The SNO+ Experiment

Lepton Photon 2021 (Jan 22)

Jeanne Wilson, on behalf of the SNO+ collaboration
These slides contain input from many people.
A Multi-purpose Liquid Scintillator Detector

Infrastructure inherited from the successful SNO experiment.
Adapted from D₂O to scintillator detecting medium to give access to low energy (~MeV) measurements.

Physics Programme
• Search for ⁰νββ in ¹³⁰Te
• Solar Neutrinos
• Reactor Anti-neutrinos
• Geo-neutrinos
• Supernova bursts
• Invisible nucleon decay
• +++

11/1/2022

Jeanne Wilson – LeptonPhoton21
The SNO+ detector

2km underground in SNOLAB, ~6000 MWE

- 780 tons of Liquid scintillator
- Contained in an Acrylic vessel (AV) 12 m diameter
- Shielded by 7 kT Ultra-pure water
- Viewed by ~9300 PMTs (8") mounted on 17 m diam. Structure
- Loaded with 0.5% double beta decay Isotope (Te130)
- Held-down by new rope system
- New DAQ and readout cards
- New calibration systems
- New interface and cover gas system
Timeline

- **2016**: Start of Commissioning Data Taking
- **Dec 2016**: Start of Commissioning Data Taking
- **May 2017**: Start of Water Phase
- **July 2019**: Start of Scintillator Fill
- **March 2021**: End of Scintillator Fill
- **Tellurium Loading**: 2023
Water Phase

2016  2017  2019  2021  2022  2023

Dec 2016
Start of
Commissioning
Data Taking

May 2017
Start of Water
Phase

July 2019
Start of
Scintillator Fill

March 2021
End of
Scintillator Fill

Tellurium
Loading

Acrylic Vessel (AV) filled with 905 tonnes of ultra-pure water (UPW)

Dataset I:  115 live days
            May 2017 -> December 2017

Dataset II: 190 live days
            October 2018 -> July 2019

H₂O
Water Phase Backgrounds

Simple detector configuration.
Measure components that don’t change with detection medium.

Box analysis performed
Fitted scale factors reduce 0νββ ROI backgrounds from 1.21 to 0.93 events / year
ie >20% below goals

<table>
<thead>
<tr>
<th>Background</th>
<th>Rate (Fraction of Nominal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AV+Ropes</td>
<td>$0.52 \pm 0.02^{+0.39}_{-0.28}$</td>
</tr>
<tr>
<td>External Water</td>
<td>$0.03 \pm 0.01^{+0.06}_{-0.03}$</td>
</tr>
<tr>
<td>PMTs</td>
<td>$2.04 \pm 0.04^{+3.69}_{-1.20}$</td>
</tr>
</tbody>
</table>
Water Phase Physics Results

Dataset I (115 days)

8B Solar neutrino flux

New limits for p, pp and pn invisible nucleon decay

~50% efficiency for triggering on a neutron in pure water

Dataset 2: (+190 days) coming soon

New solar flux and spectrum measurement, lower backgrounds → lower energy threshold

New limits, extra livetime and lower backgrounds → improved sensitivity

Measurement of reactor $\bar{\nu}$ in H$_2$O detector

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Scintillator filling

Purification and filling systems underground

LAB, Master Solution, and final scintillator assessed for quality hourly during purification plant operation and detector filling

- Observe excellent clarity above PPO absorption (UV-Vis spectroscopy)
- Light yield in excess of calibration standards

Transfer via railcar from surface to underground

SNO+ and SNOLAB scientific support

LAB + 2g/L PPO

SNO+ Preliminary

- SNO+ Scintillator [LAB + 0.62 g/L PPO]
- P-500-Q High Purity LAB
- PPO [0.62 g/L]

Density = 0.855 g/cm$^3$ at 21.6°C

N

LAB

PPO
Partial Fill Phase

Due to Covid Pandemic, paused with
- 365t (47% full) Scintillator
- 0.5g/L PPO (25% nominal)
- for approximately 7 months

Dec 2016
Start of Commissioning Data Taking

May 2017
Start of Water Phase

July 2019
Start of Scintillator Fill

March 2021
End of Scintillator Fill

Tellurium Loading
Scintillator Light Yield

Calibration sources deployed through guide tubes into external (H₂O) region

- With a PPO concentration of only 0.5 g/L (25% of the nominal value) we see a light yield equivalent to ~300 p.e. / MeV
Scintillator Backgrounds

- Measure intrinsic Uranium and Thorium chain contamination through fast time-coincidence $\beta$-$\alpha$ events
  - $^{214}\text{Bi-Po}$ (U chain) $T_{1/2} = 164\mu s$  
  - $^{212}\text{Bi-Po}$ (Th chain) $T_{1/2} = 0.30\mu s$

- Some Radon ($^{222}\text{Rn}$ half-life = 3.82 days) introduced with filling that decays away

<table>
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<tr>
<th>Decay</th>
<th>Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{214}\text{Bi}$</td>
<td>3.27</td>
</tr>
<tr>
<td>$^{214}\text{Po}$</td>
<td>7.83</td>
</tr>
<tr>
<td>$^{210}\text{Pb}$</td>
<td>164</td>
</tr>
</tbody>
</table>

U Rate: $4.7 \pm 1.2 \times 10^{-17}$ gU/gScint
Th Rate: $5.3 \pm 1.5 \times 10^{-17}$ gTh/gScint

Base rate in scintillator below requirements for the $0\nu\beta\beta$ search

Perform a “target out” $\beta\beta$ analysis
→ prepare/test analysis and techniques using real data
→ determine count rate in the ROI in the absence of Te
Scintillator Physics

- $^8$B solar $\nu + \text{Bkg}$ fit to the partial fill data,
  - 5.5m fiducial radius
  - including preliminary systematics.
  - Fitted flux compatible with other measurements.

