Aims and Current status of the Experiment
Contents

★ From SNO to SNO+
★ Phase 0: Water fill
  ★ Invisible nucleon decay
★ Phase 1: Pure scintillator fill
  ★ Solar physics
★ Phase 2: Te-loaded scintillator
  ★ Neutrino-less double beta decay
    ★ Backgrounds
    ★ Calibrations
★ All phases:
  ★ Anti-neutrino physics
  ★ Supernovae
From SNO to SNO+

- Why do we only see 1/3 of the solar neutrinos we expect?
- Measure $\nu_e$ and $\nu_x$ flux on D$_2$O target to solve the “solar neutrino problem”
- Proved neutrinos oscillate between flavour states! (DOI: 10.1103/PhysRevC.88.025501)
- They must have mass....

- How massive are neutrinos?
- How do we explain their tiny masses?
  - Probe the neutrino mass and nature through Neutrinoless double beta decay.
  - Is the neutrino a Majorana particle?

- Sensitivity to low energy interactions in low background liquid scintillator
  - Other precision physics measurements
Location

Muon flux = 70 muons/day
Class-2000 clean room lab

Adapted from http://www.deepsciences.org/contents/underground_universe_popup03.shtml
The SNO detector

1000 tons of **Heavy Water**

- **12 m** diameter
- Shielded by 7 kT Ultra-pure water

- Viewed by ~**9500 PMTs (8”)**
  mounted on 17 m diam. Structure

**Contained in an Acrylic vessel (AV)**

- Loaded with NaCl
  - In phase 2

**Electronics and DAQ**

**Calibration systems**
The SNO+ detector

- New DAQ and readout cards
- New calibration systems
- New interface and cover gas system
- 780 tons of Liquid scintillator
- Contained in an Acrylic vessel (AV) 12 m diameter
- Shielded by 7 kT Ultra-pure water
- Viewed by ~9500 PMTs (8”) mounted on 17 m diam. Structure
- Loaded with double beta decay Isotope (Te130)
- Held-down by new rope system

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SNO

PMTs

D₂O
Inner AV

H₂O

H₂O

Outer AV

cavity
Filling SNO+

★ After SNO – empty

- PMTs
- Inner AV
- Outer AV
- cavity

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AV cleaning

Top – Suspended platform

Outside on top!

One last polish

Bottom – Rotating platform
New rope system

Installed before water fill

Successfully tested the hold-down rope net, by letting cavity water go above level inside AV, applying a 280,000 lb load (127 tons, the full load) to the rope net.
Phase 0 – water fill

Fill inner and outer Volumes with UPW simultaneously
★ Phase 0 – water fill

Found leaks in cavity liner 😞 Drain to find and repair leaks
Leaks 😞

★ Major effort to find and fix leaks
★ Currently at 46 foot level and filling
★ Last boating trip this week – final fibre installations
Phase 0 – water fill

Commission and calibrate with $\text{H}_2\text{O}$ filled detector. Soon!
Invisible Nucleon Decay

★ Invisible nucleon decay modes – deposit no visible energy in detector.
  eg. $N \rightarrow 3\nu$

★ See $\gamma$ from de-excitation of residual nucleus.

$\gamma$ (6-7MeV)

$^{16}\text{O} \rightarrow ^{15}\text{O}^* \rightarrow ^{15}\text{O} + \gamma$

★ Detect $\gamma$ in SNO+ water phase with good efficiency and very little background
Phase 1 – pure scintillator fill

Scintillator is less dense than water.
Fill inner AV from the top, remove H$_2$O from bottom
Scintillator of choice Linear Alkylbenzene (LAB)
• Compatible with acrylic
• High light yield
• Optical transparency
• Low scattering
• Fast decay, different for alpha/beta
• High flash point, low toxicity
• Density = 0.78 g/cm³

Properties:
• 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 in scintillator timing response. Allows for Particle ID in observed events.
Scintillator Purification Plant
Scintillator Delivery and Purification
Purification Plant - LABPPO

★ Multi-stage distillation
  ★ Remove heavy metals, improve UV transparency
★ Pre-purification of PPO concentrated solution
★ Steam/N₂ stripping under vacuum
  ★ Remove Rn, Kr, Ar, O₂
★ Water extraction
  ★ Remove Ra, K, Bi
★ Metal scavengers
  ★ Remove Bi, Pb
★ Microfiltration
  ★ Remove dust

Target levels:
- \(^{85}\)Kr: \(10^{-25}\) g/g
- \(^{40}\)K: \(10^{-18}\) g/g
- \(^{39}\)Ar: \(10^{-24}\) g/g
- U: \(10^{-17}\) g/g
- Th: \(10^{-18}\) g/g
Phase 1 – pure scintillator fill

Characterise scintillator response and backgrounds in-situ.

