Neutrino Physics in Sudbury

Jeanne Wilson

QMUL, 12th March 2010
• Why Sudbury?
• The Sudbury Neutrino Observatory
  – Motivation
  – Physics Goals
  – Detector design
  – Challenges
  – Most recent result – low energy threshold analysis (LETA)
• From SNO to SNO+
  – New physics goals
  – New challenges
  – UK work
  – Current status
Solar Neutrino Problem
Solar Neutrinos

Bahcall–Serenelli 2005

Neutrino Spectrum ($\pm 1\sigma$)

Flux ($\text{cm}^{-2} \text{s}^{-1}$)

- $^{13}\text{N} \rightarrow$ $^{15}\text{O} \rightarrow$ $^{17}\text{F} \rightarrow$ $^{7}\text{Be} \rightarrow$ $^{8}\text{B} \rightarrow$

- $\text{pp} \rightarrow$ $\pm 1\%$
- $^{7}\text{Be} \rightarrow$ $\pm 10.5\%$
- $\text{pep} \rightarrow$ $\pm 2\%$
- $\text{hep} \rightarrow$ $\pm 16\%$

Water Cherenkov

Chlorine

Gallium
The Answer: Heavy Water

1. Elastic Scattering
Primarily sensitive to $\nu_e$
Measures $\nu$ direction

2. Charged Current
Sensitive only to $\nu_e$
Measures $\nu$ energy

3. Neutral Current
Sensitive to all flavours
Measures total $^8$B $\nu$ flux
The Sudbury Neutrino Observatory

3 phases:
1. Pure $D_2O$
2. $D_2O + NaCl$
3. $D_2O + ^3He$
proportional counters

- 1000 tonnes $D_2O$
- Support structure for 9500 PMTS
  54% coverage
- 12 m diameter acrylic vessel
- 7000 tonnes $H_2O$ shielding
Solar Neutrino Program

- Super-Kamiokande
- Cl-Ar
- SAGE & GNO
- Borexino
- D$_2$O
- D$_2$O Return
- Data Analysis
- Salt
- ³He

Projects:
- KamLAND
- KamLAND Solar
What We Measure

**PMT Measurements**
- position
- charge
- time

**Reconstructed Event**
- event vertex
- event direction
- energy
- isotropy
### Phase 1: D$_2$O

<table>
<thead>
<tr>
<th></th>
<th>CC</th>
<th>ES</th>
<th>NC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
<td><img src="image3" alt="Graph" /></td>
</tr>
<tr>
<td></td>
<td><img src="image4" alt="Graph" /></td>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
</tr>
<tr>
<td></td>
<td><img src="image7" alt="Graph" /></td>
<td><img src="image8" alt="Graph" /></td>
<td><img src="image9" alt="Graph" /></td>
</tr>
<tr>
<td></td>
<td><img src="image10" alt="Graph" /></td>
<td><img src="image11" alt="Graph" /></td>
<td><img src="image12" alt="Graph" /></td>
</tr>
<tr>
<td></td>
<td><img src="image13" alt="Graph" /></td>
<td><img src="image14" alt="Graph" /></td>
<td><img src="image15" alt="Graph" /></td>
</tr>
<tr>
<td></td>
<td><img src="image16" alt="Graph" /></td>
<td><img src="image17" alt="Graph" /></td>
<td><img src="image18" alt="Graph" /></td>
</tr>
<tr>
<td>Energy</td>
<td>$T_{\text{eff}}$</td>
<td>Isotropy</td>
<td>Position</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\beta_{14}$</td>
<td>$R^3 = R_{\text{fit}}^3/R_{\text{AV}}^3$</td>
</tr>
</tbody>
</table>
Phase 2: Salt

CC

ES

NC

Energy $T_{\text{eff}}$

Isotropy $\beta_{14}$

Position $R^3 = \frac{R_{\text{fit}}^3}{R_{\text{AV}}^3}$

Direction $\cos(\theta_\omega)$
Phase 3: NCDs
Challenges: Radioactive Backgrounds

Cosmic rays < 3/hour
Achievements: Radioactive Backgrounds

Cosmic rays < 3/hour

Contamination:

\[ D_2O \text{ U/Th} < 10^{-14} \text{ g/g} \]
\[ H_2O \text{ U/Th} < 5 \times 10^{-13} \text{ g/g} \]
Solar Flux results

![Graph showing the ratio of solar flux results to SSM prediction (BP04) against energy in 10^10 (MeV)].

