Final Phase SNO results

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BNL Physics Dep. Seminar  
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Roadmap

- A brief history of the neutrino
- Solar neutrinos and pioneers experiments
- The Solar Neutrino Problem
- Neutrino masses and oscillations
- The Sudbury Neutrino Observatory
- Results from the third phase
A brief history of the neutrino (1/)

1930’s: $\beta^-$ was thought to be $X \rightarrow Y + e^-$

Two body decay: the $e^-$ energy should come into discrete quantity.

W. Pauli: “possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons…”

N. Bohr: “I should say that we have no argument, either empirical or theoretical for upholding the energy principle in case of beta-ray disintegration”
A brief history of the neutrino (2/)

• In 1932 Chadwick discovers the neutron.

Problem: two heavy to satisfy Pauli’s explanation of energy conservation in $\beta^-$ decay.

• In 1934 Fermi publishes his theory of $\beta^-$ decay.

Assumes the existence of Pauli’s light neutral particle and names it “neutrino”.

• In 1956 direct detection of the (anti)-neutrino.

Reines & Cowan’s experiment at Savannah River nuclear reactor (S. Carolina):

\[ \bar{\nu} + p \rightarrow n + e^+ \]

\[ n + ^{113}\text{Cd} \rightarrow ^{114}\text{Cd}^* + \gamma (\sim \mu s) \rightarrow e^+ + e^- \rightarrow \gamma \gamma (0.511 \text{ MeV}) \]
Neutrinos & their detection

Standard Model

<table>
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<tr>
<th>Quarks</th>
<th>Leptons</th>
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<tr>
<td>u</td>
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<tr>
<td>d</td>
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Three flavors. No charge nor mass. Interact only via the weak force.

Big detectors & powerful sources

Going deep underground

\[ 1 \text{ KT} \]

\[ \sim 2 \times 10^{38} \text{ v/s}^{-1} \]
Solar neutrinos

The pp chain reaction:

\[
p + p \rightarrow ^2H + e^+ + \nu_e \quad \text{(pp)} \]

\[
p + e^- + p \rightarrow ^2H + \nu_e \quad \text{(pep)}
\]

\[
^2H + p \rightarrow ^3He + \gamma
\]

\[
^3He + ^4He \rightarrow ^7Be + \gamma
\]

\[
^7Be + e^- \rightarrow ^7Li + \nu_e \quad \text{(^7Be)}
\]

\[
^7Li + p \rightarrow ^4He
\]

\[
^7Be + p \rightarrow ^8B + \gamma
\]

\[
^8B \rightarrow ^8Be^* + e^+ + \nu_e \quad \text{(^8B)}
\]

\[
^8Be^* \rightarrow ^4He
\]

Pioneer experiments (1/)

The Chlorine radiochemical experiments:
First attempt by Ray Davis in Barbeton mine (Ohio, 2300 ft depth): could only obtain an upper limit due to the cosmic-ray muon background.

Second attempt in Homestake (South-Dakota, 4850 ft depth) using the reaction:

\[ \nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^- (> 814 \text{ keV}) \]

The \(^{37}\text{Ar}\) produced by neutrino interactions was then extracted by purging the tank with helium collecting the He and Ar. With a 35-day half-life the \(^{37}\text{Ar}\) could then be counted.

This experiment took data for over 30 years. Observed solar neutrino rate was 2.56 \(\pm 0.16\) (stat.) \(\pm 0.15\) (sys.) SNU compared to the predicted rate of 7.7 \(^{+1.2}_{-1.0}\) SNU.

1 SNU (Solar Neutrino Unit) = \(10^{-36}\) s\(^{-1}\) per target atom.
Pioneer experiments (2/)

The Gallium radiochemical experiments:

Another reaction which has been used to study solar neutrinos is:

\[ \nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^- (> 0.233 \text{ MeV}) \]

SAGE experiment which was located in the Baksan Neutrino Observatory (Russia) used Gallium metal and observed a neutrino rate of $67.2^{+7.2}_{-7.0} \text{ (stat.)}^{+3.5}_{-3.0} \text{ (sys.)} \text{ SNU}$ while the predicted rate for gallium is 129 SNU.

