

SNO+

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Abstract. SNO+ is an operating liquid scintillator neutrino detector. Filling with liquid scintillator was completed in April 2021. Previously, SNO+ took water-filled data and also made measurements of backgrounds during scintillator partial-fill. These measurements (included physics results) enable SNO+ to quantify backgrounds for our final objective, the search for neutrinoless double beta decay when tellurium is loaded in the liquid scintillator detector at 0.5% by weight. This article highlights several measurements made by SNO+ and summarizes the status and outlook of the experiment.

1. Introduction

The SNO+ experiment is the successor to the Sudbury Neutrino Observatory (SNO) experiment. Located in the SNOLAB underground lab sited in Vale's Creighton mine near Sudbury, Ontario, SNO+ is at an underground depth of 2 km (roughly 6000 metres water equivalent). Much of the original hardware in SNO was repurposed and adapted for SNO+, including the Acrylic Vessel (12 m diameter acrylic sphere), the Photomultiplier Support Structure (PSUP) and photomultiplier tubes (PMTs), the electronics, and the ultra-pure water system. In place of the heavy water that was in SNO, 780 tonnes (the mass in the spherical portion) of an organic liquid scintillator solvent – linear alkylbenzene (LAB) – has been filled in the detector. A fluor PPO (2,5-diphenyloxazole) is added to the LAB, at a concentration of 2 g/L (final target).

As a scintillation detector, the light output in SNO+ is higher than a water Cherenkov detector. This allows SNO+ to access lower energies. SNO+ has multiple physics goals with its primary goal being the search for neutrinoless double beta decay after ^{130}Te is added to the liquid scintillator. Other neutrino physics goals include measurements of geo and reactor antineutrino fluxes and neutrino oscillation parameters, detection of neutrinos from a galactic supernova, and solar neutrino studies at lower energy. Other rare event physics can be also searched for, such as nucleon decay.

In this article, the objectives and status of the SNO+ experiment are summarized, as they were presented at the TAUP 2021 conference on astroparticle and underground physics. Results from the SNO+ experiment's water phase and a first look at data from the SNO+ scintillator phase are also described here.



2. Three Phases of SNO+

SNO+ will take data in three phases. In the water phase, the detector was filled with water both inside and outside the Acrylic Vessel (AV). The purpose of this phase was to fully characterize the detector after it was refurbished, prior to the addition of liquid scintillator. In the scintillator phase, the detector is now filled with liquid scintillator inside the AV. As a scintillation detector, SNO+ will pursue a diverse program of neutrino physics measurements. In addition, backgrounds in the experiment will be measured in the scintillator phase with everything deployed except for the double beta decay isotope. This “target out” measurement will serve as an important constraint in the ultimate double beta decay analysis. In the third phase of SNO+, tellurium (natural isotopic abundance, no enrichment) will be added to the liquid scintillator with the objective of searching for neutrinoless double beta decay of ^{130}Te with sensitivity that probes the parameter space suggested by the Inverted Mass Ordering. To prepare for all three of these phases, several detector hardware additions, upgrades, and the construction of three major process systems have been completed. Among the major additions that transformed SNO into SNO+ are:

- the installation of a low radioactivity rope net over the acrylic sphere that holds down the AV. When filled with liquid scintillator (with water outside, surrounding the AV), the vessel becomes buoyant with an upward force of roughly 140 tonnes.
- In anticipation of higher data rates in scintillator, the SNO electronics readout and DAQ were revamped for SNO+ to enable building events across multiple crates using new crate controller cards that assemble PMT data from the individual electronics channels into Ethernet packets that are pushed over a high-bandwidth network to a central server master trigger module. The new DAQ builds events over various set Nhit thresholds using these packets. The total bandwidth for parallel readout of the full detector has now been greatly increased compared to what it was for SNO (by orders of magnitude) and is about a factor 100 greater than the (higher) nominal data rate in liquid scintillator.
- New calibration systems (for source deployment) appropriate for use in liquid scintillator have been built. A separate optics calibration system that uses embedded optical fibres to inject laser and LED light into the detector has also been installed and is now being used.
- A complex, multiple-process scintillator purification plant has been installed underground (in place of the heavy water purification system that was used for SNO). Scintillator purification processes that are available for SNO+ use include distillation, water extraction, nitrogen and steam stripping, and adsorption scavenger columns.
- Two plants have been built and installed underground for chemical processing of tellurium. One purifies tellurium to remove traces of natural radioactivity, including any long-lived cosmogenic isotopes. The second system synthesizes the tellurium organo-complexes that enable its dissolution in linear alkylbenzene scintillator.