Circulate scintillator to purify

Solar physics?
What we measure

“event”: a light pulse seen by SNO+.

For each PMT, we measure:

- PMT charge
- PMT time

From those, we “reconstruct” the original charged particle:

- position
- energy
- type
Calibrations

★ Deployed sources:
★ Radioactive: $^{46}\text{Sc}$, $^{48}\text{Sc}$, $^{57}\text{Co}$, $^{24}\text{Na}$
★ Laserball (optics), Cerenkov source
New Calibration systems

SNO: Deployed sources

SNO+: External source
Embedded LED/Laser Light Injection Entity (ELLIE)
New calibration systems: ELLIE

Will provide continuous calibrations throughout SNO+ operation

★ Timing (T)ELLIE:
  ★ 91 injection positions
  ★ Monochromatic (~520nm) from LEDs
  ★ Light coverage of entire inward-facing detector

★ Scattering module (SM)ELLIE
  ★ 12 injection points (three at each of four locations)
  ★ Multiple wavelengths from lasers

★ Attenuation module (AM)ELLIE
  ★ Eight injection points (two at each of four locations)
  ★ Multiple wavelengths (tbc)
ELLIE Installation

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New calibration systems: (SM)ELLIE

4x fixed wavelength laser heads
(375nm 407nm, 446nm and 495nm)

One continuously tunable
‘supercontinuum’ laser with a range
from 450 – 800 nm.
Solar Neutrinos

Serenelli et al. 2011
Solar Neutrino Spectra (±1σ)
Solar Neutrino Physics

★ What can the Sun tell us about neutrinos?
★ Precision pep flux
★ Low energy $^8$B spectrum
★ Day/night asymmetry?

★ What can neutrinos tell us about the Sun?
★ CNO flux -> Resolve solar metallicity problem
★ Direct pp measurement -> Luminosity constraint

<1MeV phase averaged vacuum oscillations

>5MeV Matter dominated resonant conversion
A matter of depth

Borexino

SNO+

Analytically generated spectra with 5%/\sqrt{E} resolution

Counts per 0.1 ktons per 10 years per 5 keV

Counts per 0.4 ktons per 1.0 years per 5 keV

visible energy [MeV]

visible energy [MeV]
SNO+ solar signals

Borexino Phase 1 scintillator backgrounds
★★ Phase 2 – Te-loading

Load natural Te (34% $^{130}\text{Te}$ into the scintillator)
Phase 2 – Te-loading

Load natural Te (34% $^{130}$Te into the scintillator)
Loading the scintillator

New method has been developed for loading the scintillator!

- TeBD very transparent and soluble in LAB liquid scintillator
- Expect 400 p.e./MeV

Tellurium-butanediol complex (TeBD)+ water (evaporate after synthesis)

SNO+ phase 1 loading: 0.5% = 1333 kg of isotope
Telluric acid purification

Above ground
- Dissolve Te(OH)$_6$ in water
- Re-crystallize using nitric acid
- Rinse with ethanol

Below ground
- Dissolve in 80°C water
- Thermally re-crystallize
- 50% yield

Cosmogenic reactivation
Lozza & Petzoldt, Cosmogenic activation of a natural tellurium target, Astroparticle Physics.
DOI: 10.1016/j.astropartphys.2014.06.008
First batch in storage underground
Cosmogenic cool-down since January 2015
★ Hard to explain smallness of neutrino masses with Higgs mechanism
★ Most favoured alternative = See-saw mechanism
★ Majorana neutrinos
★ Leptogenesis
Neutrinoless Double Beta Decay

2νββ

0νββ
Neutrinoless Double Beta Decay

\[
\left( T_{1/2}^{0\nu} \right)^{-1} = G^{0\nu} \cdot \left| M^{0\nu} \right|^2 \cdot \left\langle m_{\beta\beta} \right\rangle^2
\]

