2.6 & 7.5 \pm 2.4 \\
\end{array}
\]
U and Th in/on the Acrylic Vessel

Cherenkov data:
- Hot spot ("Berkeley Blob") found in outer surfaces measured prior to filling
- Dust concentration on inner and bulk acrylic assayed (NAA)
- Original Target (2 ppp): 60 mg Th or U

 Bulk acrylic assayed (NAA)
### Neutron Background Summary

<table>
<thead>
<tr>
<th>Source</th>
<th>Neutron Flux</th>
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<tr>
<td>17O(a,n)</td>
<td>(78 ± 12)</td>
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<tr>
<td>2H(a,a)</td>
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<tr>
<td>235U spontaneous fission</td>
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<tr>
<td>Atmospheric</td>
<td></td>
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<tr>
<td>H2O + AVD</td>
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<tr>
<td>D2O</td>
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<tr>
<td>External neutrons</td>
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<tr>
<td>Terrestrial &amp; reactor neutrons</td>
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</table>

For Te ≥ 5 MeV

R > 550 cm

12% of the number of observed NC neutrons assuming standard solar model flux.
Cherenkov Tail — D$_2$O

- Monte Carlo of detector response well calibrated in the D$_2$O region
  - Determine Cherenkov tail background due to D$_2$O radioactivity by Monte Carlo, using the U and Th concentration obtained above.

- MC predictions cross checked with a Th calibration source

$T > 5$ MeV, $R < 550$ cm:
- Th : $3^{+2}_{-1}$ counts
- U : $17^{+12}_{-5}$ counts
For $T_e \approx 5$ MeV, $R < 550$ cm

- Deployed an encapsulated Th calibration source in the detector. Measured the Cherenkov tail inside the fiducial volume above the energy threshold.
- Agree with Monte Carlo predictions based on radioactivity (last few slides)

\[
\begin{array}{|c|c|c|c|c|}
\hline
 & PMT & AV & H_2O & D_2O \\
\hline
\text{Total} & 45_{-11}^{+17} & 16_{-8}^{+11} & 6_{-6}^{+3} & 20_{-6}^{+13} \\
\hline
\text{Tail Bkg (counts)} & & & & \\
\hline
\end{array}
\]

[c.f.: 2928 candidates]
Cherenkov Tail (PDF Check)
Signal PDFs: T, R, \cos

Signals

Cherenkov tail & neutron background

Max. Likelihood Fit

Shape Constraint

Signals

Perturb Observables:

Amplitudes Free

Amplitudes Fixed

Shift amplitudes

(\pm 1)
Signal Extraction Results

Null hypothesis: no neutrino flavor mixing

Assume standard 8B spectrum

ES

263.6 ± 25.6 events

NC

576.5 ± 48.9 events

CC

1967.7 ± 61.9 events

no neutrino flavor mixing
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<tr>
<th>Source</th>
<th>$\Delta$ CC/CC (%)</th>
<th>$\Delta$ NC/NC (%)</th>
<th>$\Delta$ fmt/fmt (%)</th>
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<th>Neutron Capture</th>
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</tbody>
</table>

**Systematic Uncertainties (Shape constrained)**
STRONG Evidence for null hypotheses rejected at 5.3σ

Evidence for $n_e \rightarrow n_m$ and/or $n_t$ Null hypotheses rejected at 5.3σ

Constrained CC shape

$F(n e) = 1.76^{+0.09}_{-0.09}(stat.)^{+0.06}_{-0.05}(syst.) \times 10^6 cm^{-2} s^{-1}$

Unconstrained CC shape

$F(n m + n t) = 5.3^{+0.4}_{-0.4}(stat.)^{+0.43}_{-0.46}(syst.) \times 10^6 cm^{-2} s^{-1}$

$F(n e) = 2.39^{+0.24}_{-0.23}(stat.)^{+0.12}_{-0.12}(syst.) \times 10^6 cm^{-2} s^{-1}$

$F(n m + n t) = 1.76^{+0.09}_{-0.09}(stat.)^{+0.06}_{-0.05}(syst.) \times 10^6 cm^{-2} s^{-1}$

Neutral-Current Elastic Scattering

Charged-Current

Neutrino Signal (SSM BP00)
Disappearance and Reappearance

\[ \phi = 1.76^{+0.05}_{-0.05} (\text{stat.})^{+0.09}_{-0.09} (\text{syst.}) \]

Solar Model predictions are verified:

- [in 10^6 cm^2 s^-1]
- SSM: \[ f_{\text{SSM}} = 5.05 \pm 0.57 \]
- SNO: \[ f_{\text{SNO}} = 5.09 \pm 0.44 \]

\[ \phi = 6.42^{+0.57}_{-0.57} \]

\[ \phi = 5.05 \pm 0.46 \]
Day/Night Flux

Day Flux vs Night Flux

Day Flux

Night Flux

- Data divided into two sets (to test statistical bias)
- Sub-divide into 2 zenith angle bins:
  - Day: cos $q > 0$ (128.5 days)
  - Night: cos $q < 0$ (177.9 days)
- Combined day and night signals

