Calibration and rare physics searches with the SNO+ experiment

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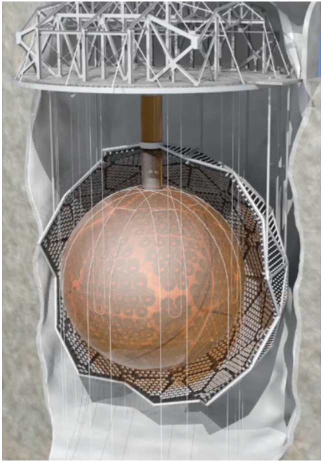
Introduction



- SNO+ experiment overview:
  - Reuses SNO detector (1999–2006) [1]
  - Located at SNOLAB (Sudbury, Canada)
  - 2070 m rock overburden (6010 m water equivalent)
  - Low cosmic backgrounds (0.27 $\mu/\mathrm{m}^2/\mathrm{d}$)

- Designed as 3-phase experiment:
  1. Water phase (2017–18)
  2. Scintillator phase (2018–19)
  3. $0\nu\beta\beta$ phase (2019+)

- Taking data since May 2017

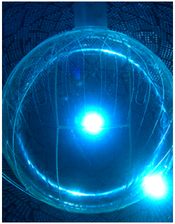
Physics goals

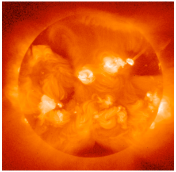
1. Water phase
   - Detector calibration
   - Background measurements
   - Nucleon decay searches
   - $^{8}\mathrm{B}$ solar neutrino flux

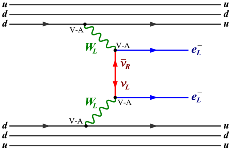
2. Scintillator phase
   - Background measurements
   - Low energy solar neutrinos ($\gtrsim$ 1 MeV)
   - Geo and reactor antineutrinos

3. Tellurium phase
   - $2\nu\beta\beta$ decay lifetime of $^{130}\mathrm{Te}$
   - $0\nu\beta\beta$ decay search with $^{130}\mathrm{Te}$
   - Geo and reactor antineutrinos

\+ Supernova neutrinos in all phases!







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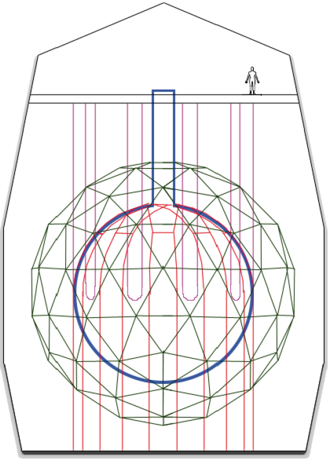
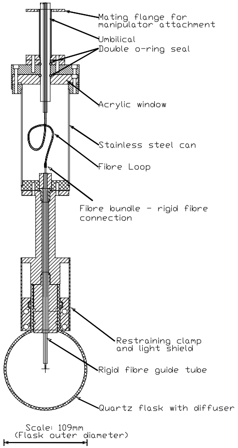
Detector

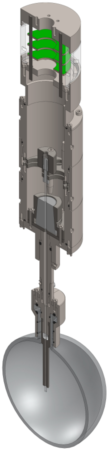


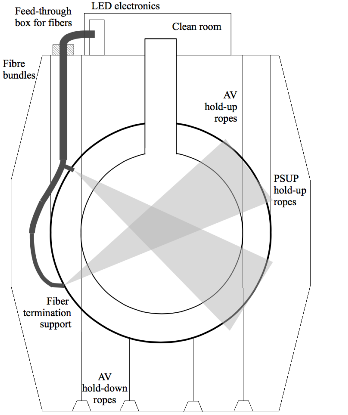
- Deck houses clean room, detector electronics
- Acrylic vessel (AV) holds target material (12 m diam.)
- PMT support structure (PSUP) holds 9300 PMTs
- Hold-up ropes hold AV in place (SNO used D_2O)
- Hold-down ropes hold AV in place (SNO+ will use LAB)

