First physics results from the SNO+ experiment

Joint APP and HEPP Annual Conference 2019

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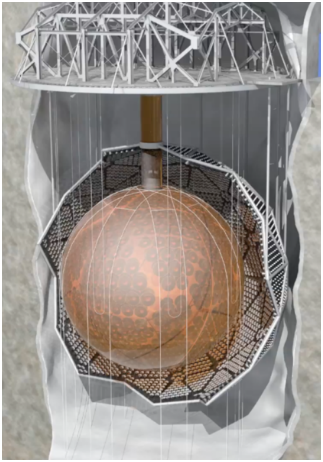
Introduction

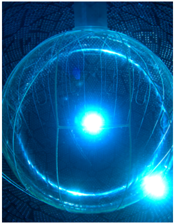


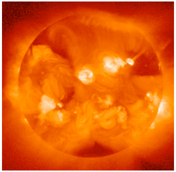
- SNO+ experiment overview:
  - Reuse SNO detector [1] (1999–2006)
  - Located at SNOLAB (Sudbury, Canada)
  - 2070 m rock overburden (6010 m water equivalent)
  - Very low cosmic backgrounds (0.27 $\mu/\mathrm{m}^2/\mathrm{d}$)
- Designed as 3-phase experiment:
  1. Water phase (2017–18)
  2. Scintillator phase (2019)
  3. Tellurium phase (2020+)
- Taking data since May 2017

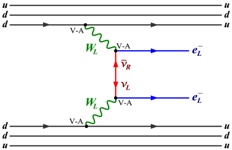
Physics goals

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
   - 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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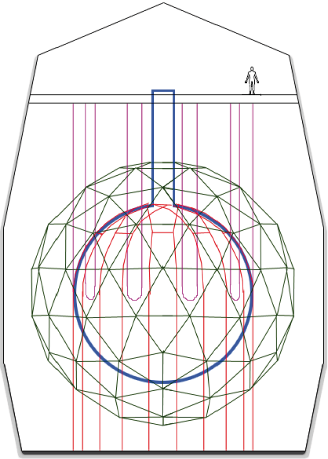
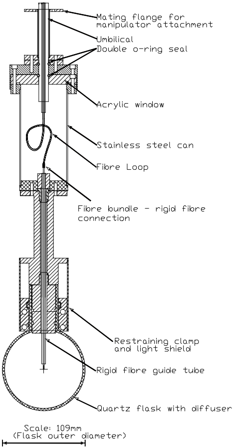
Detector

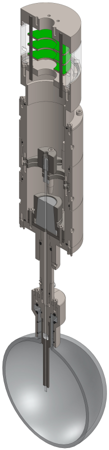


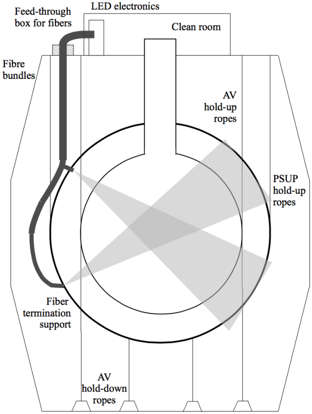
- Deck houses clean room, detector electronics
- Acrylic vessel (AV) holds target material (12 m diam.)
- PMT support structure (PSUP) holds 9300 PMTs
- Hold-up ropes hold AV in place (SNO used D_2O)
- Hold-down ropes hold AV in place (SNO+ will use LAB)