GALLEX and GNO experiments located in Gran-Sasso Laboratory (Italy) have used a gallium chloride solution and observed a rate of $74.1^{+6.7}_{-6.8} \text{ SNU}$.
Pioneer experiments (3/)

Kamiokande and Super-Kamiokande (Japan):

Both used water as target for neutrino interaction:

$$\nu_x + e^- \rightarrow \nu_x + e^- \text{(ES)}$$

Scattered electrons are detected by the Cherenkov light they produce.

Kamiokande experiment measured a $\nu$ flux that was $0.492^{+0.033}_{-0.034}$ (stat.) $\pm 0.058$ (sys.) of the expected solar neutrino signal.

Super-Kamiokande has reported detecting $0.465^{+0.015}_{-0.013}$ (stat.) $\pm 0.058$ (sys.) of the expected signal with 1496 days of data.
The Solar neutrino problem

Significant deficit of neutrinos:

- solar model flawed?
- understanding of neutrinos incomplete?

Helioseismology measurements agree with the SSM:

So, what if the neutrinos can change flavors?
Neutrino masses and oscillations

Flavor eigenstates are a mixture of mass eigenstates:

From mass to flavor:

\[ \nu_e = \cos \theta_{12} \cdot \nu_1 + \sin \theta_{12} \cdot \nu_2 \]
\[ \nu_\mu = -\sin \theta_{12} \cdot \nu_1 + \cos \theta_{12} \cdot \nu_2 \]

From the equation of evolution:

Oscillation probability:

\[ P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{12}) \cdot \sin^2(1.27 \Delta m^2_{12} \frac{L}{E}) \]

\[ \Delta m^2_{12} = m_1^2 - m_2^2 \]
The Sudbury Neutrino Observatory

- 6000 m.w.e. overburden
- 1000 tons D$_2$O
- 12 m Diameter Acrylic Vessel
- 1700 tons Inner Shield H$_2$O
- Support Structure 9500 PMTs, 60% coverage
- 5300 tons Outer Shield H$_2$O

Image courtesy National Geographic
SNO interactions (from $^8$B neutrinos)

Elastic-scattering (ES):

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

\( \nu_x \) mainly
directional
sensitivity

Charged-currents (CC):

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

\( \nu_e \) only
\( E_e \) correlated
with \( E_\nu \)

Neutral-currents (NC):

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

All flavors
equally
Total \( \nu \) flux
Neutron capture techniques

**D$_2$O Phase:**
- $\sigma = 0.0005 \text{ b}$
- $\varepsilon = 14\%$
- Energy threshold close to background noise (6.25 MeV)

**Salt Phase (2 tons NaCl):**
- $\sigma = 44 \text{ b}$
- $\varepsilon = 41\%$
- Higher energy threshold (8.6 MeV)

**NCD Phase:**
- $\sigma = 5330 \text{ b}$
- $\varepsilon = 21\%$
- New detectors ($E=0.76 \text{ MeV}$)
SNO Timeline

Construction/commissioning | D₂O phase | Salt phase | D₂O | NCD comm. | NCD phase | D₂O Return


Super-Kamiokande

CI

GNO

SAGE

KamLAND

KamLAND Solar

Borexino
Salt phase results

Fluxes and ratios ($10^{-6}$ cm$^{-2}$s$^{-1}$):

- $\Phi_{CC} = 1.68 \pm 0.06$ (stat.)$^{+0.08}_{-0.09}$ (syst.)
- $\Phi_{NC} = 4.94 \pm 0.21$ (stat.)$^{+0.38}_{-0.34}$ (syst.)
- $\Phi_{ES} = 2.35 \pm 0.22$ (stat.)$^{+0.15}_{-0.15}$ (syst.)