Calibration

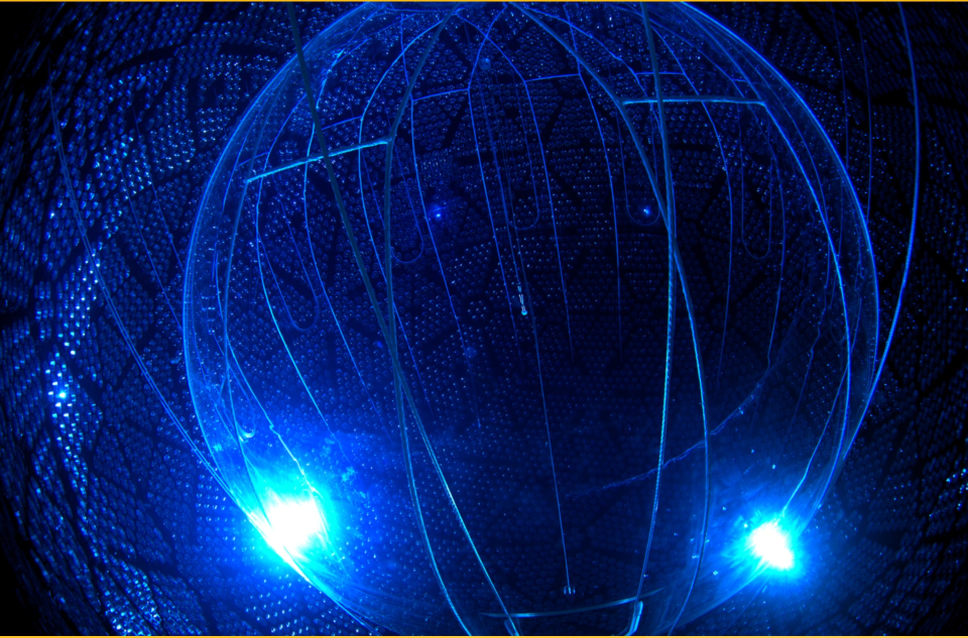
- Deployed sources (radioactive, optical)
- In-situ sources (fibre optics)





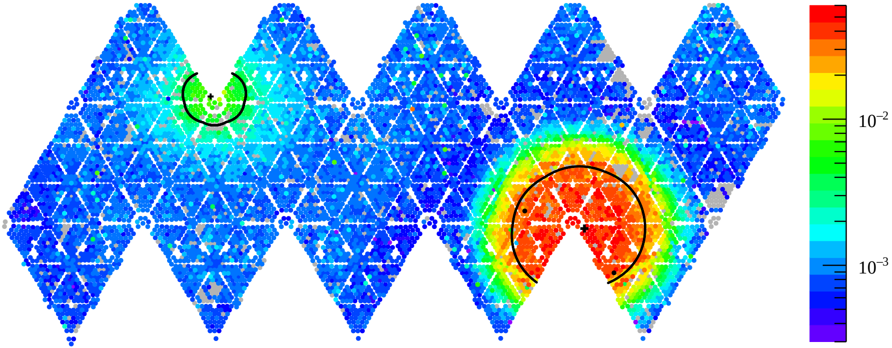


Example 1: Deployed Source



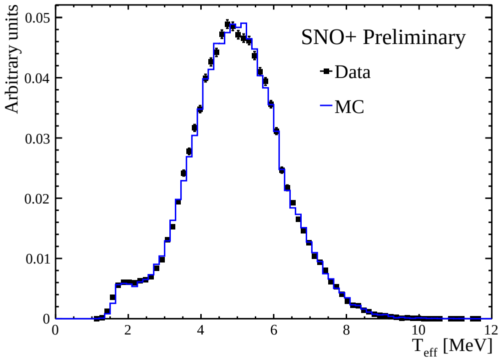
Example 2: Timing Calibration

- TELLIE subsystem used to calibrate PMT hit times
- Consists of 92 light injection points located on PSUP
- **Data** shows occupancy for $2 \cdot 10^5$ LED pulses through a single fibre

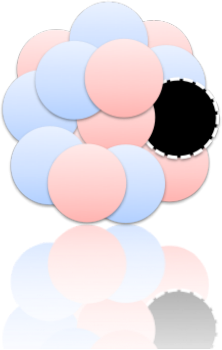


Example 3: Energy Calibration

- Deployed ^{16}N source used to determine absolute energy scale
- Emits gammas (6.13 MeV) at the level of $\sim$ 50 Hz [2]
- Various source positions to map out detector response