Calibration

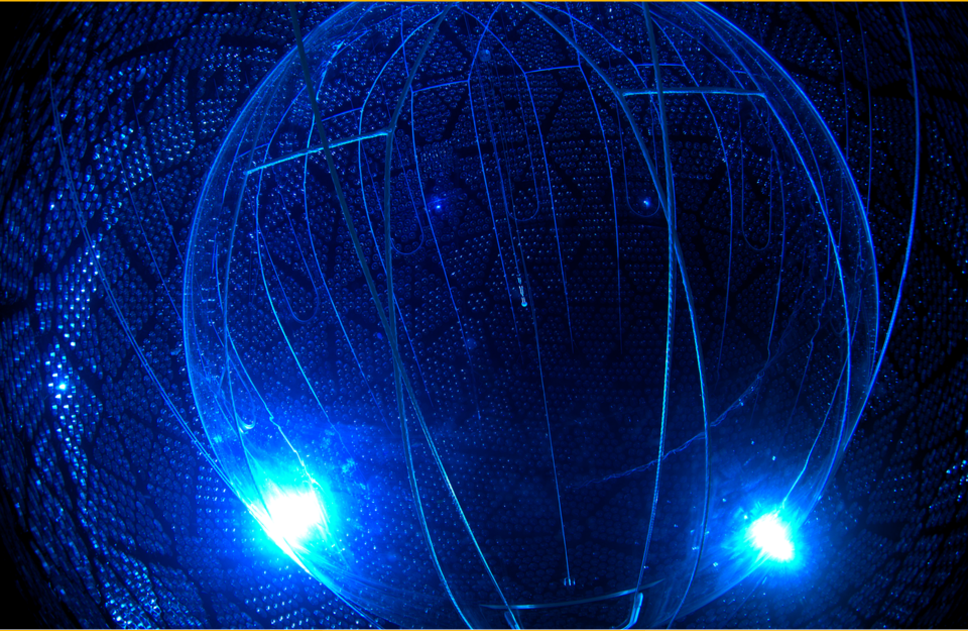
- Deployed sources (radioactive, optical)
- In-situ sources (fibre optics)





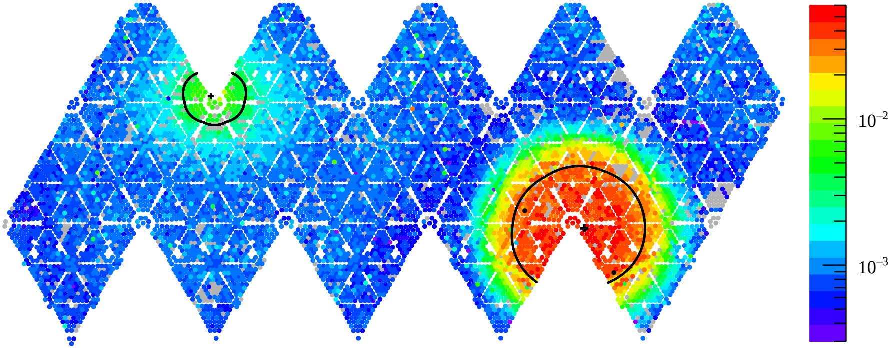


Example 1: Deployed Source



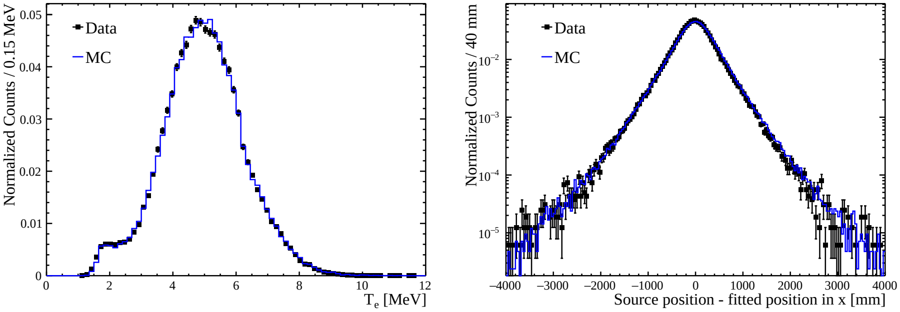
Example 2: Timing Calibration

- 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

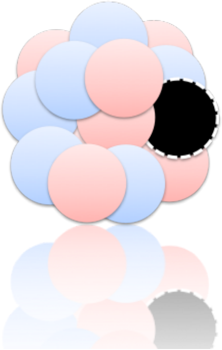


Example 3: Energy/Position Calibration

- 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
- Resolution shown for reconstructed energy (left) and position (right)



