Status of the SNO+ Experiment

Gersende Prior (LIP) on behalf of the SNO+ Collaboration

European Physical Society Conference on High Energy Physics
22-29 July 2015 - Vienna, Austria
Outline

I - The SNO+ experiment:
- collaboration
- detector
- physics goals and phases
- scintillator & isotope selection

II - SNO+ Status:
- ropes tensioning, water level
- PMTs and DAQ systems
- water/scintillation systems & isotope purification
- calibration systems

III - $0
\nu\beta\beta$ physics sensitivity:
- neutrino masses current limits
- background mitigation
- phase I & higher loading sensitivity

IV - Conclusion & outlook
Collaboration

- Armstrong Atlantic State University
- Brookhaven National Laboratory
- Lancaster University
- Laurentian University
- Lawrence Berkeley National Laboratory
- LIP Coimbra
- LIP Lisboa
- Oxford University
- Queen Mary, University of London
- Queen’s University
- SNOLAB
- Technical University of Dresden
- TRIUMF
- Universidad Nacional Autonoma de Mexico
- University of Alberta
- University of California - Berkeley
- University of California - Davis
- University of Chicago
- University of Liverpool
- University of North Carolina at Chapel Hill
- University of Pennsylvania
- University of Sussex
- University of Washington

23 Institutes
6 countries
90 members
Creighton mine, Sudbury, ON (Canada), 2 km (6000 m.w.e) depth

- SNO heavy water replaced by 780 tons of liquid scintillator
- Liquid scintillator will be loaded with different amounts of double-beta isotope
- New hold-down rope system
- New DAQ system and readout cards
- New calibration systems
- norite + granite/gabbro
- 7kt ultra pure water shield
- ∼9300 PMTs (54% coverage)
- 17 m diameter structure
- 12 m diameter, 5 cm thickness acrylic vessel (AV)
- Liquid scintillator will be loaded with different amounts of double-beta isotope
- New DAQ system and readout cards
- New calibration systems
- SNO heavy water replaced by 780 tons of liquid scintillator
- Liquid scintillator will be loaded with different amounts of double-beta isotope
- New hold-down rope system
- New DAQ system and readout cards
- New calibration systems
Physics goals & phases

- search for Majorana neutrinos
- solar neutrinos (pep, CNO, low energy $^8$B)
- reactor anti-neutrinos (3 nuclear plants @240-350 km)
- geo-neutrinos
- supernovae neutrinos (SNEWS)
- exotics (e.g. nucleon decay)

See “Anti-neutrino measurements in SNO+” poster by S. Andringa.

Water $\rightarrow$ unloaded liquid scintillator 1 $\rightarrow$ 0.3% nat Te loading
Scintillator mixture & isotope selection

**Liquid scintillator:**
- linear alkylbenzene (LAB)
- fluor: 2,5 diphenyloxazole (PPO)

**Scintillator mixture & isotope selection**

**LAB choice motivated by:**
- its long time stability
- its compatibility with acrylic
- can be produced with high radio purity
- good optical properties (high attenuation length)
- its linear response in energy
- high flash point and low toxicity

**130Te isotope choice motivated by:**
- its high natural abundance (34.08%)
- its high half-life $T^{2\nu\beta\beta}_{1/2} = 7.0 \times 10^{20}$ yr
- no inherent optical absorption lines
- $\sim 300$ detected photo-electron hits/MeV (0.3% natTe)
  
  **But low end-point ($Q_{\beta\beta} = 2.53$ MeV)**

**Loading technique:**
- dissolve telluric acid Te(OH)$_6$ in water
- combine with LAB with the help of a surfactant

**Higher loading (3%) under study**

- 0.3% of natTe loading (by weight) = 800 kg of $^{130}$Te
Rope tensioning & water level

Hold-up (SNO) rope system
+ hold-down net

Rope tensioning (float-the-boat):
tension the hold-down net to
284,000 lb (total load of liquid
scintillator) by floating the AV filled
to the equator in cavity water
and hold the tension for 2 weeks.

Partial float-the-boat:
when cavity water level was at the
AV bottom, a 80,000 lb load was applied
to the rope net. Successful & confirmed
the anchor adjustment.

Liquid scintillator adding ~130 T of buoyancy

Current water level 20 ft (18 ft below equator)
water fill to resume after cavity liner inspection
PMTs and DAQ systems

SNO+ photomultipliers (PMTs):
✴ 9522 PMTs [20 cm (8´´) Hamamatsu R1408]
✴ 850 PMTs with base short circuits (90%) or tube failure (10%)
✴ 391 PMTs repaired and replaced (1/2)

New requirements:
✴ transition from reading one crate at a time at 2-250 kB/s bandwidth (SNO) to sending data in parallel at 2.5 MB/s.
✴ event size increasing from 40 PMTs (SNO solar $\nu$) to 1500 PMTs (SNO+ $2\nu\beta\beta$).

