Results from the Sudbury Neutrino Observatory

David Waller for the SNO Collaboration
Carleton University, Ottawa, Canada
SLAC Summer Institute 2004
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August 4, 2004
Outline

- Introduction to SNO
- Previous solar neutrino results with D$_2$O
- Most recent solar neutrino result with D$_2$O + salt
- Non-solar neutrino results
- SNO’s future
- Summary
Road map to talk…

- Introduction to SNO
- Previous solar neutrino results with D$_2$O
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Purpose of SNO

- Resolve Solar Neutrino Problem (SNP): measured flux of $\nu$ from Sun is $\sim 1/3$ the predicted flux of Standard Solar Model.
  - Is Standard Solar Model wrong?
  - Do neutrinos oscillate from $\nu_e$ to $\nu_\mu$ and/or $\nu_\tau$?
  - Something else happening (e.g. $\nu_e$ to sterile $\nu$)?

- Observe $\nu$ from $^8\text{B} \beta$-decay in Sun.  
  \[ ^8\text{B} \rightarrow ^8\text{Be} + e^+ + \nu_e \]
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- If Solar Neutrino Problem due to $\nu_e$ oscillation to $\nu_\mu$ and/or $\nu_\tau$, SNO should provide direct evidence.

- SNO measures flux of $\nu_e$ and flux of ($\nu_e + \nu_\mu + \nu_\tau$).

- Previous expt’s sensitive to only $\nu_e$ or mainly $\nu_e$. 
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Radiochemical expt’s:
- $^{37}$Cl at Homestake and
- $^{71}$Ga at Gran Sasso/Baksan
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Water Čerenkov expt’s:
Kamiokande, Super-K

Radiochemical expt’s:
$^{37}$Cl at Homestake and $^{71}$Ga at Gran Sasso/Baksan
The SNO Detector

- 1,000 tonnes of D$_2$O.
- 6 m radius transparent acrylic vessel.
- 9,456 inward looking PMTs (with reflectors around PMTs have 54% geometrical acceptance).
- PMTs mounted on 9 m radius steel support structure.
- 7,000 tonnes of H$_2$O to support and shield D$_2$O.
- All materials carefully selected and tested to ensure minimal radioactive backgrounds (e.g. U, Th).
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- All materials carefully selected and tested to ensure minimal radioactive backgrounds (e.g. U, Th).
Location of SNO

- Located 2 km underground in active nickel mine near Sudbury, Canada

- Shielding from 2 km of rock reduces flux of cosmic ray muons to 70/day ($>10^9$/day on surface).

- Reduced cosmic ray background improves sensitivity to solar neutrinos.
SNO timeline


Commissioning
SNO timeline

- Phase 1: D$_2$O
SNO timeline

- Phase 1: D$_2$O
- Phase 2: D$_2$O + Salt (NaCl)
**SNO timeline**

- Phase 1: $\text{D}_2\text{O}$
- Phase 2: $\text{D}_2\text{O} + \text{Salt (NaCl)}$
- Phase 1a: $\text{D}_2\text{O}$
SNO timeline

- Phase 1: D₂O
- Phase 2: D₂O + Salt (NaCl)
- Phase 1a: D₂O

• Commissioning
• D₂O
• D₂O + Salt
• O

³He counters: Install & Commission
SNO timeline


Commissioning

• Phase 1: D$_2$O
• Phase 2: D$_2$O + Salt (NaCl)
• Phase 1a: D$_2$O
• Phase 3: D$_2$O + $^3$He counters

D$_2$O
D$_2$O + Salt
D$_2$O + $^3$He counters

$^3$He counters: Install & Commission
Neutrino reactions in SNO

[Diagram showing charged-current, neutral-current, and elastic scattering reactions involving neutrinos, protons, neutrons, and Cherenkov electrons.]
Neutrino reactions in SNO
Neutrino reactions in SNO