Phase space  Nuclear Matrix Element

Experiment options
- Select isotopes with favourable phase space
- Select isotopes with favourable matrix elements
  - Beware large uncertainty / differences between models
- Good energy resolution
- Low Backgrounds in region of interest (ROI)
Neutrinoless Double Beta Decay

\[ (T_{1/2}^{0\nu})^{-1} = G^{0\nu} |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2 \]

\[ \langle m_{\beta\beta} \rangle^2 = |\sum_i U_{ei}^2 m_{\nu_i}|^2 \]

\(\Delta m^2_{\text{sol}}\)

Normal

Inverted

\(\Delta m^2_{\text{atm}}\)

\(\sin^2 \theta_{13}\)

\(\nu_e, |U_{ei}|^2\)

\(\nu_\mu, |U_{\mu i}|^2\)

\(\nu_\tau, |U_{\tau i}|^2\)

**Backgrounds**

**LAB-PPO**
- $^{238}\text{U}$, $^{232}\text{Th}$, $^{14}\text{C}$
- Solar $^8\text{B} \nu$

**Implanted Radon daughters in AV**
- $^{210}\text{Pb}$, $^{210}\text{Bi}$, $^{210}\text{Po}$

**Tellurium**
- $^{238}\text{U}$, $^{232}\text{Th}$, $^{210}\text{Po}$
- $2\nu\beta\beta$
- Residual cosmogenically activated isotopes:
  - $^{60}\text{Co}$, $^{131}\text{I}$

**Externals:**
- $^{214}\text{Bi}$, $^{208}\text{Ti} \gamma$ from PMTs, AV, Ropes, $\text{H}_2\text{O}$

**Thermal neutrons:**
- Capture on H to $2.2\text{MeV} \gamma$:
- Muon induced neutrons, $(\alpha,n)$

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Uranium and Thorium Chain

\[ ^{238}\text{U} \xrightarrow{4.47 \times 10^9\text{y}} \alpha 4.27 \]
\[ ^{234}\text{Th} \quad \beta^- 0.26 \quad \gamma 63, 92 \]
\[ m^{234}\text{Pa} \quad 1.18m \quad \beta^- 2.21 \]
\[ ^{231}\text{U} \quad 2.45 \times 10^5\text{y} \quad \alpha 4.86 \]
\[ ^{230}\text{Th} \quad 8.0 \times 10^4\text{y} \quad \alpha 4.77 \]
\[ ^{226}\text{Ra} \quad 1599\text{y} \quad \alpha 4.87 \]
\[ ^{226}\text{Ra} \quad 3.82d \quad \alpha 5.59 \]
\[ ^{218}\text{Po} \quad 3.05m \quad \alpha 6.11 \]
\[ ^{214}\text{Pb} \quad 26.8m \quad \beta^- 1.02 \quad \gamma 352 \]
\[ ^{214}\text{Bi} \quad 19.7m \quad 0.021\% \quad \alpha 5.62 \]
\[ ^{210}\text{Tl} \quad 1.30m \quad \beta^- 5.49 \quad \gamma 800, \sim 1\% \text{ BR to } \gamma > 2200 \]
\[ ^{210}\text{Po} \quad 22.26y \quad \beta^- 0.96 \]
\[ ^{210}\text{Bi} \quad 138d \quad \alpha 5.30 \]
\[ ^{210}\text{Pb} \quad 5.01d \quad \beta^- 1.16 \]

\[ ^{232}\text{Th} \quad 1.4 \times 10^{10}\text{y} \quad \alpha 4.08 \]
\[ ^{228}\text{Ra} \quad 5.77y \quad \beta^- 0.046 \]
\[ ^{228}\text{Ac} \quad 6.13h \quad \beta^- 2.14 \quad \gamma 339, 911, 969 \]
\[ ^{228}\text{Th} \quad 1.91y \quad \alpha 5.52 \]
\[ ^{224}\text{Ra} \quad 3.66d \quad \alpha 5.79 \]
\[ ^{220}\text{Rn} \quad 55.6s \quad \alpha 6.40 \]
\[ ^{216}\text{Po} \quad 0.15s \quad \alpha 6.91 \]
\[ ^{212}\text{Pb} \quad 10.6h \quad \beta^- 0.57 \quad \gamma 239 \]
\[ ^{212}\text{Bi} \quad 60.6m \quad 36\% \quad \alpha 6.21 \]
\[ ^{208}\text{Tl} \quad 64\% \quad \beta^- 2.25 \quad \gamma 727 \]
\[ ^{208}\text{Po} \quad 3.05m \quad \beta^- 4.99 \quad \gamma 583, 860 \]
\[ ^{208}\text{Pb} \quad 2614 \text{ (100\%)} \quad \gamma 2614 \quad 0.30\mu s \quad \alpha 8.95 \]
Bi-Po Rejection 1