A detailed description of each of these SNO+ detector hardware subsystems, and all aspects of the SNO+ detector, can be found in [1].

2.1. Water Phase

The SNO+ water phase was completed between 2017-2019. Operated as a water Cherenkov detector, SNO+ has published three significant physics results so far: limits on invisible modes of nucleon decay [2], the measurement of the flux of ^8B solar neutrinos with remarkably low backgrounds [3] and a measurement of the neutron-proton capture cross section [4], a result enabled by the high neutron detection efficiency in SNO+ – the highest in an undoped water Cherenkov detector. Since the publication of these results, there was an extended period of data taking in the water phase. During this period, the levels of radon ingress into the water (into the detector) were an order of magnitude lower on account of the operation of a new cover gas system which reduce Rn levels above the internal AV water volume. With the added data from the extended water dataset, the SNO+ limits on invisible modes of nucleon decay become the best limits for both proton and neutron decay modes (publication

forthcoming). Invisible modes of nucleon decay are only detected by the deexcitation gamma rays emitted by oxygen nuclei following the decay of a nucleon. The very low backgrounds in SNO+ (on account of the deep underground location and greatly reduced spallation backgrounds) and the absence of solar neutrino events on deuterons (when compared to SNO) are the reasons for the better nucleon decay results in SNO+. An improved measurement of ^8B solar neutrinos will also be published soon, which will demonstrate even lower backgrounds (an order of magnitude lower than before).

The SNO+ water phase was also extremely useful for measuring external backgrounds. External backgrounds are those that originate from radioactivity outside the inner volume: from the AV, ropes, external water and the PMTs. The Cherenkov signals produced by these (and other) events in SNO+ water have directional information that enable background components to be statistically distinguished. Figure 1 illustrates this for a portion of the data from the water phase. From the water phase data, we were able to place a constraint on the external component of backgrounds in the eventual SNO+ double beta decay (DBD) region-of-interest (ROI). Because the radiopurity of various detector components had been assayed, we had a target value for external backgrounds that was estimated at 1.2 events/yr (in the DBD ROI). The measurements from the water phase confirm this value, determining it to be $0.93_{0.4}^{1.1}$ events/yr (in agreement and slightly better than expectation).

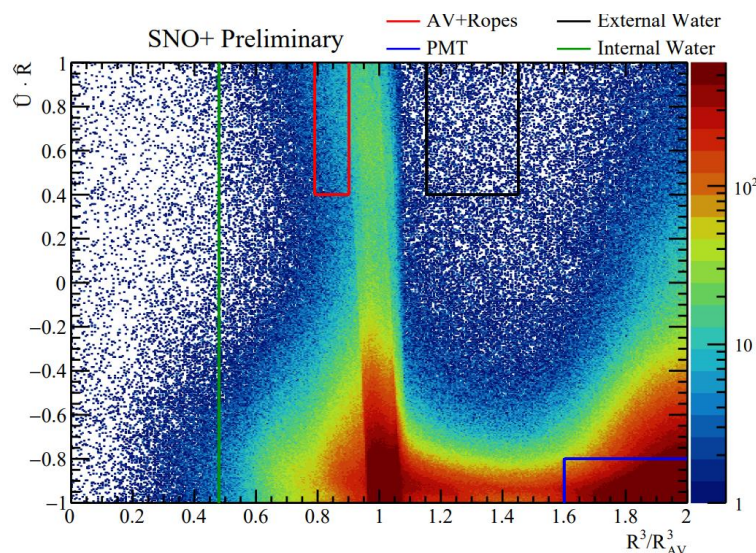


Figure 1 Event direction versus radial position of events in the SNO+ water phase. The directional information available from the Cherenkov signals enable various external background components to be distinguished from internal background events.