Neutrino Reactions on Deuterium

Charged-Current

$\nu_e$  
neutrino  
$\rightarrow$  
$\rightarrow$  
$\rightarrow$  
neutron  
deuteron  
Cherenkov electron  
protons

Neutral-Current

$\nu_x$  
neutrino  
$\rightarrow$  
$\rightarrow$  
neutron  
deuteron  
proton

Elastic Scattering

$\nu_x$  
neutrino  
$\rightarrow$  
$\rightarrow$  
Cherenkov electron  
electron  
n  
p  
$\rightarrow$  
n  
p

$\nu_x$  

Z
Neutrino reactions in SNO

**Neutrino Reactions on Deuterium**

- **Charged-Current**
  - $\nu_e$ (neutrino) + $d$ (deuteron) → $p$ (proton) + $p$ (proton) + Cherenkov electron

- **Neutral-Current**
  - $\nu_x$ (neutrino) + $d$ (deuteron) → $n$ (neutron) + $p$ (proton) + $\gamma$ (photon) + electron

- **Elastic Scattering**
  - $\nu_x$ (neutrino) + $e$ (electron) → $e$ (electron) + Cherenkov electron + $\nu$ (neutrino)
Neutrino reactions in SNO

\[
\sigma_{ES}(\nu_e) = 6 \sigma_{ES}(\nu_{\mu/\tau})
\]
Neutrino detection in SNO

- PMTs detect Čerenkov photons from relativistic $e^-$:
  - $e^-$ from CC or ES reaction
  - $\gamma$ from $n$-capture (NC reaction) usually Compton-scatters $e^-$ (pair production less likely).
Neutrino detection in SNO

- Hit pattern from Čerenkov cone indicates physics event.
- PMT hit times and locations used to reconstruct $e^-$ direction and location
- Number of PMT hits used to estimate electron energy.
Differentiating CC, ES and NC reactions

- Statistical separation based on several variables (e.g. during D$_2$O phase):
  - Electron kinetic energy, $T$ (# of PMT hits)
  - Radial position of reconstructed vertex, $(R/600)^3$ (volume-weighted)
  - Direction of electron w.r.t. Sun, $\cos \theta_{\text{sun}}$

![Graphs showing distribution of CC, NC, and ES reactions for different variables.](image)
Road map to talk…

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CC measurement with $D_2O$

- Measured CC reaction rate: $\phi_{CC} \equiv \phi(\nu_e)$
  - Can compare SNO’s $\phi(\nu_e)$ to Super-K’s $\phi(\nu_e)$ (assuming all ES interactions at Super-K due to $\nu_e$)
  - 3.3 $\sigma$ difference between $\phi(\nu_e)$’s.
NC measurement with $\text{D}_2\text{O}$

- Measured NC reaction rate: $\phi_{\text{NC}} \equiv \phi(\nu_e + \nu_\mu + \nu_\tau)$

\[
\phi_{\text{CC}} = (1.76^{+0.06}_{-0.05} \text{(stat)} \pm 0.09 \text{(syst)}) \times 10^6 \text{ cm}^{-2} \text{s}^{-1}
\]

\[
\phi_{\text{NC}} = (5.09^{+0.44}_{-0.43} \text{(stat)} ^{+0.46}_{-0.43} \text{(syst)}) \times 10^6 \text{ cm}^{-2} \text{s}^{-1}
\]

- 5.3 $\sigma$ signal for solar neutrino flavour mixing.

- $\phi_{\text{NC}}$ consistent with SSM with neutrino flavour mixing.
More results from first phase (pure D$_2$O)

- Measured Night-Day rate asymmetry ($A^e_{N-D}$) and electron energy spectra for Night and Day.