First physics analysis: Nucleon decay



$$^{16}\mathrm{O} \rightarrow {}^{15}\mathrm{O}^{*} + \mathit{inv.}$$

$$^{15}\mathrm{O}^{*} \rightarrow {}^{15}\mathrm{O} + \gamma$$

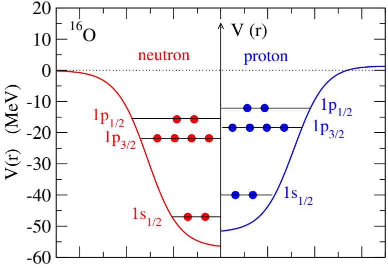
- Baryon number violating process
- Could explain matter-antimatter asymmetry in the universe
- Never been observed experimentally [3]
- Super-Kamiokande has best limits for visible decay modes (e.g. $p \rightarrow e^{+}\pi^{0}$)
- Various theories propose **invisible** nucleon decay modes (e.g. $n \rightarrow 3\,\nu$)
- Such decays could be observed indirectly (low-energy gammas)

Signal definition

- "Disappearance" of one or two nucleons in oxygen nucleus:

$^{16}\mathrm{O}$ (n → inv.) $^{15}\mathrm{O}$
$^{16}\mathrm{O}$ (p → inv.) $^{15}\mathrm{N}$

$^{16}\mathrm{O}$ (nn → inv.) $^{14}\mathrm{O}$
$^{16}\mathrm{O}$ (pn → inv.) $^{14}\mathrm{N}$
$^{16}\mathrm{O}$ (pp → inv.) $^{14}\mathrm{C}$



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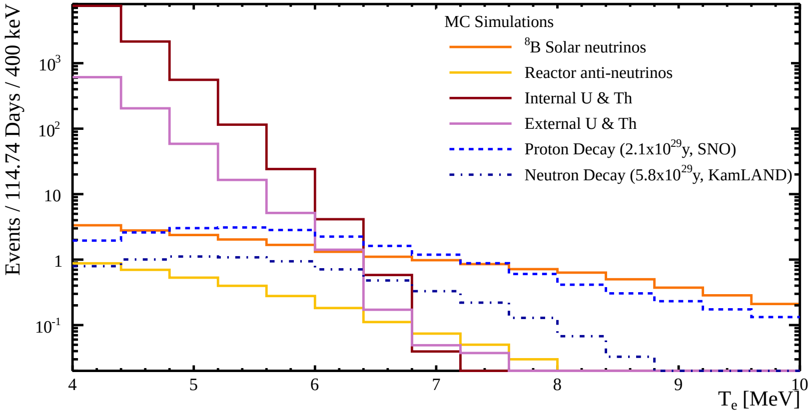
- Daughter nucleus may be left in excited state (observable decay)

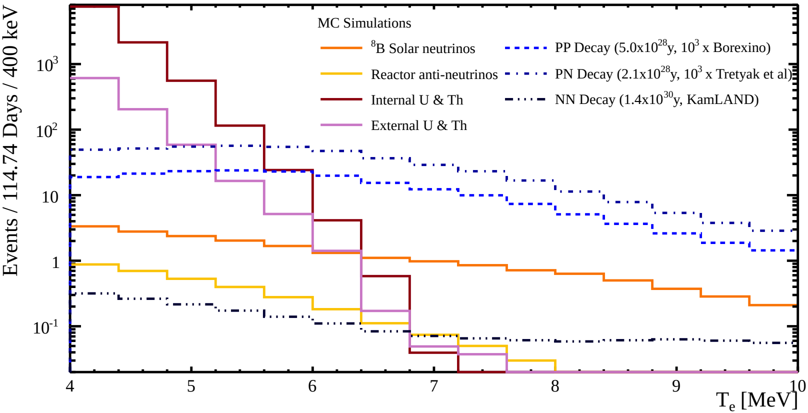
- Statistical process, need branching ratios from nuclear theory
  → Ejiri (1993) reported on nucleon decay in $^{16}\mathrm{O}$ [4]
  → Hagino & MN (2018) reported on dinucleon decay in $^{16}\mathrm{O}$ [5]

Event selection – Nucleon decay



- Data-cleaning cuts to reduce instrumental backgrounds
- Cuts on energy, position, and direction to reduce backgrounds
- Additional event classifier cuts (e.g. isotropy)