- SNO Phase I (D_2O)
- SNO Phase II (D_2O+NaCl)
- SNO Phase III (D_2O+^3He)
3.5 MeV Analysis Threshold

arXiv:0910.2984 [nucl-ex]
Analysis Improvements:

1. Lower threshold to 3.5 MeV
2. Combine 2 phases in a joint-phase fit
3. Reduce backgrounds
4. Improve MC simulation
5. Reduce systematic uncertainties
6. Create PMT $\beta$-$\gamma$ PDF directly from data
7. Improved Signal Extraction approach
8. Improved oscillation analysis
$^8$B Flux Result

Flux (10$^6$ cm$^{-2}$ s$^{-1}$)

- Previous SNO results + total uncertainty
- Systematic uncertainties

Previous Phase I  Previous Phase II  Previous Phase III  LETA I  LETA II
$^8$B Flux Result

![Graph showing flux results for different phases and uncertainties.](image)

- Previous SNO results + total uncertainty
- Systematic uncertainties
- LETA results + total uncertainty
- LETA systematic uncertainties
Fit Result

$\chi^2 = 13.6 / 16$
CC Recoil-Electron Spectrum
CC Recoil-Electron Spectrum

Flat: $\chi^2 = 21.52 / 15$ d.o.f.
CC Recoil-Electron Spectrum

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

Previous global best-fit LMA point:
$\tan^2 \theta_{12} = 0.468,$
$\Delta m^2 = 7.59 \times 10^{-5}$ eV$^2$
...To SNO+
SNO+ Liquid scintillator

- Cheap
- Safe
- Compatible with SNO acrylic
- + PPO fluor
- Good light yield: ~400 PMT hits / MeV
Physics goals

- Pep solar neutrinos
- Neutrino-less double beta decay of $^{150}\text{Nd}$
- Reactor neutrinos
- Geo-neutrinos
- Supernovae neutrinos
Physics goals

• Pep solar neutrinos
• Neutrino-less double beta decay of $^{150}\text{Nd}$
• Reactor neutrinos
• Geo-neutrinos
• Supernovae neutrinos
Low Energy Solar Neutrinos

- complete our understanding of neutrinos from the Sun
- pep, CNO, $^7$Be, pp

**p-p Solar Fusion Chain**

\[ p + p \rightarrow ^2\text{H} + e^+ + \nu_e \]

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

\[ ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2\ p \]

\[ ^3\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu_e \]

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

\[ ^7\text{Be} + e^- \rightarrow ^7\text{Li} + \gamma + \nu_e \]

\[ ^7\text{Li} + p \rightarrow \alpha + \alpha \]

\[ ^8\text{B} \rightarrow 2\ \alpha + e^+ + \nu_e \]

**CNO Cycle**

\[ ^{12}\text{C} + p \rightarrow ^{13}\text{N} + \gamma \]

\[ ^{13}\text{C} + p \rightarrow ^{14}\text{N} + \gamma \]

\[ ^{14}\text{N} + p \rightarrow ^{15}\text{O} + \gamma \]

\[ ^{15}\text{O} \rightarrow ^{15}\text{N} + e^+ + \nu_e \]

\[ ^{15}\text{N} + p \rightarrow ^{12}\text{C} + \alpha \]
Why *pep* Solar Neutrinos?

SSM *pep* flux:
- uncertainty ±1.5%
- known source
- known cross section (ν-e scattering)
- measuring the rate gives the survival probability
- precision test

for neutrino physics with low energy solar neutrinos, have to achieve precision similar to SNO or better...it’s no longer sufficient to just detect the neutrinos

*pep* solar neutrinos:
- $E_\nu = 1.44 \text{ MeV}$
- ...are at the right energy to search for new physics

observing the rise confirms MSW and our understanding of solar neutrinos
Why *pep* Solar Neutrinos?

