The SNO+ Experiment

Jeanne Wilson, QMUL

Neutrino networks, 29/09/10
Contents

• Quick experimental description

• Physics potential
  • Solar measurements
    – neutrino oscillation parameter improvements
    – new physics?
    – Solar model information
  • Double beta
  • Reactor neutrinos
  • Geoneutrinos
  • Supernovae
  • Nucleon decay
Current UK SNO+ Involvement

**Oxford University:**
Steve Biller, Nick Jelley, Armin Reichold, Phil Jones, Ian Coulter  
(UK Spokesperson & chair of Reconstruction group)

**Sussex University:**
Elisabeth Falk, Jeff Hartnell, Simon Peeters, Gwenaelle Lefeuvre, Shak Fernandes, James Sinclair  
(Head SNO+ Calibration Group)

**Leeds University:**
Stella Bradbury, Joachim Rose

**Queen Mary University of London:**
Jeanne Wilson  
(SNO+ Analysis Coordinator)

**Liverpool University**
Neil McCauley  
(Data Flow CoConvener)

10 academics
Creighton Mine

World’s Deepest Continuous Shaft
Flat Overburden

INCO - Creighton Mine

[Diagram showing depth, feet of standard rock, and muon intensity in meters squared per year, with points for WIPP, Soudan, Kamioka, Boulby, Gran Sasso, Homestake CI-Ar, Baksan, Frejus, Sudbury, and the Deep Underground Laboratory.]
This was SNO...

- Acrylic vessel (AV) 12 m diameter
- 1000 tonnes D2O ($300 million)
- 1700 tonnes H2O inner shielding
- 5300 tonnes H2O outer shielding
- ~9500 PMT's
This is SNO+

- Acrylic vessel (AV) 12 m diameter
- ~780 tonnes of LS
- 1700 tonnes H2O inner shielding
- 5300 tonnes H2O outer shielding
- ~9500 PMT’s

~50kg $^{150}$Nd
Hardware improvements

• Install hold-down ropes
• Upgraded electronics
• Repaired PMTs
• New glove box and radon sealed interface
• New calibration hardware
• Clean + survey acrylic vessel
Physics goals

- Low energy solar neutrinos
- Neutrino-less double beta decay of $^{150}$Nd
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- Supernovae neutrinos
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Low Energy Solar Neutrinos

- complete our understanding of neutrinos from the Sun

$^8\text{B}$ pep, CNO, $^7\text{Be}$, pp, hep

**p-p Solar Fusion Chain**

- $p + p \rightarrow ^2\text{H} + e^+ + \nu_e$
- $p + e^- + p \rightarrow ^2\text{H} + \nu_e$
- $^2\text{H} + p \rightarrow ^3\text{He} + \gamma$
- $^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p$
- $^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma$
- $^7\text{Be} + e^- \rightarrow ^7\text{Li} + \gamma + \nu_e$
- $^7\text{Li} + p \rightarrow \alpha + \alpha$
- $^8\text{B} \rightarrow 2\alpha + e^+ + \nu_e$

**CNO Cycle**

- $^{12}\text{C} + p \rightarrow ^{13}\text{N} + \gamma^{13}\text{N} \rightarrow ^{13}\text{C} + e^+ + \nu_e$
- $^{13}\text{C} + p \rightarrow ^{14}\text{N} + \gamma$
- $^{14}\text{N} + p \rightarrow ^{15}\text{O} + \gamma$
- $^{15}\text{O} \rightarrow ^{15}\text{N} + e^+ + \nu_e$
- $^{15}\text{N} + p \rightarrow ^{12}\text{C} + \alpha$
- $^{17}\text{F} \rightarrow ^{17}\text{O} + e^+ + \nu_e + 2.76\text{ MeV}$
Solar Neutrinos

Gallium = pp + ⁷Be + ⁸B

Borexino – ⁷Be

SNO – ⁸B

Neutrino Spectrum (±1σ)
SNO 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$^2$
Borexino

- 300tonnes
- 2200 PMTs
- 3500mwe

arXiv:0805.3843v2
What is going on in between?

- Exploring the matter vacuum transition sensitive to new physics.
- New neutrino-matter couplings can be parameterized by new MSW term, $\varepsilon$
- Relative effect of new physics largest at resonance
- for $\Delta m^2 = 8 \times 10^{-5} \text{ eV}^2$, $\theta = 34^\circ N_e$ at the centre of the Sun $\rightarrow E$ is 1-2 MeV
pep neutrinos

• $p + e^- + p \rightarrow ^2H + \nu_e$
• $1.44\text{MeV}$
• Only $\pm 1.5\%$ theoretical uncertainty
• $\nu$-e elastic scattering cross section well known

• Fantastic!
  
  — Hold on, why didn’t Borexino measure this then??
\( ^{11}\text{C} \)

- SNO+ at 6000mwe, Borexino at 3500mwe
- Muon flux factor 100 less than Borexino (>600 less than KamLAND)
Survival Probability for Solar Neutrinos: All Experimental Data Distilled

Solar Neutrino Survival Probability

- Gallium subtracting B-8 and Be-7
- 2008 Borexino Be-7
- Chlorine subtracting B-8

blue LMA \[ \Delta m^2 = 7.59 \times 10^{-5} \text{ eV}^2 \]
\[ \tan^2 \theta = 0.457 \]

magenta Friedland et al., NSI solution

what will SNO+ measure?