Rejection criteria: $\Delta T(\beta-\alpha) < 24 \times T_{1/2}^{214\text{Po}}$

- $\text{Nhits}(\alpha) > 50$
- if($\Delta T > 500\text{ns}$), $\Delta R(\beta-\alpha) < 1.5\text{m}$

Calculated rejection efficiency ($\alpha > 400\text{ns}$ after $\beta$, $R < 3.5\text{m}$):

$\varepsilon_{214} = 99.9975\%$, $\varepsilon_{212} = 99.999\%$
BiPo Rejection 2


Same event trigger (simulation)

Likelihood difference for time residual PDFs for beta and alpha vs 0νββ

Step in cumulative time distribution
214BiPo ROI rejection $\times 49$

212BiPo ROI rejection $\times 38$

< 4 BiPo total / year in ROI

Methods sensitive to scintillator optics:
  Light yield
  Timing
Random PileUp

Reconstructed mean time

PMT hits prior to event trigger

Time anisotropy of PMT hits

Spatial anisotropy of PMT hits

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Random PileUp

Reconstructed mean time

PMT hits prior to event trigger

Expect 36.3 pileup events / year in 0νββ ROI before rejection

⇒ 0.23 events/year after cuts

Time anisotropy of PMT hits

Spatial anisotropy of PMT hits

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Backgrounds for 0nuBB search

Two neutrino mode 2νββ:
- asymmetric ROI around the 0νββ signal limited by energy resolution

14 ev/yr in FV and ROI

External gammas:
- from AV, ropes, water, PMTs
- fiducial volume (20%) cut
- requires good timing

Internal U/Th chain
- betas from $^{214}\text{BiPo}$, $^{212}\text{BiPo}$
- tagged with β-α time-correlations
- same trigger window: 50% rejection
- different trigger window: 100% rejection

8B solar neutrinos:
- flat spectrum
- constrained by SNO/SK data
- also limited by resolution

Cosmogenics:
- $^{124}\text{Sb}$, $^{60}\text{Co}$, $^{110m}\text{Ag}$, $^{88}\text{Y}$, $^{22}\text{Na}$
- reduced by purification and “cool-down” UG storage
- About 1 ev/yr in ROI/FV

Internal Th chain
ROI Energy Spectrum

Counts/5 y/20 keV bin

$T_{\text{eff}}^\beta\beta$ (MeV)

- $0\nu\beta\beta$ (200 meV)
- $2\nu\beta\beta$
- U Chain
- Th Chain
- ($\alpha$, n)
- External
- $^8$B $\nu$ ES
- Cosmogenic
Sensitivity

$T_{1/2}^{0\nu}$ (y) sensitivity vs. Live time (y)

- 0.5% loading

$10^{26}$

$10^{26}$

Number of PMTs Hit / MeV

- 5 years

% Loading

0.5% loading

5 years
0νBB Sensitivity

Best Current Limits (EXO, KLZ, Gerda, NEMO-3)

Current Target Level (SNO+ Phase 1, CUORE, EXO+, GERDA+, KLZ+, Full SuperNEMO)

Inverted Hierarchy Explorers (SNO+ Phase 2/3 (?) nEXO (?), Super-KLZ (?))

There Be Dragons.....
Biller, Physical Review D, 071301R

Current
Target
Level
(SNO+
Phase
1, CUORE,
EXO+
, GERDA+,
KLZ+, Full
SuperNEMO)

Inverted Hierarchy

Best Current Limits
(EXO, KLZ, Gerda, NEMO-3)
Comparison with other experiments

Plot by S. Biller
We don’t know which of the nuclear models (diagonal lines) is best.