Event selection – Dinucleon decay



- Same analysis applied for dinucleon decay searches
- Lower existing limits lead to greater impact

Expected lifetime limits

- Assuming no signal events, lower limit for lifetime is calculated:

$$\tau > \frac{N \cdot \epsilon \cdot t}{S_{90\%}}$$

- Efficiencies and sensitivities (90% C.L.) including systematic effects for total dataset (114.7 d): expect 17.65 events in ROI

Decay (^{16}O)	Targets N	Efficiency ϵ	Current limit τ_{PDG} (y)	Sensitivity τ_{SNO+} (y)	Improvement τ_{SNO+}/τ_{PDG}
n	$2.412 \cdot 10^{32}$	0.066	$5.8 \cdot 10^{29}$ [6]	$4.4 \cdot 10^{29}$	—
p	$2.412 \cdot 10^{32}$	0.084	$2.1 \cdot 10^{29}$ [7]	$5.8 \cdot 10^{29}$	2.8
nn	$3.015 \cdot 10^{31}$	0.012	$1.4 \cdot 10^{30}$ [6]	$1.0 \cdot 10^{28}$	—
pn	$3.015 \cdot 10^{31}$	0.046	$2.1 \cdot 10^{25}$ [8]	$4.1 \cdot 10^{28}$	1900
pp	$3.015 \cdot 10^{31}$	0.080	$5.0 \cdot 10^{25}$ [9]	$7.1 \cdot 10^{28}$	1400

- No improvement expected for n, nn limits from KamLAND [6].
- Set world-leading limits on p, pn, pp decays!

Summary

- SNO+ experiment online since 2017
- Water phase completed
  - Tested various calibration methods
  - Understood dominant background contributions
  - Observe $^{8}\mathrm{B}$ solar neutrino flux
  - **Set world-leading limits for invisible nucleon decay**
- Starting scintillator fill this week!

References

[1] S.N. Ahmed et al. (SNO Collaboration). *Nucl. Instr. Meth. A*, 449(172), 2000.

[2] M.R. Dragowsky et al. *Nucl. Instr. Meth. A*, 481(1):284–296, 2002.

[3] M. Tanabashi et al. (PDG Group). *Phys. Rev. D*, 98(030001), 2018.

[4] H. Ejiri. *Phys. Rev. C*, 48(3), 1993.

[5] K. Hagino and M. Nirkko. *J. Phys. G: Nucl. Part. Phys.*, 45(10), 2018.

[6] T. Araki et al. (KamLAND Collaboration). *Phys. Rev. Lett*, 96, 2006.

[7] S.N. Ahmed et al. (SNO Collaboration). *Phys. Rev. Lett.*, 92, 2004.

[8] V.I. Tretyak, V. Yu. Denisov, and Yu. G. Zdesenko. *JETP Lett.*, 79:106–108, 2004.

[9] H.O. et al. (Borexino Collaboration) Back. *Phys. Lett. B*, 563:23–34, 2003.

Backup

Event selection for nucleon decay

- Data-cleaning cuts ("noise reduction") prior to analysis

- Energy cut (reduces internal bkg): 5.9 MeV $< E <$ 9 MeV
- Position cut (reduces external bkg): $R <$ 5.35 m
- Direction cut (reduces solar bkg): $cos(\theta_\odot) > -0.7$
- Height cut (reduces Rn ingress): $Z <$ 4 m (depends on data set)
- Event classifier cuts: $-0.12 < \beta_{14} < 0.95$ $ITR > 0.55$

- Optimisation repeated for each parameter in turn
- Performed blind analysis to reduce experimental bias
- Data "unblinded" within the past month!

Lifetime calculation

Experiments typically report lower limit (90% C.L.) on lifetime:

$$\tau > \frac{N \cdot \epsilon \cdot t}{S_{90\%}}$$

- N = number of target nucleons ($2.412 \cdot 10^{32}$)
- ϵ = signal detection efficiency (obtained from theory & simulation)
- t = detector live time for physics data (0.314 y)
- $S_{90\%}$ = upper limit (90% C.L.) for number of observed signal events
  $\rightarrow$ signal selection, background estimation, systematic effects...
  $\rightarrow$ performed box analysis ("counting experiment")
  $\rightarrow$ also performed analysis using likelihood fit (for comparison)