- At Night, $\nu$ pass through Earth; CC and ES rates may increase due to matter enhanced mixing of $\nu_\mu/\nu_\tau$ to $\nu_e$.

\[
A^e_{N-D} \equiv \frac{\phi_N - \phi_D}{(\phi_N + \phi_D) / 2} = 0.140 \pm 0.063^{+0.015}_{-0.014}
\]

\[
A^e_{N-D} \equiv \frac{\phi_N - \phi_D}{(\phi_N + \phi_D) / 2} = 0.070 \pm 0.049^{+0.013}_{-0.012}, \ A_{NC} = 0
\]
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- Introduction to SNO
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- Most recent solar neutrino result with $D_2O + \text{salt}$
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D$_2$O + Salt: why add salt?

- 2 tonnes of NaCl added.
- Change response to neutrons from NC reaction.
- Cl has larger $\sigma$ than $^2$H so $n$-capture efficiency improves.
- More energy released from $^{35}$Cl + $n$.
  - Higher E event means more NC events above kinetic E threshold of analysis (5.5 MeV)
  - Multiple $\gamma$’s $\rightarrow$ Č. photons from NC reaction more isotropic in detector (ES and CC produce single electron).

\[ \sigma = 0.0005 \text{ b} \]

\[ \sigma = 44 \text{ b} \]

\[ ^{35}\text{Cl} + n \rightarrow 8.6 \text{ MeV} \]

\[ ^{2}\text{H} + n \rightarrow 6.3 \text{ MeV} \]

\[ ^{3}\text{H} \]

\[ ^{36}\text{Cl} \]
Advantages of salt: $n$-detection efficiency

With salt, higher E release from $n$-capture and higher $\sigma$ for $n$-capture mean much higher NC detection efficiency.
Advantages of salt: event isotropy

Isotropy variable, $\beta_{14}$, function of angles between each pair of hit PMTs ($\theta_{ij}$) in event. (similar to thrust in collider physics)

$\beta_{14}$ powerful discriminating variable between NC and CC/ES events.
Calibration of detector

$^{252}\text{Cf}$ (neutron) and $^{16}\text{N}$ (6 MeV $\gamma$) sources provide check of MC for $\beta_{14}$

$^{16}\text{N}$ triggered $\gamma$ -ray source calibrates energy response.
D$_2$O + Salt analysis: data set and data reduction

- Data recorded from July 2001 to October 2002 (2/3 of D$_2$O + salt data).

- 254.2 live days (detector maintenance and calibration during remaining time).

- Blind analysis performed
  - Analysis and cuts tuned with MC and “spoiled” subset of data.

435,721,068 triggers
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Instrumental background cuts

Cosmic ray muons + spallation products
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Vtx reconstruction, PMT time and position distributions
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Cosmic ray muons + spallation products

Vtx reconstruction, PMT time and position distributions

Radius $\leq$ 550 cm, $T \geq 5.5$ MeV
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Instrumental background cuts

Cosmic ray muons + spallation products

Vtx reconstruction, PMT time and position distributions

Radius $\leq$ 550 cm, $T \geq$ 5.5 MeV

3055 events
Radioactive backgrounds

- *Ex situ* measurements show U and Th levels lower than goals (1 background neutron/day).

- *Ex situ* measurements consistent with *in situ* measurements

- *In situ* measurements more precise so used for solar neutrino analysis.
# Backgrounds