Mass:

$\Delta m^2 = 0.8^{+0.6}_{-0.4} \times 10^{-5}$ eV$^2$

Mixing angle:

$\theta_{12} = 33.9^{+2.4}_{-2.2}$ degrees

$\Phi_{CC}/\Phi_{NC} \sim \sin^2 \theta_{12}$

PRC 72, 055502 (2005)
Neutral Current Detectors (NCD)

Why:
- Different systematics compared to previous phases
- Better CC flux measurement
  Correlation between CC and NC signals reduced

Challenges:
- Low signal rate: $\sim 1000$ neutrons/year detected
- Ultra-low background materials needed
- Some light loss ($\sim 10\%$) due to array

$^3\text{He}$ strings and $^4\text{He}$ strings deployed on a $1\times1$ m grid.

36 $^3\text{He}$ strings and 4 $^4\text{He}$ strings deployed on a $1\times1$ m grid.

Total length 398 m.
High purity CVD nickel:

\[ \text{gTh/gNCD} = 3.43^{+1.49}_{-2.11} \times 10^{-12} \]

\[ \text{gU/gNCD} = 1.81^{+0.80}_{-1.12} \times 10^{-12} \]

(100 times purer than previous counters)
Oscilloscope: Digitize the pulse, trigger on amplitude, slow readout (8B)

Shaper: Energy information only, trigger on integral charge, fast readout (8B, SN)
Energy Spectrum from $^{3}\text{He}(n,p)t$

Neutrons from $^{24}\text{Na}$: $\gamma+d \rightarrow p+n$

Events per 10 keV

Energy Spectrum from $^{3}\text{He}(n,p)t$
Neutron capture efficiency

1- $^{24}$Na method: mimic the signal with mixed $^{24}$Na which generates neutrons by:
$$\gamma + d \rightarrow n + p.$$ 

$\varepsilon_n = 0.211 \pm 0.007$

2- Monte Carlo method: calibrate the Monte Carlo with point AmBe and $^{252}$Cf sources.

$\varepsilon_n = 0.210 \pm 0.003$
Neutron background

(PD = photodisintegration)

<table>
<thead>
<tr>
<th>Source</th>
<th>PMT Events</th>
<th>NCD Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_2O$ photodisintegration</td>
<td>7.6 ± 1.2</td>
<td>28.7 ± 4.7</td>
</tr>
<tr>
<td>NCD bulk/17O,18O</td>
<td>4.6$^{+2.1}_{-1.6}$</td>
<td>27.6$^{+12.9}_{-10.3}$</td>
</tr>
<tr>
<td>Atmospheric ν/16N</td>
<td>24.7 ± 4.6</td>
<td>13.6 ± 2.7</td>
</tr>
<tr>
<td>Other backgrounds †</td>
<td>0.7 ± 0.1</td>
<td>2.3 ± 0.3</td>
</tr>
<tr>
<td>NCD “hotspots”</td>
<td>17.7 ± 1.8</td>
<td>64.4 ± 6.4</td>
</tr>
<tr>
<td>NCD cables</td>
<td>1.1 ± 1.0</td>
<td>8.0 ± 5.2</td>
</tr>
<tr>
<td>Total internal neutron background</td>
<td>56.4$^{+5.6}_{-5.4}$</td>
<td>144.6$^{+13.8}_{-14.8}$</td>
</tr>
<tr>
<td>External-source neutrons</td>
<td>20.6 ± 10.4</td>
<td>40.9 ± 20.6</td>
</tr>
</tbody>
</table>
Instrumental background

- Hot spot
- Gas leak into counter inter-space
- Electrical disconnect
- Electrical micro-discharge
- Gain instability

