PROCEEDINGS OF SCIENCE

Physics results from the SNO+ scintillator phase and Neutrinoless Double Beta Decay prospects

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SNO+ is a large multi-purpose neutrino detector located 2 km underground at SNOLAB, Canada, currently in operation filled with 780 tonnes of liquid scintillator as its target mass. The high light yield, low background levels, and continually increasing livetime, allow the SNO+ collaboration to perform measurements of solar neutrinos, antineutrinos from reactors and the Earth, and searches for other rare events. The data is also being used to quantify backgrounds and understand the detector response in preparation for the search of neutrinoless double beta decay of ^{130}Te. In a first phase, SNO+ will perform this search with 0.5% of natural tellurium by weight, for a predicted half-life sensitivity of 2×10^{26} years (90% CL) with 3 years of livetime, followed by higher tellurium loadings, up to 3%, for sensitivities above 10^{27} years. These proceedings highlight the most recent physics results from the analysis of the SNO+ scintillator data, and discuss the prospects for the neutrinoless double beta decay search.

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1. The SNO+ experiment

SNO+ is a multi-purpose, low-background liquid scintillator experiment for neutrino physics, located 2 km underground at SNOLAB in Sudbury, Canada [1, 2]. The detector reuses most of the infrastructure from the Sudbury Neutrino Observatory (SNO), which operated from 1999 to 2006 [3], with several major upgrades to enable operation with liquid scintillator as the target medium. The SNO+ detector (Fig. 1) consists of a 6 m radius spherical acrylic vessel (AV) with a wall thickness of 55 mm, suspended at the centre of a geodesic stainless steel structure (PSUP) of ~8.9 m radius. The PSUP holds 9362 inward-facing photomultiplier tubes (PMTs) with low-activity glass and light concentrators. The AV contains approximately 780 tonnes of liquid scintillator (LS) [4], currently a mixture of linear alkylbenzene (LAB) doped with 2.2 g/L of 2,5-diphenyloxazole (PPO) and 2.2 mg/L of bis-MSB as wavelength shifters. The region between the AV and the PSUP, as well as the surrounding cavity, is filled with ~7000 tonnes of ultra-pure water, which provides shielding from radioactivity in the PMT array and surrounding rock. The detector is located beneath a flat overburden of 2070 m (equivalent to 6010 m.w.e), reducing the cosmic muon flux to (0.286 ± 0.009) $\mu/\text{m}^2/\text{d}$ [5]. Significant upgrades from SNO to SNO+ included a hold-down rope system to counteract the buoyancy of the AV when filled with LS, new calibration and monitoring systems, and upgraded electronics to handle higher light yields and data rates [2].

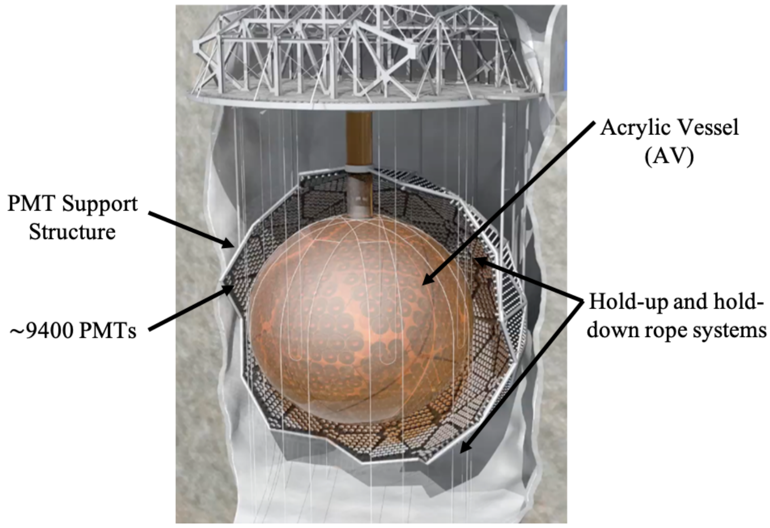

Figure 1: Schematic of the SNO+ detector.