Upgrades:
✴ new DAQ software (ORCA @UNC)
✴ new databases (couchDB, Redis)
✴ new visualization tools (D3/Cubism)
✴ new monitoring & slow-control systems

First Mock Data challenge:
successful test of near-line framework

Airfill and water commissioning runs used to test the full system.
Water/Scintillation systems & isotope purification

**Water system:**
- reconditioned to supply water inside the AV
- initial leach/wash of the AV
- achievable purity comparable to that of SNO
- also for scintillator mixing and purification
- complete and in operation

**Scintillator system:**
- provide multistage LAB/PPO distillation
- high temperature vacuum distillation
- water extraction (remove $^{40}$K, Ra, $^{210}$Pb)
- $N_2$/steam stripping (remove Rn, $O_2$, Kr, Ar)
- major piping/vessel installation done
- working on leak checking
- then cleaning and passivation

**Isotope purification:**
- double-pass (with ethanol rinsing) purification on surface (purification factor $10^4$)
- purification underground (no ethanol) additional factor 100
- investigating the possibility to move the surface purification system underground
Optical calibration systems

Purposes:
✴ measure the PMTs response
✴ measure in-situ the optical properties of the media

Systems:
✴ fixed fiber-based system using LEDs/laser light injection placed on the PMTs array
✴ deployed light (laser with dyes) source (laserball)
✴ deployed cherenkov light source

Calibration:
✴ validation of light transport models in different media
✴ PMT angular response, timing and gain calibration
✴ attenuation length, scattering properties of the media
✴ monitoring transparency of the media
✴ PMTs efficiency

Deployment system:
✴ deploy several types of sources from the top of the AV
✴ off-axis (in two planes) source location achievable
✴ radon-tight and fully sealed system

Fibers system:
✴ LEDs or laser pulses
✴ different wavelengths
✴ different fibres angles
✴ 106 different location points

New laserball under construction
69 fibers installed and tested
Cherenkov source prototype ready
Radioactive sources

**Purposes:**
- measure efficiency and systematic uncertainties of event reconstruction (energy, position, particle id)

**Systems:**
- several ($\beta, \gamma$) radioactive sources under study
- will be deployed in the detector from top of AV

<table>
<thead>
<tr>
<th>Source</th>
<th>Radiation</th>
<th>Energy [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AmBe</td>
<td>n, $\gamma$</td>
<td>2.2, 4.4 ($\gamma$)</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>$\gamma$</td>
<td>2.5 (sum)</td>
</tr>
<tr>
<td>$^{57}$Co</td>
<td>$\gamma$</td>
<td>0.122</td>
</tr>
<tr>
<td>$^{24}$Na</td>
<td>$\gamma$</td>
<td>4.1 (sum)</td>
</tr>
<tr>
<td>$^{48}$Sc</td>
<td>$\gamma$</td>
<td>3.3 (sum)</td>
</tr>
<tr>
<td>$^{16}$N</td>
<td>$\gamma$</td>
<td>6.1</td>
</tr>
<tr>
<td>$^{220}$Rn/$^{222}$Rn</td>
<td>$\alpha, \beta, \gamma$</td>
<td>various</td>
</tr>
</tbody>
</table>

**Universal deployment/interface:**
- mechanism able to deploy sources, voltages, gas, ropes...
- sealed interface with glove box, view ports, gate valves..
Experiments expect to reach the top of the inverted mass region by 2018.

SNO+ sensitivity to an effective Majorana mass $m_{\beta\beta} = 55-133$ meV with 0.3% $^{nat}\text{Te}$

From IGEX, Heidelberg-Moscow, Cuoricino and NEMO-3

From KamLAND-Zen, EXO-200 and GERDA I
Background mitigation

$2\nu\beta\beta$ (irreducible):
- use asymmetric ROI around the $0\nu\beta\beta$ signal
- energy resolution limited

External $\gamma$:
- AV, ropes, water shielding, PMTs
- use a fiducial volume (FV) cut
- PMT hit time distribution cut

Internal U/Th chain:
- dominant background from $^{214}\text{BiPo}$ and $^{212}\text{BiPo}$ decays
- coincidence-based cuts developed
- 100% rejection for events in separate trigger windows
- factor of rejection 50 (events in same trigger window) based on PMT hit timing

$^8\text{B} \nu$ ES solar neutrinos (irreducible):
- "flat" continuous background from elastically-scattered electrons
- normalized using published flux data and solar mixing parameters

$(\alpha, n)$ backgrounds:
- prompt signal & delayed gamma can leak in FV & ROI
- use coincidence-based cuts
- remove > 99.6% of the prompt signal and 90% of the delayed events

Cosmogenics:
- purification techniques
- long term underground storage
- less than one event per year in FV and ROI
**Phase I & higher loading sensitivity**

