Search for Invisible Nucleon Decay in the SNO+ Light Water Phase

International Workshop on Next Generation Nucleon Decay and Neutrino Detectors 2018

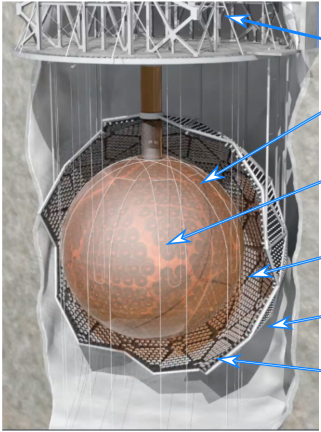
Morgan Askins,
on behalf of the SNO+ collaboration

BERKELEY LAB

Berkeley
UNIVERSITY OF CALIFORNIA

2 November 2018

SNO+ Detector



Overburden: 6800 ft. (5890 m.w.e.)

Acrylic Vessel (12 m Diameter)

905 Tonnes H_2O
780 Tonnes Te-doped Scintillator

1700 Tonnes H_2O Inner Buffer

5700 Tonnes H_2O Outer Buffer

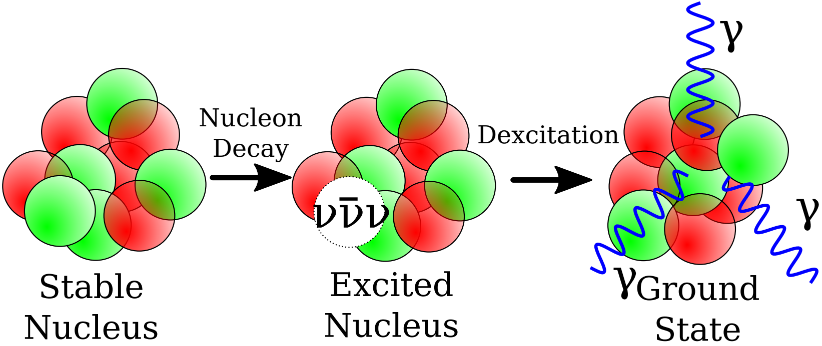
~9300 PMTs

Nucleon Decay (beyond the Standard Model)

- Nucleon decay predicted by many BSM theories.
- Observation of B-L conserving processes help in the understanding of leptogenesis.

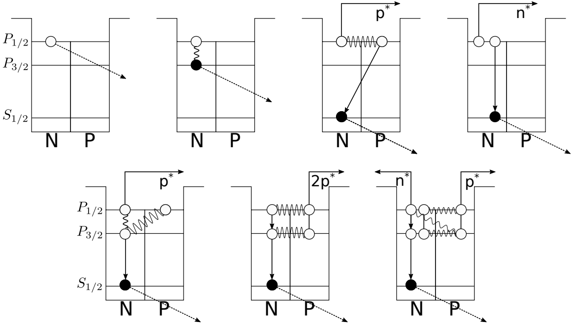
Model	Mode
Minimal SU(5)	$p \rightarrow e^{+}\pi^{0}$
Minimal SO(10)	$p \rightarrow e^{+}\pi^{0}$
SUSY SU(5)	$p \rightarrow \bar{\nu}K^{+}$
SUSY SO(10)	$p \rightarrow \bar{\nu}K^{+}$
Universal Extra Dimensions	$n \rightarrow 3\nu$, $p \rightarrow \pi^{+} + 3\nu$

