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LIP, LISBON, PORTUGAL
ON BEHALF OF THE SNO COLLABORATION
XVII INTERNATIONAL WORKSHOP ON NEUTRINO TELESCOPES
VENEZIA, MARCH 13, 2017
August 2008 meeting @ SNOLAB
dedicated to

Fraser Duncan, Davis Earle, Cliff Hargrove, John Simpson
SOLAR NEUTRINOS
Nuclear fusion reactions recognized early on as the only viable source of stellar energy production

Hans Bethe (1930’s): first solar model based on nuclear reactions

John Bahcall: increasingly detailed solar model calculations of the solar neutrino fluxes, since the 60’s

Ray Davis@Homestake: pioneering radiochemical measurements of solar neutrino captures on chlorine.
Measured flux consistently 1/3 of Bahcall’s predictions
SOLAR NEUTRINO SPECTRUM

BPS(GS98) 2008
Neutrino Spectrum (±1σ)

Flux (cm⁻² s⁻¹)

Neutrino Energy in MeV

Gallium, Borexino, Chlorine, SuperK, SNO

PP, ⁷Be, pep, ⁸B, CNO, hep

±0.5%, ±5.8%, ±15.5%, ±11.3%, ±1.1%
Gribov and Pontecorvo suggested (1968) flavor change from electron to muon neutrinos.
EARLY DAYS OF SNO

- **Herb Chen**: neutral current reaction on deuterium can measure the total flux in all flavors, regardless of oscillations
- **George Ewan** brings the Canadian side: availability of large quantities of heavy water, and deep mines
- **Art McDonald**: SNO director since 1990, for the construction, operation, and data analysis phases
  - 2015 Nobel Prize in Physics
1986 SNO MEETING

Spokespersons

1985
Sinclair: UK

1984
Chen: US

1984
Ewan: Canada

McDonald
1987: US
1989: Director

SNO Collaboration Meeting, Chalk River, 1986

PROPOSAL TO BUILD A NEUTRINO OBSERVATORY IN SUDBURY, CANADA

[ref. 2]
Experimental Aspects
Construction and Observatory
Sudbury Neutrino
THE SUDBURY NEUTRINO OBSERVATORY (SNO)

- **D$_2$O (heavy water):** 1000 ton
- **PMT Support structure:** 9500 PMTs
- **Acrylic Sphere:** 12 m diameter
- **Internal H$_2$O layer:** 1700 ton
- **External H$_2$O layer:** 5300 ton
- **Urylon liner:** Radon seal

[ref. 3]
SNO was built in the active Creighton mine (INCO, now VALE), close to Sudbury, Ontario.

The experimental cavities were dug on purpose for SNO, at 6800 ft (2 km) depth.
CONSTRUCTION OF SNO
ACRYLIC VESSEL (AV)

Made of 5 cm thick pre-curved tiles. Bonding the joints in-situ was a big challenge.
PMTS
REATIONS ON DEUTERIUM

Charged Current reaction
W boson exchange
Only electron neutrinos
Detect electron in final state

Neutral Current reaction
Z boson exchange
All neutrino flavors
Detect neutron in final state

also: \( \nu_x + e^- \rightarrow \nu_x + e^- \)

Elastic Scattering reaction
Directional, lower statistics
Less sensitive to \( \nu_\mu, \nu_\tau \)
THE 3 PHASES OF SNO

Phase I (D$_2$O)
Nov. 99 - May 2001

Phase II (salt)
July 2001 - Sept. 2003

Phase III (NCD)
Nov. 2004 - Dec. 2006

neutrons captured by deuterons
E(\gamma) = 6.25 MeV

neutrons captured by chlorine
\Sigma(E(\gamma)) = 8.6 MeV

neutrons captured by $^3$He
array of 40 proportional counters

n + $^3$He \rightarrow p + $^3$H
hit PMTs:
• position
• time
• charge

From these we calculate:
• event position
• direction
• energy
• isotropy

SNO used extensive calibrations to tune response models and determine systematics.
Deploy optical and radioactive sources in many positions inside and outside the AV Glove box on top of AV neck.

Also: radioactivity spikes uniformly distributed in the heavy water: $^{222}\text{Rn}, ^{24}\text{Na}$.
6.13 MeV $\gamma$ tagged source

- Energy estimator using number of prompt hits
- Later using all PMT hits, including late times
- Number of detected PMT hits varies with event position by up to 8% due to PMT angular response, attenuation in heavy and light water, and acrylic
- Need to measure the optical properties in-situ -> optical calibration

Other sources used to validate higher energies

- $6.13 \text{ MeV } N16$ source in the center
- $19.8 \text{ MeV } pT$
- $6.13 \text{ MeV } N16$ source in the center
- $19.8 \text{ MeV } pT$

$6.13 \text{ MeV } N16$ source in the center

$19.8 \text{ MeV } pT$

$6.13 \text{ MeV } N16$ source in the center

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$6.13 \text{ MeV } N16$ source in the center

$19.8 \text{ MeV } pT$

$6.13 \text{ MeV } N16$ source in the center

$19.8 \text{ MeV } pT$
OPTICAL CALIBRATION

- PMT + reflector response versus incidence angle
- Reflectivity degraded over time

In salt phase, a drift in energy response was identified as caused by increasing attenuation of heavy water

After all corrections, energy scale systematics were < 0.6%
NEUTRON CALIBRATION

- AmBe and $^{252}$Cf point sources
- Adding salt improved capture and detection efficiencies

[ref. 14]
\[ \beta_l \approx \left\langle P_l \left( \cos \theta_{ij} \right) \right\rangle_{i \neq j} \]

\( P_l = l_{th} \) order Legendre polynomial

best separation found with \( \beta_{14} = \beta_1 + 4\beta_4 \)

\(<\theta_{ij}> \) average over all PMT pairs

single gamma

electrons

multiple gammas

[ref. 14]
Heavy and light water regularly purified and assayed.
Well below target levels.