Large uncertainties.

Need experiments with different isotopes!

Plot by S. Biller
What if we see a bump?

SNO+ Approach
Discovery Flow

- Measure non-Tc backgrounds before loading
  - Agree with model?
    - Yes: Add Tc and run
    - No: Continue purification
  - No: Set lifetime limit
- Excess above expected backgrounds?
  - Yes: Re-purify Tc, further running
  - No: Set lifetime limit
- Excess persists at same level?
  - Yes: Increase Tc load
  - No: Remove Tc
- Excess scales?
  - Yes: Consider alternate isotope or enrichment
  - No: Set lifetime limit
- Increase Tc load
Anti-neutrinos in SNO+

~ 100 events / year; oscillation sensitivity after 3-5 year LAB run

more bkg in low E geo-nu region
The left half shows the simulated production distribution for the geoneutrinos detectable with KamLAND, and the right half shows the Earth structure.
Sanduleak -69 202

Supernova 1987A
23 February 1987
SuperNova Detection in SNO+

★ Core-collapse supernovae: 99% of their gravitational binding energy released in the form of neutrinos (several $10^{53}$ erg)

★ 10MPc SN, interactions in 5.5m FV:

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC: $\nu + p \rightarrow \nu + p$</td>
<td>$429.1 \pm 12.0$</td>
</tr>
<tr>
<td>CC: $\bar{\nu}_e + p \rightarrow n + e^+$</td>
<td>$194.7 \pm 1.0$</td>
</tr>
<tr>
<td>CC: $\bar{\nu}<em>e + ^{12}\text{C} \rightarrow ^{12}\text{B}</em>{g.s.} + e^+$</td>
<td>$7.0 \pm 0.7$</td>
</tr>
<tr>
<td>CC: $\nu_e + ^{12}\text{C} \rightarrow ^{12}\text{N}_{g.s.} + e^-$</td>
<td>$2.7 \pm 0.3$</td>
</tr>
<tr>
<td>NC: $\nu + ^{12}\text{C} \rightarrow ^{12}\text{C}^*(15.1\text{ MeV}) + \nu'$</td>
<td>$43.8 \pm 8.7$</td>
</tr>
<tr>
<td>CC/NC: $\nu + ^{12}\text{C} \rightarrow ^{11}\text{C}$ or $^{11}\text{B} + X$</td>
<td>$2.4 \pm 0.5$</td>
</tr>
<tr>
<td>$\nu$–electron elastic scattering</td>
<td>$13.1^b$</td>
</tr>
</tbody>
</table>

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*a118.9±3.4 above a trigger threshold of 0.2 MeV visible energy.*

*bThe Standard Model cross section uncertainty is < 1%.

★ Member of SNEWS
SNO+ is a low background, low energy, liquid scintillator detector
★ Lots of work
★ Lots of challenges
★ Lots of physics
★ Phase-0, water-fill imminent

Thanks for listening!
OnuBB Sensitivity: Assumptions

- Scintillator loaded with 0.5% natTe by mass
- $M_{0^{\nu}} = 4.03$ (IBM-2) \[1\]
- $G_{0^{\nu}} = 3.69 \times 10^{-14} \text{y}^{-1}$ \[2\]
- $R < 3.5 \text{ m (FV = 20\%)}$
- $> 99.99\%$ (98\%) rejection of $^{214}\text{BiPo}$ ($^{212}\text{BiPo}$)
- Light yield 390 NHits/MeV
- Energy resolution is gaussian with width $\sigma(E) = \sqrt{(E \text{ [MeV]} / 390)}$

Pep neutrinos — test for new Physics

Non-standard interactions
(flavour changing NC)

Sterile Neutrinos

Mass varying neutrinos (MaVaNs)

Friedland, Lunardini, Peña-Garay,

Holanda & Smirnov
PRD 83 (2011) 113011

M.C. Gonzalez-Garcia, M.
Maltoni

Low energy (<1MeV):
Phase-averaged vacuum oscillations

β = \frac{2\sqrt{2} G_F N_e E_v}{\Delta m^2}

β < \cos 2\theta_{13}

1 - \frac{1}{2} \sin^2 2\theta_{12}

β > 1

\sin^2 2\theta_{12}

‘High’ energy (>5MeV):
Matter-dominated resonant conversion