SSM pep flux:

uncertainty ±1.5%

known source

known cross section (ν-e scattering)

→ measuring the rate gives the survival probability

→ precision test

for neutrino physics with low energy solar neutrinos, have to achieve precision similar to SNO or better...it’s no longer sufficient to just detect the neutrinos

pep solar neutrinos:

$E_\nu = 1.44$ MeV

...are at the right energy to search for new physics

$\Delta m^2 = 8.0 \times 10^{-5}$ eV$^2$

$\tan^2\theta = 0.45$

observing the rise confirms MSW and our understanding of solar neutrinos
Why *pep* Solar Neutrinos?

**SSM pep flux:**
- uncertainty ±1.5%
- known source
- known cross section (ν-e scattering)
- measuring the rate gives the survival probability
- precision test

For neutrino physics with low energy solar neutrinos, have to achieve precision similar to SNO or better...it’s no longer sufficient to just detect the neutrinos

**pep solar neutrinos:**
- \( E_\nu = 1.44 \text{ MeV} \)
- ...are at the right energy to search for new physics

\[ \Delta m^2 = 8.0 \times 10^{-5} \text{ eV}^2 \]
\[ \tan^2 \theta = 0.45 \]

**observing the rise confirms MSW and our understanding of solar neutrinos**
Mass-Varying Neutrinos

- cosmological connection: mass scale of neutrinos and the mass scale of dark energy are similar
- postulating a scalar field and neutrino coupling results in neutrinos whose mass varies with the background field (e.g. of other neutrinos)

- solar neutrinos affected?
- $\text{pep } \nu$: a sensitive probe


Barger, Huber, Marfatia, hep-ph/0502196
**pep ν and θ_{13}**

- Solar neutrinos are complementary to long baseline and reactor experiments for θ_{13}
- Hypothetical 5% stat. 3% syst. 1.5% SSM measurement
- Has discriminating power for θ_{13}
Why don’t others measure pep?

- SNO+ at 6000mwe
- Muon flux factor 800 less than KamLAND (factor 100 less than Borexino)
SNO+ *pep* Solar Neutrino Signal

3600 *pep* events/(kton·year), for electron recoils >0.8 MeV
Physics goals

• Pep solar neutrinos
• Neutrino-less double beta decay of $^{150}\text{Nd}$
• Reactor neutrinos
• Geo-neutrinos
• Supernovae neutrinos
Double Beta Decay ($2\nu\beta\beta$)

$\mathbf{n} \rightarrow \mathbf{p} + \mathbf{p} + 2\,\mathbf{e}^- + 2\mathbf{\nu}_e$

Only 35 isotopes known in nature
Neutrinoless mode ($0\nu\beta\beta$)

- Can only occur for Majorana neutrinos
- Rate proportional to absolute neutrino mass scale

$$\Delta L = 2$$

$$(A,Z) \rightarrow (A,Z+2) + 2\ e^-$$
**ββ Decay**

- **Two Neutrino Spectrum**
- **Zero Neutrino Spectrum**

1% resolution

\[ \Gamma(2\,\nu) = 100 \times \Gamma(0\,\nu) \]

**Endpoint Energy**
SNO+ Double Beta Decay

- $^{150}\text{Nd}$
  - $Q = 3.37\text{MeV}$
  - large phase space, fast rate
  - 5.6% natural abundance, enrichment possible

- Large, homogeneous liquid detector leads to well-defined background model
- Source in–source out capability
- Poor energy resolution but high statistics
0νββ in SNO+
SNO+ sensitivity
Future sensitivity

• Nd enrichment is difficult
  – AVLIS – French facility not available 😞

• Different isotopes
  – $^{96}$Zr, $^{100}$Mo

• Nanoparticles
  – Different absorption characteristics – higher loading
150Nd 2νββ, 148Nd ββ

Excited states

144Nd, 145Nd α

Lanthanides and rare Earth
176Lu, 152Gd
147Sm 148Sm

Acrylic vessel – 214Bi, 208Tl, (α,n)

H2O and PMT backgrounds

Ropes and calibration system

Nd

Scintillator

Solar neutrinos

40K, 39Ar, 85Kr...