[refs. 9-10, 17]
NEUTRAL CURRENT Detectors

- Array of $^3$He-filled proportional counters deployed in the AV
  
  $n + ^3He \rightarrow p + ^3H$

- Neutron capture efficiency: 21.5%

- Pulse-shape allows background discrimination

  - neutron pulses, obtained from calibrations
  
  - alpha pulses, obtained from $^4$He-filled counters

[refs. 11, 17, 18]
SUDBURY NEUTRINO OBSERVATORY
SOLAR NEUTRINO RESULTS
SNO DATA-TAKING

<table>
<thead>
<tr>
<th>Phase</th>
<th>Start date</th>
<th>End date</th>
<th>Total time [days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>November 1999</td>
<td>May 2001</td>
<td>119.9 157.4</td>
</tr>
<tr>
<td>II</td>
<td>July 2001</td>
<td>August 2003</td>
<td>176.5 214.9</td>
</tr>
<tr>
<td>III</td>
<td>November 2004</td>
<td>November 2006</td>
<td>176.6 208.6</td>
</tr>
</tbody>
</table>

Large fraction of data-taking used in calibrations

Signal-loss from cuts, phase I

CC: $(1.43^{+0.39}_{-0.21})\%$,  
ES: $(1.46^{+0.40}_{-0.21})\%$,  
neutrons: $(2.28^{+0.41}_{-0.23})\%$.  

[ref. 15]
SIGNAL EXTRACTION

- Fit distributions of direction, position, isotropy
- Measure number of events and energy spectrum of CC, NC, ES
- (Energy fixed in phase I result)
RESULTS, D20 AND SALT

simulated in 1987

measured 1999-2003

NaCl

[refs. 12,13]
RESULTS, PHASE III

Results of all 3 phases compatible

[ref. 17, 18]
SOLAR NEUTRINO PROBLEM, SOLVED!

1) $\nu_e$ is 1/3 of all $\nu$: neutrinos change flavour!
2) measurement in all flavours confirms solar model

[ref. 14]
SNO SOLAR NEUTRINO RESULTS
AIMING FOR PRECISION
COMBINING PHASES

• Instead of measuring CC, NC, ES $\nu_e$-equivalent fluxes independently for each phase, fit data of all 3 phases with less free parameters: flux of $^8$B solar neutrinos, and parametrization of oscillation survival probability

• Need to consider different responses to signals across different phases, and correlated systematics

• Example: NC isotropy and energy in phase I and II

[ref. 16]
LOWERING THE THRESHOLD

• Improved energy resolution and background description, pushed threshold down to 3.5 MeV
• Search for LMA survival probability upturn; allows much better NC detection efficiency

\[ \Phi_{\text{NC}}^{\text{binned}} = 5.140^{+0.160}_{-0.158} \text{(stat)} +^{0.132}_{-0.117} \text{(syst)} \times 10^6 \text{ cm}^{-2} \text{s}^{-1} \]

\[ \Phi_{\text{NC}}^{\text{kernel}} = 5.171^{+0.159}_{-0.158} \text{(stat)} +^{0.132}_{-0.114} \text{(syst)} \times 10^6 \text{ cm}^{-2} \text{s}^{-1} \]
COMBINATION ALL PHASES

SNO measurement
5.25 ± 0.16^{+0.011}_{-0.013}

4% total uncertainty

Consistent with LMA (including MSW effect)

[ref. 18]
• SNO results crucial to good precision on $\theta_{12}$
• Complementary with KamLAND’s $\Delta m_{12}^2$ sensitivity
• Tension led to early hints of non-zero $\theta_{13}$, SBL experiments (Daya Bay, Reno, Double-Chooz, and also T2K, Minos) then measured it

[ref. 18]

And 14 who have passed away: Herbert Chen, John C. Barton, John Cowan, Andre Hamer, Clifford Hargrove, Barry C. Knox, Jan Wouters, Peter Trent, Robert Storey, Keith Rowley, Neil Tanner, John Simpson, Davis Earle and Fraser Duncan
ONWARD TO SNO+

- replace heavy water with 780 tons of liquid scintillator (LAB+PPO)
- load it with 3900 kg of nat. Tellurium, but there is the potential to 6x higher loadings
- search for $^{130}$Te neutrinoless double beta decay

$$T_{1/2} \geq 1.96 \times 10^{26} \text{yr (90\% CL, 5 yr)}$$

- good self-shielding of externals
- purification on-site of LAB and Te
- variable loadings
- Tellurium: high isotopic abundance and 2ν mode half-life
STATUS OF SNO+

- Filled with water
- Water phase about to start, to measure backgrounds and calibrate
  - a few interesting events already
- Scintillator fill late 2017
- Tellurium loading 2018
**SUMMARY**

- SNO designed to solve the Solar Neutrino Problem
- Challenges on detector construction, keeping cleanliness, nailing systematics down with calibrations
- Groundbreaking results showing Solar Models were correct and that neutrinos do change flavor
- Precision contributing to global oscillations analysis
- Field wide open for new experiments
  - CP violation
  - Dirac or Majorana neutrinos?
  - Absolute neutrino mass and ordering
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REFERENCES