First physics analysis: Nucleon decay



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

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

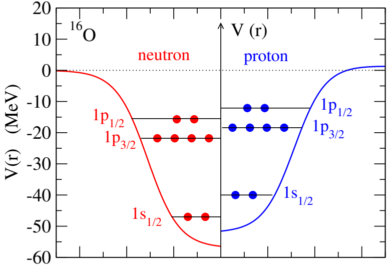
- Baryon number violating process
- Could explain matter-antimatter asymmetry in the universe
- Never been observed experimentally [3]
- Super-Kamiokande has best limits for visible decay modes (e.g. $p \rightarrow e^+\pi^0$)
- Various GUT theories propose **invisible** nucleon decay modes (e.g. $n \rightarrow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

Signal definition

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

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

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

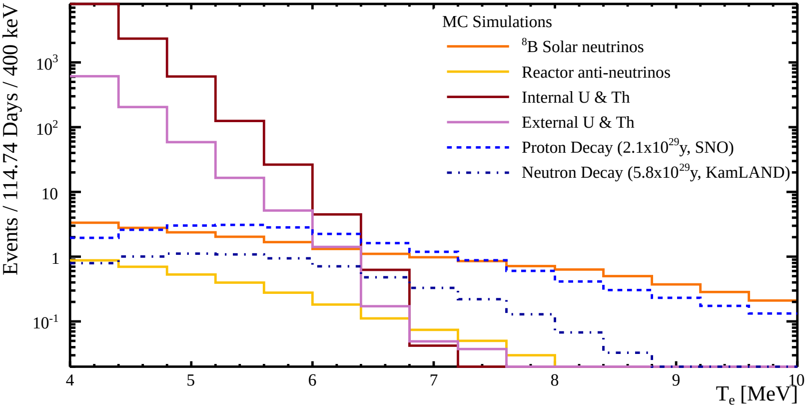


J.Phys.G: Nucl.Part.Phys. **45** 105105

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

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

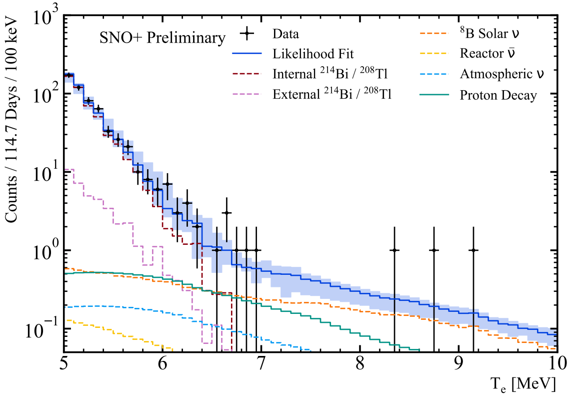
Event selection



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

Unblinding

- Expected 17.65 events for total dataset (114.7 d)
- **Observed 22 events** in ROI
- Within errors, does not match signal hypothesis



Lifetime limits

- No signal excess, calculate lower limit for lifetimes:

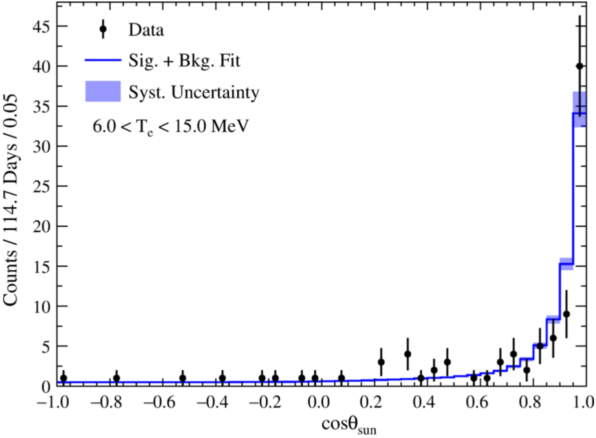
$$\tau > \frac{N \cdot \epsilon \cdot t}{S_{90\%}}$$