<table>
<thead>
<tr>
<th>Source</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{D}_2\text{O}$ photodisintegration</td>
<td>$73.1^{+24.0}_{-23.5}$</td>
</tr>
<tr>
<td>$^2\text{H}(\alpha, \alpha)pn$</td>
<td>$2.8 \pm 0.7$</td>
</tr>
<tr>
<td>$^{17,18}\text{O}(\alpha,n)$</td>
<td>$1.4 \pm 0.9$</td>
</tr>
<tr>
<td>Fission, atmospheric $\nu$ (NC + sub-Cherenkov threshold CC)</td>
<td>$23.0 \pm 7.2$</td>
</tr>
<tr>
<td>Terrestrial and reactor $\bar{\nu}$'s</td>
<td>$2.3 \pm 0.8$</td>
</tr>
<tr>
<td>Neutrons from rock</td>
<td>$\leq 1$</td>
</tr>
<tr>
<td>$^{24}\text{Na}$ activation</td>
<td>$8.4 \pm 2.3$</td>
</tr>
<tr>
<td>$n$ from CNO $\nu$'s</td>
<td>$0.3 \pm 0.3$</td>
</tr>
<tr>
<td>Total internal neutron background</td>
<td>$111.3^{+25.3}_{-24.9}$</td>
</tr>
<tr>
<td>Internal $\gamma$ (fission, atmospheric $\nu$)</td>
<td>$5.2 \pm 1.3$</td>
</tr>
<tr>
<td>$^{16}\text{N}$ decays</td>
<td>$&lt; 2.5$ (68% CL)</td>
</tr>
<tr>
<td>External-source neutrons (from fit)</td>
<td>$84.5^{+34.5}_{-33.6}$</td>
</tr>
<tr>
<td>Cherenkov events from $\beta - \gamma$ decays</td>
<td>$&lt; 14.7$ (68% CL)</td>
</tr>
<tr>
<td>“AV events”</td>
<td>$&lt; 5.4$ (68% CL)</td>
</tr>
</tbody>
</table>

Recall: 3055 candidate events
Measurement of CC, NC, ES events

- MC PDFs compared to data; extended unbinned ML fit used to estimate free parameters in fit.

- 3 (or 4) variables used to calculate likelihood PDFs:
  - Radial position of reconstructed vertex
  - Direction of electron w.r.t. Sun, \( \cos \theta_{\text{sun}} \)
  - Event isotropy, \( \beta_{14} \) (PMT hit pattern)
  - Electron kinetic energy (PMT hits) *(optional)*

- Free parameters in fit:
  - number of NC, CC, ES signal events
Measurement of CC, NC, ES events

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  - Electron kinetic energy (PMT hits) \((\text{optional})\)

- Free parameters in fit:
  - number of NC, CC, ES signal events

Matter enhanced oscillations change ES and CC spectra
PDFs for signals and backgrounds

Isotropy

Radius of fitted vertex

$\beta_{14}$

$(R_{\text{fit}}/6 \text{ m})^3$
PDFs for signals and backgrounds

Sun-electron direction

To Sun

Away from Sun

Sun-electron direction

Electron kinetic energy

$T_{\text{eff}}$ (MeV)

$\cos \theta_{\text{sun}}$
Flux results from fit

Energy spectrum of $^8$B $\nu$’s constrained to Ortiz, et al. spectrum

Units for $\phi$ are $10^6 \text{ cm}^{-2} \text{ s}^{-1}$

\[
\begin{align*}
\phi_{CC}^{\text{SNO}} & = 1.70 \pm 0.07 \text{ (stat.)}^{+0.09}_{-0.10} \text{ (syst.)} \\
\phi_{ES}^{\text{SNO}} & = 2.13^{+0.29}_{-0.28} \text{ (stat.)}^{+0.15}_{-0.08} \text{ (syst.)} \\
\phi_{NC}^{\text{SNO}} & = 4.90 \pm 0.24 \text{ (stat.)}^{+0.29}_{-0.27} \text{ (syst.)}
\end{align*}
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Flux results from fit

Energy spectrum of $^8B$ ν’s constrained to Ortiz, et al. spectrum

Energy spectrum of $^8B$ ν’s unconstrained (Energy not used in fit)

Units for $\phi$ are $10^6$ cm$^{-2}$ s$^{-1}$

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\end{align*}
\]

\[
\begin{align*}
\phi_{\text{SNO CC}} &= 1.59 + 0.08 \text{(stat.)} + 0.06 \text{(syst.)} \\
\phi_{\text{SNO ES}} &= 2.21 + 0.31 \text{(stat.)} \pm 0.10 \text{(syst.)} \\
\phi_{\text{SNO NC}} &= 5.21 \pm 0.27 \text{(stat.)} \pm 0.38 \text{(syst.)}
\end{align*}
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Flux results from fit