Day/Night Signals

Set 1

Set 2

Combined

† $Ax = 2 \times \frac{(F_{\text{NIGHT}} + F_{\text{DAY}})}{(F_{\text{NIGHT}} - F_{\text{DAY}})}$

$A (\%)$

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>D</th>
<th>N</th>
<th>D</th>
<th>N</th>
<th>D</th>
<th>N</th>
<th>D</th>
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</thead>
<tbody>
<tr>
<td>CC</td>
<td>1.53 ± 0.12</td>
<td>1.95 ± 0.10</td>
<td>1.69 ± 0.12</td>
<td>1.77 ± 0.11</td>
<td>1.62 ± 0.08</td>
<td>1.87 ± 0.07</td>
<td>1.5 ± 0.10</td>
<td>-14.0 ± 6.3 ± 1.5</td>
</tr>
<tr>
<td>ES</td>
<td>2.91 ± 0.52</td>
<td>1.59 ± 0.38</td>
<td>2.35 ± 0.51</td>
<td>2.88 ± 0.47</td>
<td>2.64 ± 0.37</td>
<td>2.22 ± 0.30</td>
<td>-2.12 ± 0.12</td>
<td>-17.4 ± 19.5 ± 2.4</td>
</tr>
<tr>
<td>NC</td>
<td>7.09 ± 0.97</td>
<td>3.95 ± 0.75</td>
<td>4.56 ± 0.89</td>
<td>5.33 ± 0.84</td>
<td>5.69 ± 0.66</td>
<td>5.3 ± 0.54</td>
<td>4.01 ± 0.47</td>
<td>-20.4 ± 16.9 ± 2.5</td>
</tr>
</tbody>
</table>

- B shape constrained extraction
- Data divided into two sets
Checks did not turn up any significant diurnal asymmetry. D-N systematic checks did not.
The D-N analysis is currently statistics limited.

<table>
<thead>
<tr>
<th>Day/Night Systematics</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>Cut Inefficiencies</td>
<td>0.50</td>
</tr>
<tr>
<td>PMT backgrounds</td>
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<tr>
<td>D2O backgrounds</td>
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<tr>
<td>AV+H2O backgrounds</td>
<td>0.50</td>
</tr>
<tr>
<td>External neutron backgrounds</td>
<td>0.50</td>
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<tr>
<td>PMT backgrounds</td>
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</tr>
<tr>
<td>Directional energy resolution var.</td>
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<tr>
<td>Directional vertex resolution var.</td>
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<tr>
<td>Directional vertex shift var.</td>
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<tr>
<td>Directional angular recon. var.</td>
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<tr>
<td>External neutron backgrounds</td>
<td>0.50</td>
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<tr>
<td>Long-term energy scale</td>
<td>0.50</td>
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<tr>
<td>External neutron backgrounds</td>
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<tr>
<td>Long-term energy scale</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Systematic Uncertainties (D-N)

Shape constrained
\( A_{\text{e}} vs A_{\text{total}} \)

Signal Extraction in \( f_{\text{CC}}, f_{\text{NC}}, f_{\text{ES}} \):

\[
\begin{align*}
A_{\text{SK}} &= 5.3 \pm 1.7_{-0.2}^{+0.0} \\
A_{\text{e}} &= 7.0 \pm 4.9_{+1.3}^{-1.2} \\
\end{align*}
\]

\( f_{\text{total}} = f_{\text{e}} + f_{\text{m}} + f_{\text{t}} \)

\[
\begin{align*}
A_{\text{e}} &= 12.8 \pm 6.2_{+1.4}^{-1.5} \\
A_{\text{total}} &= 24.2 \pm 16.1_{+7.2}^{-2.5} \\
\end{align*}
\]

Signal Extraction in \( f_{\text{e}}, f_{\text{total}} + A_{\text{total}} = 0 \):

\[
\begin{align*}
A_{\text{SK}} &= 5.3 \pm 1.7_{-0.2}^{+0.0} \\
A_{\text{e}} &= 7.0 \pm 4.9_{+1.3}^{-1.2} \\
\end{align*}
\]

Signal Extraction in \( f_{\text{e}}, f_{\text{total}} + A_{\text{total}} = 0 \):

\[
\begin{align*}
A_{\text{total}} &= 20.4 \pm 16.9_{+2.4}^{-1.8} \\
A_{\text{ES}} &= 14.0 \pm 6.3_{+1.4}^{-1.5} \\
\end{align*}
\]
Global Solar \n
Analysis