Due to its large target mass, high radiopurity, and deep underground location, SNO+ enables a broad and versatile physics program, including topics such as solar neutrinos, reactor antineutrinos, geo-neutrinos, supernova neutrinos, and searches for other rare processes and interactions. However, the primary long-term goal of SNO+ is the search for the neutrinoless double beta decay ($0\nu\beta\beta$) of ^{130}Te by loading the liquid scintillator with natural tellurium (Section 3).

During its initial water phase (May 2017–June 2019), SNO+ operated as a pure-water Cherenkov detector with the AV filled with 905 tonnes of ultra-pure water. This period was essential for detector commissioning, detailed calibration campaigns [6, 7], and background characterization of non-target-medium detector components (external backgrounds). Several physics results were achieved during this phase, including low-background measurements of the ^{8}B solar neutrino flux [8, 9], the first evidence of antineutrinos from distant reactors in a water Cherenkov detector [10], and improved limits on the search for invisible nucleon decay modes [11, 12].

The transition to the scintillator phase began in late 2018 with the gradual replacement of water in the AV by liquid scintillator. The full fill was completed in March 2021, followed by a PPO top-up campaign concluded in 2022. Since then, SNO+ has continuously acquired data with scintillator, producing several important physics results which will be summarized in Section 2. Serving as a crucial milestone toward the upcoming $0\nu\beta\beta$ search, this phase has enabled a detailed understanding of the liquid scintillator background levels prior to the loading of ^{130}Te, as well as a phased characterization of the scintillator's optical response as different components of the cocktail are added. In the next phase, expected to begin in 2026, the liquid scintillator will be initially loaded with approximately 3.9 tonnes of natural tellurium (0.5% by weight) to start the search for the $0\nu\beta\beta$ decay of ^{130}Te (Section 3).

2. Physics results with scintillator

2.1 ^{8}B solar neutrino flux and oscillations

The SNO+ detector is sensitive to the elastic scattering of ^{8}B solar neutrinos on electrons in the liquid scintillator. These events are detected in a window of reconstructed energies above approximately 3 MeV, where the dominant background arises from the β–γ decays of ^{208}Tl. Flux measurements are performed using different fiducial volumes to balance signal statistics with background rejection and detector model uncertainties, which are higher at larger radii closer to the AV. Current measurements, shown in Figure 2, are still limited by statistical uncertainties but are consistent with expectations based on the Standard Solar Model (SSM) and neutrino oscillation parameters.

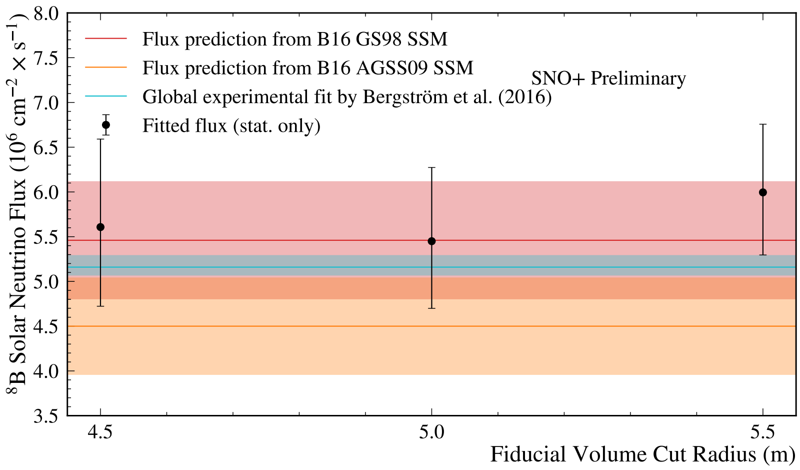

Figure 2: Preliminary ^{8}B solar neutrino flux measurements (E > 3 MeV) at three different spherical fiducial volumes with radius of 4.5 m, 5.0 m, and 5.5 m.