SNO LETA polynomial band
SNO+ pep Solar Neutrino Signal

3600 pep events/(kton·year), for electron recoils >0.8 MeV
CNO neutrinos

Bahcall–Serenelli 2005
Neutrino Spectrum (±1σ)
CNO neutrinos

- Large theoretical uncertainties
- Never measured.
- Flux linearly dependent on core solar metallicity.
- Solar models assume initial core metallicity to be same as photosphere.
- Discrepancy between photospheric absorption lines, 3D modelling and helioseismology data casts doubt on this assumption.
- Test with CNO measurement.
SNO+ CNO and SNO $^8$B

- use the SNO $^8$B measurement to constrain “environmental variables” in the solar core which also affects CNO ν
- measure CNO flux (to ±10%) and compare with solar models to differentiate high-Z / low-Z core metallicity

which band will SNO+ measure?

SNO LETA $^8$B Result
Physics goals

• Pep solar neutrinos
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\[ \text{Two Neutrino Spectrum} \]
\[ \text{Zero Neutrino Spectrum} \]
\[ \Gamma(2\nu) = 100 \times \Gamma(0\nu) \]
SNO+ Double Beta Decay

- $^{150}\text{Nd}$
  - $Q = 3.37 \text{MeV}$
  - largest 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
Phase 1 $0\nu\beta\beta$ in SNO+

Simulations of signals and backgrounds for one year of data

Fit residuals $<m_\nu> = 0.27\text{eV}$
Natural Nd in SNO+ - sensitivity
Physics goals

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Reactor neutrinos

• characteristic coincidence signal
  • $p + \bar{\nu}_e \rightarrow n + e^+$

• Bruce, Pickering and Darlington nuclear power stations

• $L > \text{KamLAND}$

• Flux 5 times less

• Confirmation of KamLAND result in different situation
• Should be first experiment to "see" an oscillation-induced dip in a neutrino spectrum
Reactor neutrinos

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Geoneutrinos

• From $\beta$-decay of radioactive isotopes in the earth's mantle and crust, $^{40}$K and $^{238}$U and $^{232}$Th chains

  $p + \bar{\nu}_e \rightarrow n + e^+$

• Higher signal, less background than KamLAND

• KamLAND: 33 events per year (1000 tons CH$_2$) / 142 events reactor

• SNO+: 44 events per year (1000 tons CH$_2$) / 38 events reactor
Geoneutrinos

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Supernovae neutrinos

- SN @ 10kPc $\rightarrow$ $\sim$600 events in SNO+
- Scintillator sensitive to many modes
- $\nu$ and $\bar{\nu}$
- Some only $\nu_e$, some all flavours
- Different thresholds
- Some modes have distinctive gamma signatures

We will also participate in SNEWS
Physics goals

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Nucleon decay

- SNO made limit on invisible modes such as
  \[ n \rightarrow 3\nu \]

- Search for \(~6\text{MeV}\) \(\gamma\) from de-excitation of residual \(^{16}\text{O}\) nucleus after loss of \(n\) or \(p\).
- Compare \(\text{D}_2\text{O}\) and salt data

Nucleon decay

• Current bound $\tau_{\text{inv}} > 5.8 \times 10^{29}$ years (Araki et al., PRL, 96, 2006)
• Virtually no background above 6MeV in SNO+
• If no signal in 1 month expect
  \[ \tau_{\text{inv}} > 2 \times 10^{30} \text{ years} \]
• We need to take $\text{H}_2\text{O}$ data when commissioning and filling SNO+ detector anyway.
Timescale

2010
• Cavity work
• Cleaning
• PMT repairs

2011
• Install hold-down ropes
• Install purification systems
• Install new calibration hardware
• Electronics upgrades completed
• Begin water fill

2012
• Summer: Detector filled with scintillator
• Start data taking
Summary

• SNO+ experiment going ahead
• Strong UK involvement
• Rich physics programme
  – Solar neutrino oscillations
    • Oscillation parameters and MSW, new physics
  – Majorana?
  – Neutrino mass
  – Reactor neutrino oscillation confirmation
  – Supernovae probe of oscillations
  – Stellar modelling
  – Geothermal power
  – Nucleon decay
SNO+ is in SNOLAB
Allowed phase space

H-M evidence?

We Are Here

Inverted

Degenerate

Next Generation

Our Dreams

$U_{e1} = 0.866 \quad \delta m_{\text{sol}}^2 = 70 \text{ meV}^2$

$U_{e2} = 0.5 \quad \delta m_{\text{atm}}^2 = 2000 \text{ meV}^2$

$U_{e3} = 0$

$^{76}\text{Ge}$

$\sim 10^{25} \text{ yrs}$

$\sim 10^{26} \text{ yrs}$

$\sim 10^{27} \text{ yrs}$

$\sim 10^{28} \text{ yrs}$

$\sim 10^{29} \text{ yrs}$
**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
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stat + syst + SSM errors estimated

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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 $\nu$ and $\theta_{13}$

- Solar neutrinos are complementary to long baseline and reactor experiments for $\theta_{13}$
- Hypothetical 5% stat. 3% syst. 1.5% SSM measurement
- Has discriminating power for $\theta_{13}$
SNO...
...To SNO+

- Existing AV Support Ropes
- AV Hold Down Ropes
SNO+ Liquid scintillator

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

• Radioactive backgrounds from Borexino purification levels
• We hope to do better
• Plus analytical rejection:
  – $\alpha$-$\beta$ differentiation (alpha quenching)
  – Timing coincidences eg Bi-Po
shown (right) is the 90% CL lower limit on the half-life as expected sensitivity and the coloured bands show the “frequentist” interval in which the limit is expected to fall

- Modified Frequentist CLs method*