Inputs:
• 37Cl, latest Gall-ex/GNO, new SAGE, SK 1258-day day & night spectra
• SNO day spectrum (total: CC+NC+ES+background)
• SNO night spectrum (total: CC+NC+ES+background)
• \( \Delta m^2, m^2 > \) m'\(m^2 \)
• SNO day spectrum (total: CC+NC+ES+background)
• SNO night spectrum (total: CC+NC+ES+background)
• \( \beta \) floats free in fit, hep at 1 SSM
Global Analysis Fit Results

<table>
<thead>
<tr>
<th>Region</th>
<th>( \tan^2 \theta )</th>
<th>( A^e(%) )</th>
<th>( \rho )</th>
<th>( m^2 )</th>
<th>CL(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOW</td>
<td>0.34 x 10^{-5}</td>
<td>6.4</td>
<td>5.86</td>
<td>72.0 SNU</td>
<td></td>
</tr>
<tr>
<td>LMA</td>
<td>0.30 x 10^{-5}</td>
<td>5.9</td>
<td>5.95</td>
<td>72.8 SNU</td>
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<tr>
<td>LOW</td>
<td>0.5 x 10^{-5}</td>
<td>5.0</td>
<td>4.95</td>
<td>72.0 SNU</td>
<td></td>
</tr>
<tr>
<td>LMA</td>
<td>0.5 x 10^{-5}</td>
<td>5.9</td>
<td>4.95</td>
<td>72.0 SNU</td>
<td></td>
</tr>
<tr>
<td>LOW</td>
<td>0.7 x 10^{-5}</td>
<td>6.4</td>
<td>6.4</td>
<td>72.0 SNU</td>
<td></td>
</tr>
<tr>
<td>LMA</td>
<td>0.7 x 10^{-5}</td>
<td>6.4</td>
<td>6.4</td>
<td>72.0 SNU</td>
<td></td>
</tr>
<tr>
<td>LOW</td>
<td>0.9 x 10^{-5}</td>
<td>5.9</td>
<td>5.9</td>
<td>72.0 SNU</td>
<td></td>
</tr>
<tr>
<td>LMA</td>
<td>0.9 x 10^{-5}</td>
<td>5.9</td>
<td>5.9</td>
<td>72.0 SNU</td>
<td></td>
</tr>
<tr>
<td>LOW</td>
<td>1.1 x 10^{-5}</td>
<td>5.9</td>
<td>5.9</td>
<td>72.0 SNU</td>
<td></td>
</tr>
<tr>
<td>LMA</td>
<td>1.1 x 10^{-5}</td>
<td>5.9</td>
<td>5.9</td>
<td>72.0 SNU</td>
<td></td>
</tr>
</tbody>
</table>

Experimental results: SK=2.32 x 10^6 cm^2 s^{-1}, Ga=72.0±4.5 SNU, Cl=2.56±0.23 SNU, 

- SNO CC/NC measurement directly constrains the survival probability at high energy
- Low solution forces LMA to confront the Ga experimental results
- SNO CC/NC measurement directly constrains the survival probability at high energy
Prediction for KamLAND

Global fit:

LMA: $\Delta m^2 = 5 \times 10^{-5} \text{ eV}^2$

KamLAND + spectrum with and without oscillations. $\sin^2 2\theta = 0.17$
The Salt Phase

- Running since June 2001
- Light isotropy differs from e
- Higher event light output
- Higher n-capture
- 2 tonnes of NaCl added to D$_2$O

To be deployed in early 2003

The Proportional Counters

$^3$He + p + 1
$^3$He $+ n + 1$

Neutral Current Detectors

Present Status & Future of SNO
Salt Phase

Salts are in Great Shape

Injection began on May 28, 2001

\[ \frac{t}{2} = 15 \text{ hrs} \]

24Na Background

24Na activated in the SNO detector by neutrons from the rock wall.

We observed the decay of 24Na after the brine is injected in the SNO detector.

Counts

Time Since Salt Injection (hrs)

100

0

-100

-200

0

100

200

Counts

10

100

1000

The NaCl brine in the underground buffer tank was activated by neutrons from the rock wall. We observed the decay of 24Na after the injection of NaCl into the SNO detector.
Newest SNO results:

- \( n_e \sim n_{nt} \) appearance at 5.3 s
- Total 8B flux measured for \( E_n > 2.2 \text{ MeV} \)

Global fit including the newest SNO results:

- LMA highly favored (\( m_2 \sim 5 \times 10^{-5} \text{ eV}^2 \))
- No "dark side" (\( m_2 > m_1, \tan^2 \theta < 1 \))
- Predictions for Borexino & KamLAND

The NC and Day-Night papers (accepted for publication in PRL)

Global fit including the newest SNO results:

- Day-Night results consistent with MSW hypothesis
- SSM prediction for total active 8B flux verified
- Total 8B flux measured for \( E_n \sim 2.2 \text{ MeV} \)
- MSW hypothesis consistent with SNO results

Available at the official SNO website:

http://sno.phy.queensu.ca