2.2. Scintillator Phase

The filling of the SNO+ detector with liquid scintillator was a long and difficult campaign. The logistics involved regularly receiving shipments (20-40 tons each) of linear alkylbenzene, transporting the LAB from surface to underground in dedicated rail cars, unloading those rail cars into underground storage tanks, and purifying the LAB by distillation prior to filling the AV, then turning around each of the operations in time for the next iteration. This operation was greatly complicated by the COVID-19 pandemic restrictions on operations and access. With great dedication and perseverance, the filling of SNO+ with liquid scintillator was completed in early April 2021. During the procurement, and the purification and filling operations, there were ongoing quality assurance tests that had to be completed, to ensure that our purified scintillator product was of the highest quality prior to sending it to the AV. The fluor PPO was also purified by water extraction and by distillation, prior to inline mixing into the purified LAB stream.

Because of the prolonged filling period, during the first COVID-19 “lockdown” when access to the underground lab was strictly limited, there was a quiet period of data taking that we refer to as “partial

fill". During this period, there was 365 tonnes of LAB in the detector, floating above a volume of ultra-pure water. The PPO concentration in the scintillator was roughly 0.5 g/L during this period. The observed light yield in the detector was ~ 300 photoelectrons/MeV (slightly better than expected from calibration standards at this concentration). This tells us that the quality of the scintillator in the detector was very good.

The quiet period of data taking allowed Rn levels in the detector to decay to very low levels. Radon gets injected into the detector during filling operations; the source of Rn in the scintillator process is being ascertained. All previous liquid scintillator experiments have experienced the challenge of controlling small amounts of Rn leaking into the process during filling (and recirculation) operations.

With Rn at low levels during partial fill, and using delayed coincidence events from $^{214}\text{Bi-Po}$ and $^{212}\text{Bi-Po}$, SNO+ measured the levels of U and Th in the intrinsic scintillator. The U-chain equivalent level (of supported ^{222}Rn) was measured to be $(4.7 \pm 1.2) \times 10^{-17}$ gU/gLAB, while the Th-chain equivalent level is $(5.3 \pm 1.5) \times 10^{-17}$ gTh/gLAB. At these levels, the contribution to the background budget in the DBD ROI from the intrinsic liquid scintillator is subdominant. The purity of the intrinsic liquid scintillator (prior to the addition of tellurium) is certainly good enough to satisfy our DBD targets.

2.2.1. Neutrino Physics in the SNO+ Scintillator Phase. Physics measurements in the SNO+ scintillator phase have begun (including in the partial-fill period). A preliminary look at ^8B solar neutrinos in SNO+ liquid scintillator is displayed in Figure 2. Figure 2 shows the Nhit spectrum (roughly equivalent to an energy spectrum). At high enough energies, external backgrounds from ^{208}Tl fall off leaving only events that can be clearly attributed to the elastic scattering of ^8B solar neutrinos with electrons (in the scintillator). The low background nature of the SNO+ liquid scintillator is evident.

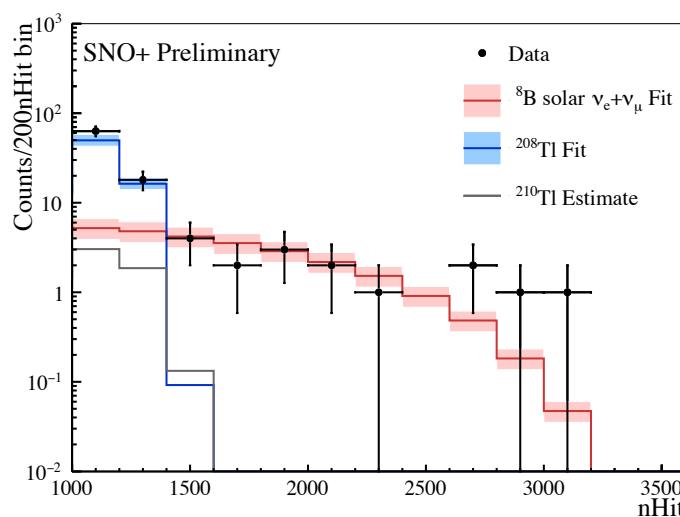


Figure 2 Solar neutrino events in the SNO+ liquid scintillator (partial fill) plotted as an Nhit energy spectrum.