“Invisible” Nucleon Decay



Extracting the “Invisible” Signal

Deexcitation Mode of Neutron Hole in ^{15}N



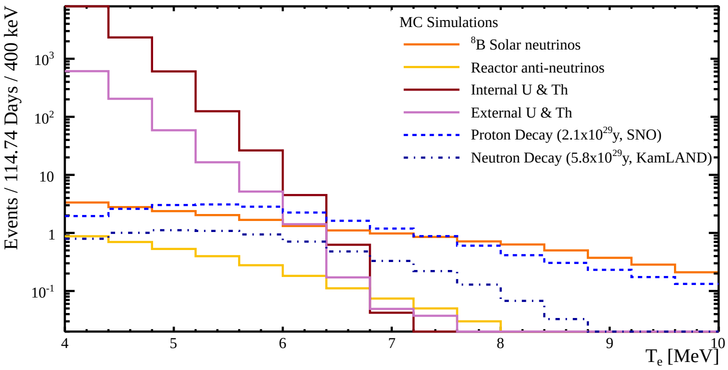
$^{16}O \rightarrow ^{15} N^*$

3%: 9.932 MeV γ
41%: 6.32 MeV γ

$^{16}O \rightarrow ^{15} O^*$

44%: 6.18 MeV γ

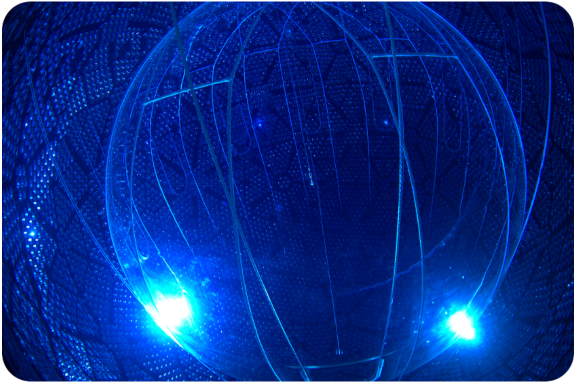
Comparison of Signal and Background



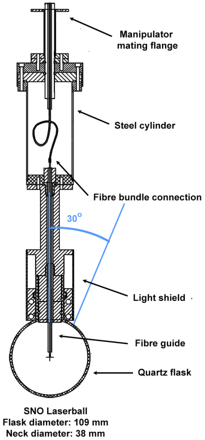
Calibration and Monte Carlo Verification

Deployed Calibration Sources

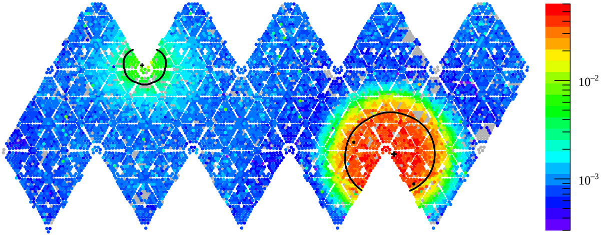
- Laserball (optical calibration)
- Tagged ^{16}N for event reconstruction.
- AmBe for neutron capture.



Timing Calibration

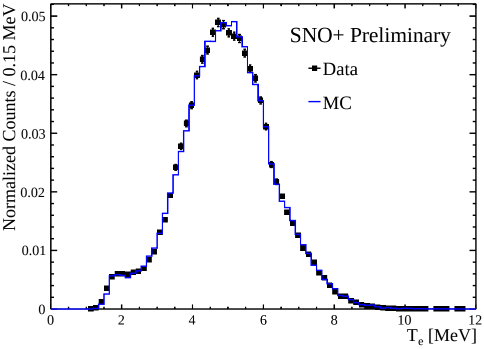


Photomultiplier timing calibrations performed using a diffused laser ball and in-situ fiber optic injection points.



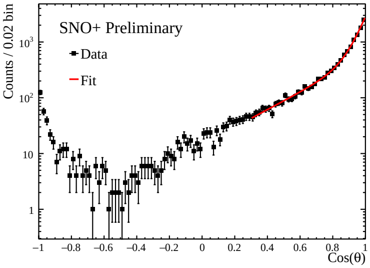
Energy Calibration with a Tagged ^{16}N Source

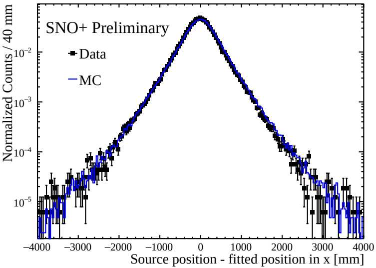
- Great agreement between MC and data.
- Difference used to estimate energy systematic uncertainties.
- Dominant systematic for nucleon decay.



Position and Direction Reconstruction with ^{16}N

Direction fit used to isolate background from solar neutrinos.
Position fit used for fiducial volume selection.



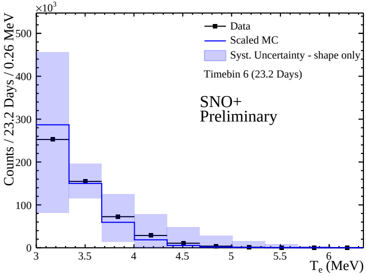


Data Taking

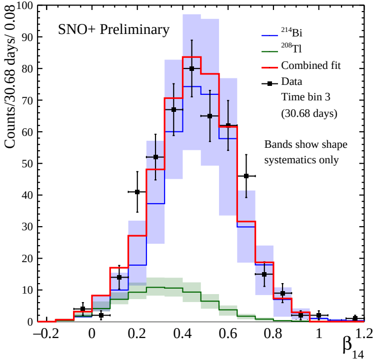
- Official data taking began May 2017.
- Data was split into 6 data sets, during each of which the background levels were relatively stable. Each set has its own analysis cuts and background estimates.
- 114.7 days of livetime used for the background and nucleon decay analysis, running through December 2017.