**SNO+ sensitivity at 0.3% \( ^{nat}\text{Te} \) loading:**
- Fiducial volume cut \( R < 3.5 \text{ m} \) (20%)
- > 99.99% rejection for \(^{214}\text{BiPo} \) assumed
- > 98% rejection for \(^{212}\text{BiPo} \) assumed
- 200 Nhits/MeV light yield
- Phase space factor \( G = 3.69 \times 10^{-14} \text{ yr}^{-1} \)
- \( g_A = 1.269 \)
- \( M_{0\nu\beta\beta} = 4.03 \) (IBM-2)

**1 year data:**
- \( T^{0\nu\beta\beta}_{1/2} = 3.9 \times 10^{25} \text{ yr} \)
- \( m_{\beta\beta} \sim 105 \text{ meV} \)

**5 years data:**
- \( T^{0\nu\beta\beta}_{1/2} = 9.4 \times 10^{25} \text{ yr} \)
- \( m_{\beta\beta} \sim 68 \text{ meV} \)

**Higher loading sensitivity:**
- R&D efforts show that at 3% \(^{nat}\text{Te} \) loading a light yield of 150 Nhit/MeV can be achieved with perylene as second wavelength shifter
- Loss of light yield can be compensated by HQE PMTs/PMTs concentrator improvements
- Could set a lower limit on \( T^{0\nu\beta\beta}_{1/2} = 7 \times 10^{26} \text{ yr} \) (mass range of 19 - 46 meV)

Summary plot of all background and a hypothetical \( 0\nu\beta\beta \) signal corresponding to a mass \( m_{\beta\beta} = 200 \text{ meV} \) for 5 years of data-taking.
Conclusion & outlook

- Water plant finished and under operation
- Scintillator plant undergoing final cleaning and passivation work
- Source insertion and deployment mechanisms under construction
- DAQ / dataflow / monitoring / nearline tools in benchmarking
- Detector ready to take data

**SNO+ main physics goal** is the search for $0\nu\beta\beta$ for a mass range in the top of the IH mass region

SNO+ multi-purpose detector able to study also:
- Solar neutrinos
- Reactor and geo-neutrinos (see S. Andringa poster)
- Supernova neutrinos
- Nucleon decay

- 2015-2016 water commissioning phase
- 2016 scintillator phase
- 2017 Te loading phase I
This work was partially funded by Fundação para a Ciência e a Tecnologia (FCT, Portugal) through the following project grants:

✴ PTDC/FIS/115281/2009
✴ IF/00863/2013
✴ IF/00863/2013/CP1172/CT0006
✴ EXPL/FIS-NUC/1557/2013
What do we do if we see a bump?

1. Measure non-Te backgrounds before loading
2. Agree with model?
   - Yes: Add Te and run
   - No: Continue purification
3. Excess above expected backgrounds?
   - Yes: Re-purify Te, further running
   - No: Set lifetime limit
4. Excess persists at same level?
   - Yes: Increase Te loading
   - No: Remove Te
5. Excess scales?
   - Yes: Consider alternative isotope or enrichment
   - No: Increase Te loading
Neutrinoless double beta decay

Decay rate
\[ \Gamma^{0\nu\beta\beta} = \ln(2) \cdot (T^{0\nu\beta\beta}_{1/2})^{-1} = \ln(2) \cdot G^{0\nu\beta\beta}(Q_{\beta\beta}, Z) \cdot |M^{0\nu\beta\beta}|^2 \cdot <m_{\beta\beta}^2>/m_e^2 \]

\[ <m_{\beta\beta}> = \sum m_i \times U_{ei}^2 \]

effective Majorana mass


scaling with isotope quantity (e.g. internal U/Th)

independant of isotope quantity (e.g. solar $^8$B)

N total number of isotope nuclei
\( n_\sigma \) number of standard deviation
\( f(\delta\epsilon) \) energy window acceptance fraction
M isotope mass in kg
\( \delta E \) energy window in keV
b background counts in (keV.kg.yr)$^{-1}$
c background count in (keV.yr)$^{-1}$
Backgrounds from the natural 238U and 232Th chains

- β - α coincidence tagging for events in different trigger windows
- PMTs hit time analysis for events in same trigger window

- α - β coincidence tagging for events in different trigger windows
- PMTs hit time analysis for events in same trigger window

2.6 MeV γs from external $^{208}\text{Tl}$
- can be suppressed with FV cut
- from AV can be removed via PMT hit time analysis
Other physics in SNO+

Solar neutrinos:
✴ with scintillator purity at Borexino level, sensitivity to CNO, pep and low-energy $^8$B with unloaded scintillator
✴ if can source scintillator with reduced (one order magnitude) $^{14}$C level can also measure pp
✴ $^8$B with energy above the $^{130}$Te end-point can be measured in the scintillator loaded phases

Anti-neutrinos from reactors and the Earth (see poster by S. Andringa)

Supernova neutrinos:
✴ measurements of Core Collapse supernovae neutrinos can shed light on explosion mechanism
✴ member of the Supernova Early Watching System (SNEWS)

Exotics physics:
✴ search for invisible nucleon decay mode signature in the water phase
✴ axion-like particle search in all SNO+ phases