Energy spectrum of $^8$B ν’s constrained to Ortiz, et al. spectrum

Energy spectrum of $^8$B ν’s unconstrained (Energy not used in fit)

Standard Solar Model (Bahcall, Pinsonneault 2004)

Units for $\phi$ are $10^6$ cm$^{-2}$ s$^{-1}$

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$$
\phi_{BP04} = 5.82 \pm 1.34
$$
## Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>NC uncert. (%)</th>
<th>CC uncert. (%)</th>
<th>ES uncert. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy scale</td>
<td>-3.7,+3.6</td>
<td>-1.0,+1.1</td>
<td>±1.8</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>±1.2</td>
<td>±0.1</td>
<td>±0.3</td>
</tr>
<tr>
<td>Energy non-linearity</td>
<td>±0.0</td>
<td>-0.0,+0.1</td>
<td>±0.0</td>
</tr>
<tr>
<td>Radial accuracy</td>
<td>-3.0,+3.5</td>
<td>-2.6,+2.5</td>
<td>-2.6,+2.9</td>
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<tr>
<td>Vertex resolution</td>
<td>±0.2</td>
<td>±0.0</td>
<td>±0.2</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>±0.2</td>
<td>±0.2</td>
<td>±2.4</td>
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<tr>
<td>Isotropy mean †</td>
<td>-3.4,+3.1</td>
<td>-3.4,+2.6</td>
<td>-0.9,+1.1</td>
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<td>Vertex Z accuracy †</td>
<td>-0.2,+0.3</td>
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<tr>
<td>Internal background neutrons</td>
<td>-1.9,+1.8</td>
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<td>Internal background γ’s</td>
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<td>Cherenkov backgrounds</td>
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<td>Total experimental uncertainty</td>
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<td>Cross section [13]</td>
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<tr>
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## Systematic uncertainties

<table>
<thead>
<tr>
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Comparison to previous results and SSM (BP2000)

More precise salt results confirm D$_2$O results.
Interpretation of salt flux results: neutrino oscillation parameters

- Ratio of CC/NC fluxes gives $P(\nu_e \rightarrow \nu_e)$

- $P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$
Interpretation of salt flux results: neutrino oscillation parameters

SNO data only
Interpretation of salt flux results: neutrino oscillation parameters

SNO data only

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

$\Delta m^2$ vs. $\tan^2 \theta$

- $\chi^2$ min. at (4.07e-01, 7.08e-05)
- SNO pure D$_2$O day & night spectra
- SNO salt CC & NC & ES fluxes
- SK-I zenith spectra + Cl + Ga
- KamLAND $^8$B free

August 4, 2004
Interpretation of salt flux results: neutrino oscillation parameters

1-D projections of oscillation parameters give marginal uncertainties on $\tan^2 \theta$ and $\Delta m^2$.

$\theta = 32.5^{+1.7}_{-1.6}$ degrees

Maximal mixing ($\theta = 45$ degrees) excluded at 5.4 $\sigma$.

$\Delta m^2 = (7.1^{+1.0}_{-0.3}) \times 10^{-5}$ eV$^2$
Road map to talk…

- Introduction to SNO
- Previous solar neutrino results with D$_2$O
- Most recent solar neutrino result with D$_2$O + salt
- Non-solar neutrino results
- SNO’s future
- Summary
Recent non-solar $\nu$ SNO results

Nucleon Decay

- “Invisible” decay of $n$ and $p$ (e.g. $N \rightarrow 3 \nu$) from $^{16}$O produces $\gamma$-ray of 6→7 MeV.

- In SNO, $\gamma$-ray of 6→7 MeV looks like $n$-capture.