Background Measurements

1. U/Th in PMTs, Water, Ropes, etc.
2. Solar, Reactor, and Atmospheric ν



PMT β/γ Backgrounds



Internal radioactivity fit using photon isotropy

Two Independent Analysis Chains

Rate-only counting analysis

1. Optimized in each data set for maximum sensitivity.
2. Inputs from side-band analysis for all backgrounds.

Spectral profile likelihood fit

1. Higher signal efficiency due to larger energy window.
2. Independent fit to internal backgrounds, and separate external background fit.
3. Profiled nuisance parameters.

Data was blind from 5-15 MeV except for the first 10 days which was used to validate the analysis techniques.

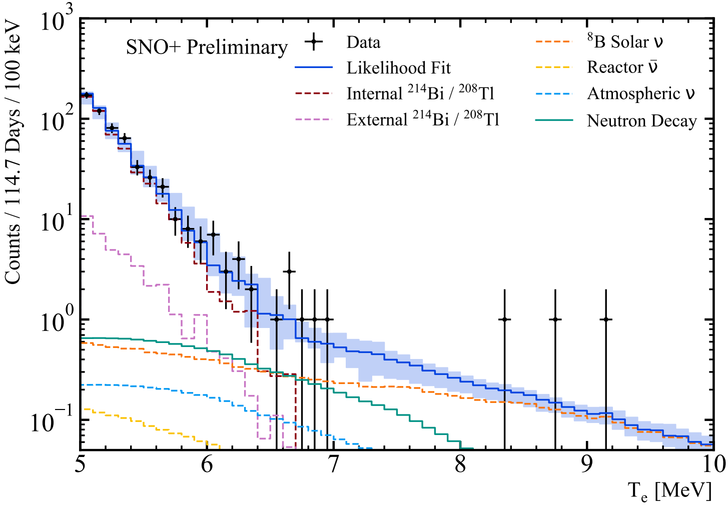
Event Selection Criteria

Blind Analysis

Data Set	Livetime	T_e (Likelihood)	T_e (Counting)	$\cos\theta_{sun}$	$\lvert\boldsymbol{R}\rvert$	Z
1	5.05 days	(5, 10) MeV	(5.75, 9) MeV	(-1, 0.80)	(0, 5.45) m	(-6, 4) m
2 ($z > 0$)	14.85 days	(5, 10) MeV	(5.95, 9) MeV	(-1, 0.75)	(0, 4.75) m	(0, 6) m
2 ($z < 0$)	14.85 days	(5, 10) MeV	(5.45, 9) MeV	(-1, 0.75)	(0, 5.05) m	(-6, 0) m
3	30.68 days	(5, 10) MeV	(5.85, 9) MeV	(-1, 0.65)	(0, 5.30) m	(-6, 6) m
4	29.44 days	(5, 10) MeV	(5.95, 9) MeV	(-1, 0.70)	(0, 5.35) m	(-4, 6) m
5	11.54 days	(5, 10) MeV	(5.85, 9) MeV	(-1, 0.80)	(0, 5.55) m	(-6, 0) m
6	23.19 days	(5, 10) MeV	(6.35, 9) MeV	(-1, 0.70)	(0, 5.55) m	(-6, 6) m
Bin-width	—	0.1 MeV	0.1 MeV	0.1	—	—

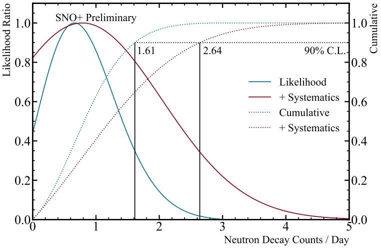
- Energy region extended to allow a for higher signal efficiency as well as constraints on the backgrounds for the spectral fit.
- Cuts on the reconstructed direction made to remove ^{8}B Solar Neutrinos.
- Radius and Z position cuts applied to select for the lowest background regions of the detector.

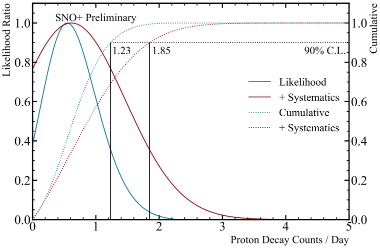
Full Spectral Fit



Results of the Spectral Fit at 90% C.L.

Mode	SNO+ Limits (years)	Current Limits
n	2.49×10^{29}	5.8×10^{29} [KamLAND]
p	3.56×10^{29}	2.1×10^{29} [SNO]
pp	4.68×10^{28}	5.0×10^{25} [Borexino]
pn	2.57×10^{28}	2.1×10^{25} [Tretyak et. al.]
nn	1.25×10^{28}	1.4×10^{30} [KamLAND]





Conclusions

- SNO+ has completed its water phase analysis with world leading results on invisible p, pn, and pp decay.
- Backgrounds relevant for neutrinoless double beta decay have been measured and are consistent with expectations.
- SNO+ has started filling with liquid scintillator, commencing the next phase of analysis.