An on-going goal for this analysis is to lower the energy threshold below 3 MeV to increase sensitivity to the spectral transition point from the matter-dominated oscillations within the Sun to the vacuum-dominated oscillations. The backgrounds in this lower energy region and within a stricter fiducial volume (Figure 3) are low. The dominant ^{208}Tl can be mitigated using tagging techniques and a multisite event classifier [13]. A parallel analysis framework was created to extract oscillation parameters from the energy spectrum and event rate. Preliminary results with a limited dataset show sensitivity to $\sin^2\theta_{12}$, although current uncertainties are dominated by limited statistics. Future plans include extending the dataset and combining the solar neutrino oscillation analysis with the parallel SNO+ reactor antineutrino oscillation analysis (Section 2.3).

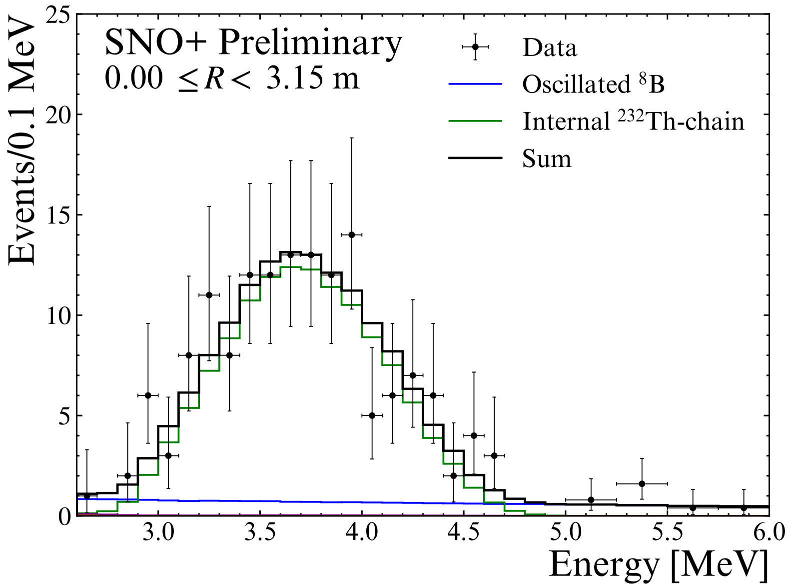

Figure 3: Fitted energy spectrum within 2.6 and 6.0 MeV, using data in a spherical fiducial volume with radius of 3.15 m.

2.2 Solar neutrino charged-current interactions on ^{13}C

SNO+ has performed the first observation of solar neutrino charged-current interactions on ^{13}C in the SNO+ liquid scintillator [14]. In this process, a ^{8}B neutrino interacts with a ^{13}C nucleus via

$$\nu_e + {}^{13}\mathrm{C} \rightarrow e^- + {}^{13}\mathrm{N}, \tag{1}$$

followed by the β^+ decay of ^{13}N with a half-life of 10 minutes:

$$^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^+ + \nu_e. \tag{2}$$

This delayed coincidence signature between the prompt electron and the subsequent positron provided a distinct signal for this measurement. The analysis used 231 days of scintillator data, selecting prompt events with energies above 5 MeV, where the dominant background arises from ^{8}B ES interactions. The delayed component is primarily affected by accidental coincidences, which were estimated through a data-driven background model. A likelihood-based discriminant was employed to separate (correlated) signal from (uncorrelated) accidental background pairs.

The $5.6^{+3.0}_{-2.3}$ observed events in the data set are consistent with the expectation of $4.7^{+0.6}_{-1.3}$ events. This result is the second real-time measurement of CC interactions of ^{8}B neutrinos with nuclei and constitutes the lowest energy observation of neutrino interactions on ^{13}C generally. This enables the first direct measurement of the CC electron neutrino reaction to the ground state of ^{13}N, yielding an average cross section of $(16.1^{+8.5}_{-6.7}(\text{stat.})^{+1.6}_{-2.7}(\text{syst.})) \times 10^{-43}$ cm^2 over the relevant ^{8}B solar neutrino energies.