- Anti-neutrino measurement in progress
  - Using time coincidence of inverse beta decay (IBD)
  - Capacity to probe tension in $\Delta m^2_{12}$

- Live for supernova
  - Burst monitoring part of SNEWS-1
  - Pre-supernova monitor enabled (IBD)

$\Phi_{8B} = 5.66 \times 10^6 \pm 20.6\%_{(\text{stat.})} \pm 6.3\%_{(\text{syst.})} \text{ cm}^{-2} \text{ s}^{-1}$
Detector is now full of scintillator

- Circulating scintillator and adding PPO to increase dopant to 2g/L → Completion early 2022
Data collected with lower PPO concentrations than our final cocktail. Lower scintillation light yield and slower rise time means we have potential to see initial (directional) Cherenkov light as well as isotropic scintillation light.

Holy grail for solar background rejection
Working on proof of principle with partial fill data

Double Beta Decay

• What is absolute neutrino mass scale?
• Why are neutrinos so light compared to other (Dirac) fundamental particles?
• Are they Majorana particles?

$0\nu\beta\beta$ can only occur for Majorana particles with a rate proportional to the mass

Experimental signature:
• Emission of 2 electrons at precise Q-value of decay
SNO+ 0νββ strategy

- Massive detector → High statistics
  → Shielding through fiducialisation
- Liquid scintillator → purification methods
  → Loading can be scaled
  → Homogeneous loading of isotope in detection medium

Tellurium-130 → Highest natural abundance (34%), no enrichment required, low cost
→ Q-value at 2.527 MeV – less background from natural radioactivity
→ Load into scintillator with Butanediol

Develop a scalable and affordable approach to push towards the NH in the future

Initial phase loading: 0.5% natural Te by weight = 1333 kg of $^{130}$Te.
Te loading

• ~8 tons of telluric acid (TeA) has been “cooling” underground for several years.

• Ton-scale underground purification of TeA for further background reduction.

• Target purification for Te cocktail:
  ~ $10^{-15}$ g/g U
  ~ $10^{-16}$ g/g Th
Our telluric acid has been “cooling” underground for several years.
+ Te purification
+ multi-site rejection *

Suppressed by asymmetric ROI: 2.42 – 2.56 MeV [-0.5σ - 1.5σ]
Assuming ~460 PMT hits / MeV

Measured in water data
Reduce by 23%

Pure scintillator phase allows “Te-out” measurement to test for any unexpected backgrounds

Staged Te-loading allows us to assess remaining Te-backgrounds

Well measured from previous experiments

Already measured U <10^{-16} g/g in partial fill (pure LAB) below requirements

Already measured Th <10^{-16} g/g in partial fill (pure LAB) below requirements

* See NIM 943, 162420, 2019 for more details
Projected spectrum: 0.5% loading

Half-life sensitivity:
$T_{1/2} > 2 \times 10^{26}$ years
Sensitive to $m_{\beta\beta} = 37$-89 meV

Full likelihood analysis using Energy, radius and multi-site discriminators achieves this sensitivity with 3 years of data.
Potential future $0\nu\beta\beta$ sensitivity

- SNO+ approach can be scaled up → SNO+ Phase II
  - Te loading up to several % with good light yield and stability
  - Cost is relatively very low ($< $2M per ton of decay isotope)

- Competitive results with different isotopes important given theoretical uncertainties
Summary

• Well understood detector from water phase data: backgrounds are low
  → Solar, nucleon decay, neutron capture, anti-neutrino physics

• Early scintillator data (partial fill and low PPO loading) analysed
  → scintillator performance and backgrounds, first scintillator physics measurements underway

• Scintillator physics → 0νββ, Solar, reactor-ν, geo-ν, Supernova ...

• Te-loading gives competitive 0νββ search with 0.5% loading

• Scalable approach of SNO+ has huge potential for extending 0νββ sensitivity
Backup material
Measuring with different isotopes is very important given theoretical uncertainties.
Discovery potential – multidimensional fit

- Fit in E, R and 2 PSD dimensions
- Each point obtained from an Asimov dataset with different strength of signal injected into it (corresponding to different effective Majorana mass)
- Discovery credible interval for $0\nu\beta\beta$ after 3 years
- Dashed lines indicate 3σ C.I. for analyses with and without PSD

\[ G_{0\nu} = 3.69 \times 10^{-14} \text{ y}^{-1}, \quad M_{0\nu} = 4.03 \]