2.3. Tellurium Double Beta Decay Phase

Due to the (large) 34% natural abundance of ^{130}Te , deploying natural tellurium in SNO+ at 0.5% by weight would result in 1,330 kg of ^{130}Te isotope loaded in the SNO+ liquid scintillator. The SNO+ approach to double beta decay, with natural tellurium-loaded liquid scintillator is highly scalable and orders of magnitude less expensive than other approaches that use isotopically enriched elements. Tellurium can be loaded in the SNO+ liquid scintillator at up to 3%wt, maintaining good light yield and stability. Tellurium has several traits that make it well suited for a neutrinoless double beta decay experiment (e.g., see the experimental review talk by A. Giuliani at this conference). Some of the

major advantages of the loaded liquid scintillator approach include that very low backgrounds can be achieved. SNO+ targets a “background index” in the Te-loaded liquid scintillator of 5×10^{-7} counts/keV/kg_{fiducial}/yr, which is remarkably low. An additional feature of the SNO+ DBD experiment is the fact that we will measure all non-Te-related backgrounds prior to isotope addition. This “target out” measurement will be used as a powerful constraint in the final DBD analysis. The capability to demonstrate that a putative signal of neutrinoless double beta decay varies as the quantity of isotope loaded is one that SNO+ can exploit. Figure 3 shows the predicted SNO+ DBD background budget.

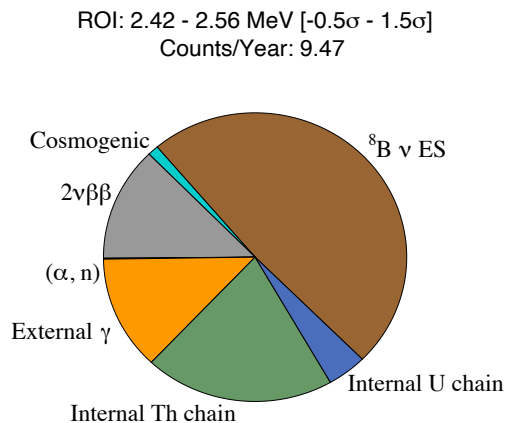


Figure 3 SNO+ neutrinoless double beta decay ROI background estimates. SNO+ has already measured many of these components and will use these measurements as constraints when fitting the spectral shape in the DBD analysis.

Both tellurium plants have been built, installed, and commissioned underground. We are waiting for approvals from SNOLAB to enable us to proceed with tests with full batches (250 kg each) of purification of telluric acid, and synthesis of Te-butanediol (the LAB-soluble complexes that SNO+ will use to load Te to 0.5%wt). These are the next steps in the SNO+ Te DBD program.

3. Outlook

Currently, there are ongoing scintillator operations that involve topping up the PPO concentration to reach 2.0 g/L in the AV. Meanwhile, SNO+ is measuring background levels in the full scintillator detector. The program of antineutrino physics has begun. The IBD signal ($\bar{\nu}_e + p \rightarrow e^+ + n$) is more resilient to higher Rn levels that occur during filling and recirculation operations. The SNO+ measurement will be an interesting test of the value of Δm_{12}^2 measured using the oscillations of reactor antineutrinos (from nuclear power plants in Ontario). This will enable SNO+ to test the tension in this value between current reactor measurements and the global solar best-fit value [5]. Moving forward with the double beta decay phase is anticipated to start towards the end of next year. The double beta decay program will commence following more than a year of pure scintillator measurements of backgrounds and neutrino physics.

References

- [1] SNO+ Collaboration V. Albanese *et al.* 2021 *JINST* **16** P08059.
- [2] SNO+ Collaboration M. Anderson *et al.* *Phys. Rev. D* **99**, 032008 (2019).
- [3] SNO+ Collaboration M. Anderson *et al.*, *Phys. Rev. D* **99**, 012012 (2019).
- [4] SNO+ Collaboration M.R. Anderson *et al.*, *Phys. Rev. C* **102**, 014002 (2020).
- [5] I. Esteban *et al.*, *JHEP* **1901**, 106 (2019) and A. Gando *et al.* (KamLAND Collaboration), *Phys. Rev. D* **83**, 052002 (2011).