U and Th chains

Instrumental backgrounds
# Pure source of Nd

<table>
<thead>
<tr>
<th>Source</th>
<th>Sample mass (g)</th>
<th>Name of supplier</th>
<th>Stated purity (%)</th>
<th>Date counted</th>
<th>138(^{\text{La}}) ((\mu\text{g La/g Nd}))</th>
<th>176(^{\text{Lu}}) ((\mu\text{g Lu/g Nd}))</th>
<th>40(^{\text{K}}) ((\mu\text{g K/g Nd}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd(_2)O(_3)</td>
<td>1811.3</td>
<td>Hefa</td>
<td>(~\sim 99)</td>
<td>080225</td>
<td>513 ± 32</td>
<td>3.4 ± 0.3</td>
<td>6.3 ± 1.1</td>
</tr>
<tr>
<td>Nd(_2)O(_3)</td>
<td>1794.7</td>
<td>Alfa</td>
<td>99.9</td>
<td>080319</td>
<td>21 ± 3</td>
<td>8.5 ± 1.4</td>
<td>14.0 ± 1.2</td>
</tr>
<tr>
<td>Nd(_2)O(_3)</td>
<td>24.80</td>
<td>Stanford</td>
<td>(&gt; 99.95)</td>
<td>080930</td>
<td>0 ± 19</td>
<td>0 ± 23</td>
<td>25 ± 6</td>
</tr>
<tr>
<td>Nd(_2)O(_3)</td>
<td>24.13</td>
<td>Stanford</td>
<td>(&gt; 99.95)</td>
<td>080827</td>
<td>0 ± 25</td>
<td>0 ± 460</td>
<td>18 ± 6</td>
</tr>
<tr>
<td>Nd(_2)O(_3)</td>
<td>65.53</td>
<td>Stanford</td>
<td>Not given</td>
<td>080927</td>
<td>175 ± 42</td>
<td>0 ± 1700</td>
<td>12 ± 5</td>
</tr>
<tr>
<td>Nd(_2)O(_3)</td>
<td>73.90</td>
<td>Stanford</td>
<td>Not given</td>
<td>080926</td>
<td>240 ± 40</td>
<td>0 ± 1500</td>
<td>4.5 ± 3.0</td>
</tr>
<tr>
<td>Nd(_2)O(_3)</td>
<td>359.2</td>
<td>Nanoproduets</td>
<td>99.9</td>
<td>091015</td>
<td>61 ± 14</td>
<td>0.07 ± 0.08</td>
<td>9.5 ± 2.4</td>
</tr>
<tr>
<td>Nd(_2)O(_3)</td>
<td>997.8</td>
<td>Metall</td>
<td>99.999</td>
<td>091117</td>
<td>&lt; 0.24</td>
<td>0.15 ± 0.01</td>
<td>0.39 ± 0.22</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>Sample mass (g)</th>
<th>Name of supplier</th>
<th>Stated purity (%)</th>
<th>Date counted</th>
<th>227(^{\text{Ac}}) ((\mu\text{Bq/g Nd}))</th>
<th>214(^{\text{Bi}}) ((\mu\text{Bq/g Nd}))</th>
<th>212(^{\text{Bi}}) ((\mu\text{Bq/g Nd}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd(_2)O(_3)</td>
<td>1811.3</td>
<td>Hefa</td>
<td>(~\sim 99)</td>
<td>080225</td>
<td>193 ± 20</td>
<td>19.7 ± 3.9</td>
<td>189 ± 10</td>
</tr>
<tr>
<td>Nd(_2)O(_3)</td>
<td>1794.7</td>
<td>Alfa</td>
<td>99.9</td>
<td>080319</td>
<td>873 ± 47</td>
<td>17.0 ± 1.9</td>
<td>75 ± 5</td>
</tr>
<tr>
<td>Nd(_2)O(_3)</td>
<td>24.80</td>
<td>Stanford</td>
<td>(&gt; 99.95)</td>
<td>080930</td>
<td>1900 ± 100</td>
<td>0 ± 23</td>
<td>330 ± 60</td>
</tr>
<tr>
<td>Nd(_2)O(_3)</td>
<td>24.13</td>
<td>Stanford</td>
<td>(&gt; 99.95)</td>
<td>080827</td>
<td>2300 ± 100</td>
<td>9 ± 30</td>
<td>210 ± 50</td>
</tr>
<tr>
<td>Nd(_2)O(_3)</td>
<td>65.53</td>
<td>Stanford</td>
<td>Not given</td>
<td>080922</td>
<td>41000 ± 2500</td>
<td>250 ± 50</td>
<td>200 ± 50</td>
</tr>
<tr>
<td>Nd(_2)O(_3)</td>
<td>73.90</td>
<td>Stanford</td>
<td>Not given</td>
<td>080926</td>
<td>41000 ± 2500</td>
<td>40 ± 30</td>
<td>125 ± 40</td>
</tr>
<tr>
<td>Nd(_2)O(_3)</td>
<td>359.2</td>
<td>Nanoproduets</td>
<td>99.9</td>
<td>091015</td>
<td>120 ± 20</td>
<td>195 ± 16</td>
<td>570 ± 30</td>
</tr>
<tr>
<td>Nd(_2)O(_3)</td>
<td>997.8</td>
<td>Metall</td>
<td>99.999</td>
<td>091117</td>
<td>&lt; 1.2</td>
<td>0.43 ± 0.56</td>
<td>3.4 ± 0.9</td>
</tr>
</tbody>
</table>