Energy spectrum before and after cuts

Spectrum after instrumental background cuts

- Raw shaper-ADC spectrum
- Shaper and scope trigger

Energy spectrum before and after cuts

- preamp microdischarge
- baseline noise

- $^3$He
- $^4$He
NCD pulse simulation

Energy deposition, electron drift

Charge multiplication, ion drift, pulse propagation, electronics

Noise

neutrons alphas background:
- wall Po alphas
- wire Po alphas
- wire U/Th alphas
- endcap Po alphas
- wall U/Th alphas
Blindness scheme and observables

First month of neutrino data open
1- Subtract an unknown fraction of neutrino candidates
2- Add an unknown amount of muon follower neutrons

Log-likelihood fit \( L = L_{PMT} + L_{NCD} \):

\[
L_{PMT} = - \sum_{d=1}^{N_d} \log \left( \sum_{s=1}^{N_s} n_s f_s(x_d) \right) + \sum_{s=1}^{N_s} n_s \frac{1}{2} \sum_{p=1}^{N_p} \left( \frac{\lambda_p - \bar{\lambda}_p}{\sigma_p} \right)^2
\]

\[
L_{NCD} = - \sum_{d=1}^{N_d'} \log \left( \sum_{s=1}^{N_s'} n_s' f_s'(x_d') \right) + \sum_{s=1}^{N_s'} n_s' \frac{1}{2} \sum_{p=1}^{N_p'} \left( \frac{\lambda_p' - \bar{\lambda}_p'}{\sigma_p'} \right)^2
\]

Signal:
\[
f(T, \cos \theta_{\text{sun}}, \rho) f(E_{\text{ADC}})
\]

Background:
\[
f(T) \times f(\cos \theta_{\text{sun}}) \times f(\rho) f(E_{\text{ADC}})
\]

Box Opened May 2, 2008:

\(~10\%\) difference in NC flux uncertainties between the 3 signal extraction codes: after correction of the input energy resolution systematic constraint the errors agree, no effect on the central fit values.

• Parametrization failure of the algorithm (for one extraction code) used to fit the peak value from each ES bin ‘s distribution: more robust fit method implemented, ES fluxes agree.
Markov Chain Monte Carlo

The physics parameters ("fluxes") are fitted allowing nuisance parameters (calibration constants, etc.) to vary weighted by their external uncertainties. The likelihood is maximized via randomized search steps.

**Algorithm:**

Initial step $i$
- parameter guesses $p_i$
- calculate likelihood $L_i$

Add random amounts to all parameters
- $p_{i+1} = p_i + \text{Norm}(0, \sigma_i)$
- calculate likelihood $L_{i+1}$

Keep $p_i$ or $p_{i+1}$:
- $p_{\text{keep}} = \max(1, L_{i+1} / L_i)$

62-parameter likelihood function
- 13 CC flux energy bins
- 13 ES flux energy bins
- NC flux
- 35 systematic parameters
Results
Fluxes and number of events

Fluxes (in unit of \(10^6\) cm\(^{-2}\) s\(^{-1}\)): 

CC  \(1.67^{+0.05}_{-0.04}\) (stat) \(+0.07_{-0.08}\) (sys) 

ES  \(1.77^{+0.24}_{-0.21}\) (stat) \(+0.09_{-0.10}\) (sys) 

NC  \(5.54^{+0.33}_{-0.31}\) (stat) \(+0.36_{-0.34}\) (sys) 

PMT events: 

CC  \(1867^{+91}_{-101}\) 

ES  \(171^{+24}_{-22}\) 

NC  \(267^{+24}_{-22}\) 

Background  \(77^{+12}_{-10}\) 

Correlation Matrix for the Salt phase: 

\[
\begin{array}{ccc}
CC & ES & NC \\
CC & 1.00 & \ & \ \\
ES & -0.16 & 1.00 & \ \\
NC & -0.52 & -0.06 & 1.00 \\
\end{array}
\]

Correlation matrix for the NCD phase: 

\[
\begin{array}{ccc}
CC & ES & NC \\
CC & 1.00 & \ & \ \\
ES & 0.24 & 1.00 & \ \\
NC & -0.19 & 0.02 & 1.00 \\
\end{array}
\]

NCD events: 

NC  \(983^{+77}_{-76}\) 

Background  \(185^{+25}_{-22}\)
Salt and NCD phases comparison

**Salt phase**

Better measurement of the CC flux.

