Recent results from the Sudbury Neutrino Observatory Experiment

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Solar Neutrinos – Pre 2001

Neutrino Spectrum ($\pm 1\sigma$)

- $^{\text{pp}}$ $\rightarrow +1\%$
- $^{13}\text{N}$ $\rightarrow +10.5\%$
- $^{17}\text{O}$ $\rightarrow +16\%$
- $^{7}\text{Be}$ $\rightarrow +10.5\%$
- $^{\text{pep}}$ $\rightarrow +2\%$
- $^{8}\text{B}$ $\rightarrow +16\%$
- $^{\text{hep}}$ $\rightarrow +16\%$

Experiment ≠ Theoretical predictions
The Sudbury Neutrino Observatory
Located 6800 ft underground in Vale Creighton Mine, Sudbury, Ontario.

ES Reaction
- Primarily sensitive to $\nu_e$.
- Sensitive to direction.

CC Reaction
- Sensitive to $\nu_e$ only.
- Can be used to obtain $\nu_e$ energy.

NC Reaction
- Sensitive to all active flavours.
- Measures total flux of $^8$B solar neutrinos.

1000 tonnes $D_2O$ held in acrylic vessel
7000 tonnes $H_2O$ shielding
~9,500 Photomultiplier tubes
The Sudbury Neutrino Observatory

Three phases of operation

**Phase I – Pure D\(_{2}\)O**
1999 - 2001
- Simple detector configuration
- Low neutron detection
- Poor electron neutron discrimination

**Phase II – Pure D\(_{2}\)O + NaCl**
2002 - 2004
- Enhanced neutron detection
- Improved electron neutron discrimination

**Phase III – Pure D\(_{2}\)O + \(^3\)He**
Proportional counters
2004 - 2008
- Good neutron detection
- Excellent separation between neutrons and electrons
What do we know from SNO so far?

Flux of electron neutrinos is less than SSM prediction
Total flux of neutrinos is in agreement with SSM prediction

What else can be learned from SNO?
Low Energy Threshold Analysis

Basic overview
- Lower threshold to 3.5 MeV
- Combine data from phases I and II
- Fit for all signals and backgrounds
- Improvement of background exclusion
- Improve Monte Carlo simulation
- Reduction of systematic uncertainties
- Improved signal extraction methods
- Improved oscillation analysis

Results
- Measurement of 8B flux from NC rates
- Binned electron energy spectrum using CC and ES
- Two flavour and three flavour extraction of mixing parameters
- Parametrized survival probability
Low Energy Threshold Analysis
Radioactive backgrounds

Limited by backgrounds
- Naturally occurring radioactivity $^{238}U$, $^{222}Rn$ and $^{232}Th$
- Present in $D_2O$, Acrylic Vessel and $H_2O$ shielding
- Main concern are $^{208}Tl$ and $^{214}Bi$

Can constrain using assay results

New energy estimator improved background rejection by around 60%.
Low Energy Threshold Analysis

Systematic uncertainty improvement

- n capture
  - LETA I
  - LETA II
- Teff scale
- N/A
- \( \beta^{14} \) (isotropy)
- Fiducial volume
Low Energy Threshold Analysis

Signal extraction

3 Neutrino signals + 17 backgrounds for EACH phase

Multidimensional pdfs

\[ P(\beta_{14}, R^3, \cos \theta_\odot) \quad \text{ES and CC} \]
\[ P(T_{\text{eff}}, \beta_{14}, R^3) \times P(\cos \theta_\odot) \quad \text{NC and backgrounds} \]

Two distinct methods used

1. Maximum Likelihood approach using binned pdfs
   Manual scan of likelihood space
   Data assists with constraint of systematics

2. Kernel estimation
   Essentially unbinned Maximum Likelihood approach
   CPU intensive... use a graphics card!
   Can float all systematics
Low Energy Threshold Analysis
Signal extraction results – 1D projections
Low Energy Threshold Analysis

$^8\text{B}$ Flux results using “unconstrained” cc spectrum

\[
\Phi_{\text{NC}} = 5.140 \pm 0.160^{\text{(stat)}} + 0.132^{\text{(syst)}}
\]
Low Energy Threshold Analysis

"unconstrained" CC electron spectrum

Flat: $\chi^2 = 21.52 / 15$ d.o.f.
LMA: $\chi^2 = 22.56 / 15$ d.o.f.

Previous global best-fit
LMA point:
$\tan^2\theta_{12} = 0.468,$
$\Delta m^2 = 7.59 \times 10^{-5} \text{ eV}^2$
Low Energy Threshold Analysis
Oscillation analysis – SNO ONLY

LETA paper 2009:
LETA joint-phase fit + Phase III ($^3$He)

Best-fit point:
$\tan^2\theta_{12} = 0.437 \pm 0.058$
$\Delta m^2 = 1.15 \times 10^{-7} \pm 0.43 \pm 0.18 \text{ eV}^2$
(LOW)

SNO Collaboration, Phys. Rev C81, 55504
Low Energy Threshold Analysis
Oscillation analysis - SNO + KAMLAND 2 Flavour

LETA paper 2009:
LETA joint-phase fit
+ Phase III
+ all solar expts
+ KamLAND

2 flavour overlay
Low Energy Threshold Analysis
Oscillation analysis – SNO + KAMLAND 3 Flavour

LETA paper 2009:
LETA joint-phase fit
+ Phase III
+ all solar expts
+ KamLAND

3-flavor fit/overlay
-> Pointed out by many authors

Best-fit:
\[ \sin^2 \theta_{13} = 2.00 \pm 0.09 \pm 1.63 \times 10^{-2} \]

\[ \sin^2 \theta_{13} < 0.057 \text{ (95\% C.L.)} \]
Full 3-Phase Analysis
Combine LETA and Phase III (NCD) in a single fit

Pulse shape analysis to separate $^3$He signal from background

Number of neutrons determined by fitting to the counter energy spectrum.
Constrain 3-phase fit using $^3$He count.

Expected improvement in $\Delta m^2$
Other SNO results

High Frequency Periodicity Search
*ApJ.* 710:540-548

Low Multiplicityity burst search
*In Progress*

Neutron and spallation product study
*In Progress*
Summary

- LETA analysis improved precision of SNO Neutral Current measurement by > factor 2

- LOWEST analysis threshold yet achieved using a water Cherenkov detector
- Low energy spectrum is consistent with NO distortion

- 3-Flavour analysis shows non-zero $\theta_{13}$ but consistent with $\theta_{13} = 0$

$$\sin^2 \theta_{13} = 2.00^{+2.09}_{-1.63} \times 10^{-2} \quad \sin^2 \theta_{13} < 0.057 \ (95\% \ C.L.)$$

- Expect further improvement with forthcoming 3 phase analysis

- Low multiplicity burst search paper expected soon

- Other “technical” papers expected soon - Spallation products, surface radioactivity measurements etc