References

Ahmed, S. N. e. a. (2004).
Constraints on nucleon decay via invisible modes from the sudbury neutrino observatory.
Phys. Rev. Lett., 92:102004.

Andringa, S. et al. (2016).
Current Status and Future Prospects of the SNO+ Experiment.
Adv. High Energy Phys., 2016:6194250.

Ejiri, H. (1993).
Nuclear deexcitations of nucleon holes associated with nucleon decays in nuclei.
Phys. Rev. C, 48:1442–1444.

Hagino, K. and Nirkko, M. (2018).
Branching ratios for de-excitation processes of daughter nuclei following invisible dinucleon decays in 16 o.
Journal of Physics G: Nuclear and Particle Physics, 45(10):105105.

Mohapatra, R. N. and Pérez-Lorenzana, A. (2003).
Neutrino mass, proton decay, and dark matter in tev scale universal extra dimension models.
Phys. Rev. D, 67:075015.

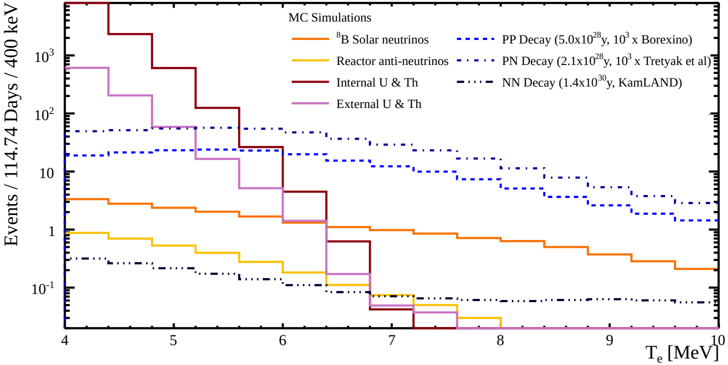
Backup Slides

Likelihood Systematic Uncertainties

Systematic	N (events/day)	P (events/day)	PP (events/day)	PN (events/day)	NN (events/day)
Best Fit	0.661	0.548	0.568	0.988	2.339
Energy Scale	+0.421, -0.208	+0.248, -0.129	+0.213, -0.121	+0.409, -0.234	+0.531, -0.281
Energy Resolution	±1.013	±0.666	±0.594	±1.106	±1.200
X-Shift	±0.016	±0.008	±0.008	±0.020	±0.020
Y-Shift	±0.014	±0.009	±0.008	±0.015	±0.026
Z-Shift	+0.022, -0.011	+0.013, -0.007	+0.014, -0.005	+0.031, -0.010	+0.045, -0.011
XYZ-Scale	+0.140, -0.129	+0.097, -0.086	+0.095, -0.081	+0.188, -0.157	+0.311, -0.250
β_{14}	±0.040	±0.025	±0.030	+0.070, -0.001	±0.137
Direction	+0.143, -0.071	+0.106, -0.069	+0.108, -0.075	+0.212, -0.132	+0.441, -0.279
Total (Syst.)	+1.117, -1.046	+0.726, -0.688	+0.648, -0.617	+1.216, -1.150	+1.426, -1.295
Statistical	+0.566, -0.481	+0.421, -0.373	+0.418, -0.399	+0.746, -0.705	+2.163, -1.589
90% C.L.	2.64	1.85	1.76	3.21	6.59

Comparison of Signal and Background

pp, pn, nn modes



Likelihood Function

$$
\begin{aligned}
-\ln \mathcal{L}(\eta_s, \boldsymbol{\eta_b} | \boldsymbol{D}, \hat{\boldsymbol{\eta}}_{\boldsymbol{b}}, \sigma_{\boldsymbol{b}}, t_k) = & -\Sigma_{k=1}^{T}\Sigma_{i=1}^{n} \ln\{\eta_s \epsilon_s \mathcal{P}_s(\boldsymbol{\theta}_i) + \boldsymbol{\eta_b \epsilon_b} \cdot \boldsymbol{\mathcal{P}_{bk}}(\boldsymbol{\theta}_i)\} t_k \quad \text{(Shape Likelihood)} \\
& + \Sigma_{k=1}^{T}(\eta_s \epsilon_s + \boldsymbol{\eta_b \epsilon_b}) t_k \quad \text{(Extended Likelihood)} \\
& + \Sigma_{k=1}^{T} \frac{(\boldsymbol{\eta_{b,k}} - \hat{\boldsymbol{\eta}}_{\boldsymbol{b,k}})^2}{2\sigma_{\boldsymbol{b}}^2} \quad \text{(Nuisance)}
\end{aligned} \tag{1}
$$