Tolerable: 0.5, 0.1, \(~0.08\)
Removing the U/Th

- NdCl₃ salt + BaCl + (NH₄)₂SO₄
  - co-precipitate any Ra with BaSO₄
- + HZrO
  - co-precipitate Th
  - reduction factor of 1000/pass
  - 2 passes gives 10⁶ reduction and desired scintillator level of 10⁻¹⁷gTh/gLAB.
Or ... Self scavenging

- Th is more soluble than Nd at certain pH levels
- Dissolve salt in ultra-pure water at controlled pH
- Adjust pH – Th is removed (95 - 100%), Nd remains
- Can incorporate in existing Nd-LS production scheme
Alpha discrimination

- Alphas highly quenched – factor ~10
- More late light due to different excitation mode of scintillator by heavier particles
Pile-up rejection

- Low energy backgrounds in coincidence with $2\nu\beta\beta$ could move event into $0\nu\beta\beta$ window
- Rejection criteria
  - Timing
  - Hit isotropy
  - Goodness of fit – single vs multiple vertex fitter
Calibration - ELLIE

- **Embedded LED Light Injection Entity**
  - Timing calibration of PMTs
  - PMT response
  - Attenuation length
  - DAQ test (Supernova response)
  - Test for coincidence signals
- 91 light injection points on PMT support structure
- ~500nm, fast pulses, ~12 degree opening angle
Calibration - SMELLIE

• **Scattering Module of ELLIE**
  – 6 beams of ~6 degree opening angle
  – Sample different path lengths and detector regions
  – Range of wavelengths (350nm – 550nm)

• Feedback to assess light level
  – Attenuation measurement
Calibration – SMELLIE
**Timescale**

- **Jan 2010**
  - Repair cavity liner
  - Electronics repairs and upgrades
  - Cavity work
  - Sanding the AV (water fill)

- **Jan 2011**
  - Install Rope hold-down
  - Install ELLIE fibres
  - Drain & clean
  - Water fill

- **Jan 2012**
  - Start data taking, Pure scintillator
  - Water fill
  - Scintillator fill
Summary

• Sudbury is a great venue for low background physics
• SNO hugely successful, still publishing results
• SNOLAB major new underground facility
• SNO+ aims to make a timely double beta decay search and precision solar neutrino measurements + lots of other physics/astrophysics