- Compare $n$-capture rates in SNO Phases 1 and 2 (different $n$-efficiencies) to set limit on $\tau_{\text{inv}}$ of $p$ and $n$.

  \[ \tau_{\text{inv}}^p > 2.1 \times 10^{29} \text{ years, 90\% CL} \]

  \[ \tau_{\text{inv}}^n > 1.9 \times 10^{29} \text{ years, 90\% CL} \]

$\bar{\nu}_e$ search

- Solar $\nu_e$ might convert to $\bar{\nu}_e$ via Spin Flavour Precession or $\nu_e$ decay.

- Look for 2- or 3-fold coincidences from $\nu_e + d \rightarrow n + n + e^+$

- 2 candidate coincidences (one 2-fold, one 3-fold) in Phase 1.

- 1.68$^{+0.93}_{-0.45}$ background expected (mainly $\nu_{\text{atm}}$)

\[ \text{Prob}(\nu_e \rightarrow \bar{\nu}_e) < 0.81\%, 90\% \text{ CL} \]
Road map to talk...

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- Previous solar neutrino results with D\textsubscript{2}O
- Most recent solar neutrino result with D\textsubscript{2}O + salt
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Future of SNO: $^3$He counters

- Detect neutrons from NC interactions via
  \[ n + ^3\text{He} \rightarrow p + ^3\text{H} \]

- $^3$He-filled proportional tubes detect recoiling $p$ and $^3$H.

- 40 $^3$He-filled proportional tubes in 1m grid (398 m total length).

- $\sigma(n + ^3\text{He}) = 10^7 \sigma(n + ^2\text{H})$

- Event-by-event identification of NC interactions (no correlation with CC rate like in earlier phases).
Future of SNO: $^3$He counters

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Advantage of $^3$He counters

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<tr>
<th></th>
<th>$D_2O$</th>
<th>$Salt$</th>
<th>$^3He$</th>
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<tbody>
<tr>
<td>CC,NC</td>
<td>-0.950</td>
<td>-0.521</td>
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<tr>
<td>NC,ES</td>
<td>-0.297</td>
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<tr>
<td>CC,ES</td>
<td>-0.208</td>
<td>-0.156</td>
<td>~-0.2</td>
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</table>

- Reduction in anti-correlation between NC and CC will help to reduce uncertainty in CC/NC ratio.
- Smaller uncertainty in CC/NC ratio means smaller uncertainty in $\tan^2\theta$. 
Installation of $^3$He counters complete!
Commissioning in progress.
Summary

- SNO has completed data-taking for first two phases ($\text{D}_2\text{O}$ and $\text{D}_2\text{O}$ +Salt).
- Results from first two phases give convincing evidence of solar neutrino flavour change (first direct evidence of $\nu_e$ flavour change!).
  - $\nu_e$ has non-zero mass.
- Solar Neutrino Problem resolved after 30+ years (SSM correct!).
- Searches for “invisible” nucleon decay and electron anti-neutrinos have set interesting new limits.
- Last phase with $^3\text{He}$ proportional counters has begun.
SNO Collaboration

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

Brookhaven National Laboratory
Lawrence Berkeley National Laboratory
Los Alamos National Laboratory
University of Pennsylvania
University of Texas at Austin
University of Washington

Oxford University
Rutherford Laboratory
University of Sussex
References

- SNO detector details:

- CC flux in D2O:

- NC flux in D2O:

- Night-Day Asymmetry in D2O:

- NC in in D2O+Salt:

- Nucleon Decay:

- Anti-neutrino Search:
Extra slides...
$^3$He proportional counters

Cu anode wire (50 microns)

$^3$He-CF$_4$ gas

Nickel body

10 m

5 cm
$^3$He proportional counters
Advantage of adding salt to D$_2$O
PMT timing and $T_{\text{eff}}$ vs. NHIT
Ex-situ
- Ion exchange ($^{224}$Ra, $^{226}$Ra)
- Membrane Degassing ($^{222}$Rn)

In-situ
- Count daughter product decays
- Low energy data analysis
- Separate $^{208}$Tl & $^{214}$Bi

![Graph showing distributions of events per bin in arbitrary units vs. mean angle between PMT hits - $\theta_\parallel$.]