Lower ES flux.

**NCD phase**

ES results deviation from prior results due to a statistical fluctuation.
Comparisons

**CC Flux**
- D$_2$O Constrained - 306 days
- Salt - 391 days
- NCD - 385 days

**ES Flux**
- SuperK-I - 1496 days
- D$_2$O Constrained - 306 days
- Salt - 391 days
- NCD - 385 days

- stat. + syst.
- stat.
Comparisons

Fluxes (in unit of $10^4$ cm$^{-2}$ s$^{-1}$)

CC: 167(9)
ES: 177(26)
NC: 554(49)
Super-K: 235(8) [PRD 73, 112001, 2006]

Agreement with previous measurements (estimated p-value = 0.328)

Agreement with standard solar models
2-neutrinos oscillation contours

(a) SNO only: D$_2$O & Salt day and night spectra, NCD phase fluxes

(b) Solar Global: SNO, Super-K, Cl, Ga, Borexino

(c) Solar Global + KamLAND

Solar+KamLAND best fit:

$\Delta m^2_{12} = 7.59 \pm 0.19 \times 10^{-5} \text{ eV}^2$

$\theta_{12} = 34.4 \pm 1.3 \text{ degrees}$

$\tan^2 \theta_{12} = 0.468 \pm 0.048$
Results from the NCD phase:
Independent measurement of the $^8$B flux.
NCD results agree well with previous SNO phases.
Reduced correlations between CC and NC.
Different systematics.
New precision on $\theta_{12}$, 40% improvement on our previous result. [Phys. Rev. Letter 101 11301 (2008)]

More from SNO:
LETA (Low Energy Threshold Analysis)
Three phase analysis
Three neutrino analysis
$hep$ flux
Day-night, other variations
Muons, atmospheric $\nu$ [accepted by PRD]
The SNO Collaboration


University of Alberta, University of British Columbia, Carleton University, University of Guelph, Laurentian University, Queen's University, SNOLAB, TRIUMF.

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Canada Research Chairs
Westgrid

US:
Department of Energy
NERSC PDSF

UK:
STFC (formerly Particle Physics and Astronomy Research Council)

Portugal:
FCT
Backup Slides
The big picture

The Maki-Nakagawa-Sakata-Pontecorvo (MNSP or PMNS or MNS) matrix:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\
s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}
\end{pmatrix}
\begin{pmatrix}
e^{i\alpha_{1/2}} & 0 & 0 \\
0 & e^{i\alpha_{2/2}} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Equation of evolution:

\[|\nu_\alpha (L)>| = \sum_{\alpha} U^*_{\alpha i} \exp(-i m^2_{i} L/2E) |\nu_i (L=0)>|\]

Oscillation probability (vacuum case):

\[P(\nu_\alpha \rightarrow \nu_\beta) = |<\nu_\alpha | \nu_\beta>|^2 = \delta_{\alpha\beta} - 4\sum_{\alpha i} U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \sin^2(\Delta m^2_{ij} L/4E)\]

3 mixing angles 1 CP violation phase 2 Majorana phases
Change in parameterization for ES fit

Old method

New method

ES 5\textsuperscript{th} energy bin posterior
Angular distributions for ES

Distribution for the energy bin 6.5-7.0 MeV: no peak at $\cos(\theta_{\text{sun}}) = 1$ as expected. Statistical fluctuation (1.3% probable to obtain such a low number in this bin assessed by a MC of 10000 trials).
$\chi^2$ map (SNO collaboration)