Decay (^{16}O)	Targets N	Efficiency ϵ	PDG limit τ_{PDG} (y)	SNO+ limit τ_{SNO+} (y)	Improvement τ_{SNO+}/τ_{PDG}
n	$2.41 \cdot 10^{32}$	6.6%	$5.8 \cdot 10^{29}$ [6]	$2.5 \cdot 10^{29}$	—
p	$2.41 \cdot 10^{32}$	8.4%	$2.1 \cdot 10^{29}$ [7]	$3.6 \cdot 10^{29}$	1.7
nn	$3.02 \cdot 10^{31}$	1.15%	$1.4 \cdot 10^{30}$ [6]	$1.3 \cdot 10^{28}$	—
pn	$3.02 \cdot 10^{31}$	4.6%	$2.1 \cdot 10^{25}$ [8]	$2.6 \cdot 10^{28}$	1200
pp	$3.02 \cdot 10^{31}$	8.0%	$5.0 \cdot 10^{25}$ [9]	$4.7 \cdot 10^{28}$	940

- No improvement on *n*, *nn* limits from [6]
- Set world-leading limits on *p*, *pn*, *pp* decays! [10]

Solar neutrino measurement

- Observed $^{8}\mathrm{B}$ solar neutrino flux [11]
- Very low background rate, good result despite limited data ($\sim$0.3 kt·y)



Summary

- SNO+ experiment online since 2017
- Water phase completed
  - Tested various calibration methods
  - Understood dominant backgrounds
  - Observed $^{8}\mathrm{B}$ solar neutrino flux
  - **Set world-leading limits for invisible nucleon decay**
- Started scintillator fill, will continue soon

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.

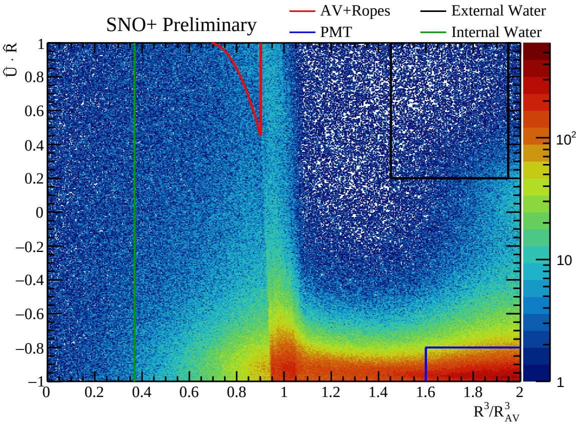
[9] H.O. Back et al. (Borexino Collaboration). *Phys. Lett. B*, 563:23–34, 2003.

[10] M. Anderson et al. (SNO+ Collaboration). *Phys. Rev. D*, 99:032008, Feb 2019.

[11] M. Anderson et al. (SNO+ Collaboration). *Phys. Rev. D*, 99:012012, Jan 2019.

Backup

- Dedicated studies done for specific background regions
  x-axis = event position from centre (volume-normalised)
  y-axis = event direction w.r.t. centre



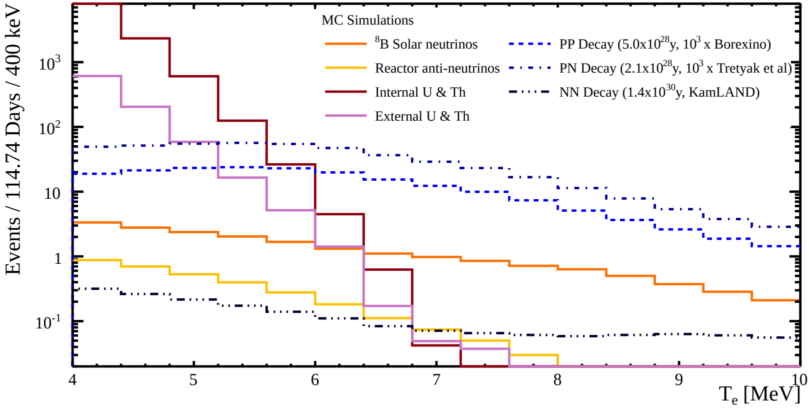
Event selection for nucleon decay

- Data-cleaning cuts (“noise reduction”) prior to analysis

- Energy cut (reduces internal bkg): $5.9 \text{ MeV} < E < 9 \text{ MeV}$
- 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 dataset)
- 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

Event selection – Dinucleon decay



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

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
  → signal selection, background estimation, systematic effects...
  → performed box analysis ("counting experiment")
  → also performed analysis using likelihood fit (for comparison)