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  - Multipurpose, low background, low energy neutrino detector.

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    - Solar model information
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    - Neutrino mass
  - Reactor neutrinos
  - Geoneutrinos
  - Supernovae
  - Nucleon decay
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
Creighton Mine

World’s Deepest Continuous Shaft
Flat Overburden
SNO+ is in SNOLAB
SNO...
...To SNO+
SNO+ Liquid scintillator

- Cheap
- Safe: high flash point, low toxicity
- Compatible with SNO acrylic
- Nd-carboxylate solutions have been stable at 0.1% and 1% concentrations for over 2.5 years.
SNO+ Liquid scintillator

- + PPO fluor
- Good light yield: ~400 PMT hits / MeV
Scintillator response

“bucket” test in water-filled SNO+

Study response to αs (\(^{222}\text{Rn}\)) and βs (AmBe) of the scintillator (with and without Nd)
Scintillator response

- 450 observed photons per MeV
- Resolution of 5% at 1 MeV
- $k_B = 71.9 \pm 3.9 \mu m/MeV$
- We can observe the difference between $\alpha$s and $\beta$s

Nd-LAB at centre of SNO(+)
Scintillator response

- Beta – alpha separation,
- Alpha tags for radioactive chains
Hardware improvements

• Install hold-down ropes
• Upgraded electronics
• Repaired electronics and PMTs
• Clean + survey acrylic vessel
• New glove box and radon sealed interface
• New calibration hardware
• New fluid processing systems
Electronics upgrades & cleaning

H₂S in mine air attacks our electronics
(Filters have been installed)
Hardware improvements

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Glove box

- Air tight seal to top of neck
- Scintillator fill level in glove box
- Nitrogen atmosphere
- Store calibration sources in glovebox
Hardware improvements

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Embedded LED Light Injection Entity

Collimated fibres mounted on the PMT support structure emitting LED light for:

• Timing calibration (fast light pulses, broad bundles ~30°)
• Scattering and Absorption length monitoring (different wavelengths, collimated bundles ~1-2°)

Scattering Module of ELLIE (SMELLIE)
Hardware improvements

• Install hold-down ropes
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Purification Systems

- Several fluids to handle
  - Light water
  - Bulk scintillator
  - Fluor (PPO) solution
  - Neodymium-loaded compound

- Scintillator plant
  - Distillation
  - Water extraction
  - Gas removal
  - Filtration and ultra-filtration
  - R&d on metal scavenger columns

- Goals
  - Scintillator purity of $1 \times 10^{-17}$ g/g U/Th
    - Reached by Borexino
    - C-14, Kr-85 not a problem because of low energy, C-11 not a problem because of depth
  - Nd-compound purity of $< 1 \times 10^{-14}$ g/g U/Th
    - Need factor of $10^6$ reduction

- Status
  - designed
  - pit excavation underway
Purification Spike Tests

- spike scintillator with $^{228}$Th (80 Bq) which decays to $^{212}$Pb
- counted by $\beta$-$\alpha$ coincidence liquid scintillation counting
- Achieve factor 1000 reduction per pass
Physics goals

- Low energy solar neutrinos
- Neutrino-less double beta decay of $^{150}\text{Nd}$
- Reactor neutrinos
- Geo-neutrinos
- Supernovae neutrinos
- Nucleon decay
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Neutrino Oscillations

• Oscillations require:
  – Neutrinos have different masses: $\Delta m^2$
  – Weak eigenstates are not mass eigenstates
  – In the two flavour case the mixing is characterised by a single parameter $\theta$ analogous to the Cabbibo angle.

• This leads to vacuum oscillations governed by:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2 (1.27 \frac{\Delta m^2 L}{E})$$
The MSW Effect

- $\nu_e$ have an extra diagram for scattering from electrons (W as well as Z exchange)

\[
\begin{array}{c}
\nu_x \quad e \\
\nu_x \quad Z \\
e
\end{array} \\
\begin{array}{c}
\nu_x \quad Z \\
e
\end{array}
\begin{array}{c}
e \\
\nu_e \quad W \\
\nu_e \quad W \\
e
\end{array}
\]

- This gives $\nu_e$ an “effective mass” in matter proportional to the electron density $N_e$

When $N_e = G_f \Delta m^2 / E$ this can lead to an energy dependent resonant enhancement of oscillations for both large (LMA) and small (SMA) mixing angles.
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**

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

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

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

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

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

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

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

**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 = \( pp + ^7\text{Be} + ^8\text{B} \)

Borexino – \(^7\text{Be}\)

SNO – \(^8\text{B}\)

Neutrino Spectrum (±1σ)

Bahcall–Serenelli 2005

pp → ±1%

\(^7\text{Be} \rightarrow ±10.5\%

\(^8\text{B} \rightarrow ±16\%\)
Borexino

- 300tonnes
- 2200 PMTs
- 3500mwe

arXiv:0805.3843v2
SNO CC Recoil-Electron Spectrum

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

Previous global best-fit

LMA point:

$tan^2 \theta_{12} = 0.468,$

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

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 $\Delta m^2 = 8 \times 10^{-5}$ eV$^2$, $\theta = 34^\circ$ $N_e$ at the centre of the Sun $\rightarrow$ $E$ is 1-2 MeV.

from Friedland, Lunardini, Peña-Garay, hep-ph/0402266

Hamiltonian for neutrino propagation in the Sun
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?
- \textit{pep }\nu: \textit{a sensitive probe}

Barger, Huber, Marfatia, hep-ph/0502196

pep neutrinos

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

- Fantastic!
  - Hold on, why didn’t Borexino measure this then??
• SNO+ at 6000mwe, Borexino at 3500mwe
• Muon flux factor 100 less than Borexino (>600 less than KamLAND)
SNO+ *pep* Solar Neutrino Signal

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

Bahcall–Serenelli 2005
Neutrino Spectrum (±1σ)

Flux (cm⁻² s⁻¹)

Neutrino Energy in MeV

pp → ±1%

¹³N → ¹⁵O → ⁷Be → ±10.5%

¹⁷F → ⁷Be → ±10.5%

pep → ±2%

³B → ±16%

hep → ±16%
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 $\nu$
- measure CNO flux (to ±10%) and compare with solar models to differentiate high-Z / low-Z core metallicity
Physics goals

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Neutrino Nature

**DIRAC**
- Neutrino and antineutrino distinct
- Masses via Higgs

**MAJORANA**
- Right handed helicity state *is* antineutrino
- Masses via see-saw

\[
\begin{pmatrix}
\nu \\
\nu \\
\bar{\nu} \\
\bar{\nu}
\end{pmatrix}
\]

or

\[
\begin{pmatrix}
\nu \\
\nu \\
\nu \\
\nu
\end{pmatrix}
\]
SNO
PLUS

SEE YOU IN HELL!
Double Beta Decay (2νββ)

\[ (A,Z) \rightarrow (A,Z+2) + 2 \text{e}^- + 2\bar{\nu}_e \]

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

\[ \Delta L = 2 \]

\[(A,Z) \rightarrow (A,Z+2) + 2 \, e^-\]
$\beta\beta$ Decay

Two Neutrino Spectrum

Zero Neutrino Spectrum

1% resolution

$\Gamma(2\nu) = 100 \times \Gamma(0\nu)$

Endpoint Energy
SNO+ Double Beta Decay

- \(^{150}\text{Nd}\)
  - \(Q = 3.37\text{MeV}\)
  - 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
- ~5% energy resolution but high statistics
Carboxylate loading

- 1% loading → 56 kg of $^{150}$Nd is equal to:
  - ~220 kg of $^{136}$Xe
  - ~230 kg of $^{130}$Te
  - ~950 kg of $^{76}$Ge

- ~400 hits/MeV
Backgrounds in unenriched $^{150}$Nd

- $\text{NdCl}_3$ needs to be purified (U, Th): need $10^6$ purification
- Purification being developed at Queen’s University: successful spike tests done.

- $^{150}$Nd is a Lanthanide – hard to chemically separate.
- Found 5 grade (99.999%) source.
Nd Self Scavenging

- Tests carried out at BNL
- Nd salt dissolved in pure water, pH adjusted using ammonium hydroxide to 6.03 solution
- stirred for 60 min, followed by gravitational filtration at 20-25 μm
- filtrate was dried with infrared heat lamp; obtained purple crystalline neodymium chloride for Ge gamma counting
- Very Promising – appears to remove other lanthanides as well as U and Th
Phase 1 $0\nu\beta\beta$ in SNO+

Simulations of signals and backgrounds for one year of data

Fit residuals $<m_\nu> = 0.27$eV
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*

Natural Nd in SNO+ - sensitivity
SNO+ upgrade possibilities

1. Enriched isotope (not necessarily ${}^{150}\text{Nd}$)

   Original option of using ${}^{150}\text{Nd}$ AVLIS in France was cancelled. Alternative options are being explored.
   - Atomic Vapour Laser Isotope Separation, AVLIS
   - Ion Cyclotron Resonance, ICR
   - Gaseous diffusion
   - Ultra-centrifugation
   - Distillation
   - Crown ethers

2. Nanoparticles
   - Significant less optical absorption while dissolving more isotope
   - Raleigh scattering negligible when particle size < 5 nm

LS technique itself can of course scaled up!
Physics goals

- Pep solar neutrinos
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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

- characteristic coincidence signal
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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

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

- SN @ 10kPc \( \rightarrow \) \( \sim 600 \) events in SNO+
- Scintillator sensitive to many modes
- \( \nu \) and \( \overline{\nu} \)
- 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 D\(_2\)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 $\tau_{\text{inv}} > 2 \times 10^{30}$ years
• We need to take H$_2$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
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
(Head SNO+ Processing Group)

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

**Liverpool University**
Neil McCauley
Processing CoConvener

10 academics
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