2.3 Reactor and geo antineutrinos

SNO+ is sensitive to antineutrinos ($\bar{\nu}_e$) produced by nuclear reactors and from radioactive decays within the Earth, detected via the inverse beta decay (IBD) reaction,

$$\bar{\nu}_e + p \rightarrow e^+ + n, \tag{3}$$

in which the prompt positron annihilates to produce a coincident signal of two 511 keV γ rays, followed by the delayed neutron capture on a proton emitting a characteristic 2.2 MeV γ. The dominant antineutrino flux at SNO+ originates from several nuclear reactor complexes located at baselines of 240–355 km, primarily the Bruce, Pickering, and Darlington power stations in Ontario, Canada. Additional contributions come from more distant reactors across North America, as well as from natural radioactivity within the Earth's crust and mantle, producing geo-neutrinos. The expected event rates in the scintillator phase are approximately 100 reactor antineutrino events and 25 geo-neutrino events per year (after oscillations). The primary background arises from (α, n) reactions on ^{13}C, producing neutrons that can mimic the delayed coincidence signal. The main source of α particles within the scintillator are the decays of ^{210}Po. Additional accidental and cosmogenic backgrounds are suppressed through fiducial volume cuts, timing and spatial coincidence requirements, and muon vetoes.

With 286 tonne-years of data, SNO+ performed the second most precise measurement of $\Delta m^2_{21} = (7.96^{+0.48}_{-0.42}) \times 10^{-5}$ eV^2, while also measuring $\sin^2\theta_{12} = 0.62^{+0.16}_{-0.40}$ [15]. These results are in good agreement with KamLAND[16] but showing mild tension with the solar neutrino value derived from global fits. In parallel, SNO+ also performed the first measurement of the flux of geoneutrinos in the Western Hemisphere, with 73^{+47}_{-43} TNU. On-going work is focusing on extended datasets and further (α, n) background reduction, with new results to be published soon.

3. Towards a Te-loaded SNO+

The main goal of the SNO+ experiment is the search for neutrinoless double beta decay ($0\nu\beta\beta$) of ^{130}Te, a process that, if observed, would demonstrate the Majorana nature of neutrinos and provide direct insight into the absolute neutrino mass scale. The detection of $0\nu\beta\beta$ would also demonstrate violation of lepton number conservation, with profound implications for particle physics and cosmology. SNO+ selected Tellurium-130 as the target isotope due to its high natural abundance (34%), eliminating the need for costly enrichment, its relatively long two-neutrino double beta decay ($2\nu\beta\beta$) half-life of 8.76×10^{20} years [17], and its high Q-value of 2.527 MeV, which lies above most natural radioactive backgrounds.

For this endeavour, SNO+ will load the liquid scintillator with natural tellurium using a novel technique developed by the collaboration, fully described in [18]. The extensive research and development program of the SNO+ tellurium loaded cocktail has demonstrated excellent long-term chemical stability, radiopurity, and optical transparency for loadings of up to a few percent by weight. Furthermore, the SNO+ detector offers several advantages for a sensitive $0\nu\beta\beta$ search. Its large detection volume enables self-shielding through fiducialisation to suppress external backgrounds; the Te concentration in the liquid scintillator can be increased over time; the phased approach of SNO+ towards the Te-loaded phase allows characterization of detector response, optical model, and background components prior to full Te loading. These characteristics allow SNO+ to systematically constrain internal and external background sources while progressively improving sensitivity.

In an initial phase, SNO+ will deploy a 0.5% Te loading by weight, corresponding to approximately 1333 kg of ^{130}Te. After three years of live time, this configuration is projected to achieve a $0\nu\beta\beta$ half-life sensitivity of $T^{0\nu}_{1/2} > 2 \times 10^{26}$ years (90% C.L.). With the target background levels for this loading, the expected number of events in the search region-of-interest (ROI) between 2.42 and 2.56 MeV is 9.47 events per year. The main contribution comes from the irreducible but well-characterized ^{8}B solar neutrinos. The contribution from the internal U and Th chains in the unloaded scintillator have been measured to be below target for the Te phase. Additional U/Th contributions from the tellurium itself will be reduced during the Te purification process. External γ rays from contamination in the other detector components were thoroughly characterized and constrained during the water phase, and are efficiently removed through optimized fiducial volume cuts. Other expected backgrounds from the cosmogenic activation of Tellurium when it was on surface are expected to be considerably lower given that the telluric acid has been stored underground for several years, and reduction of these backgrounds is expected from the Te underground purification systems prior to deployment. Finally, the contribution of the tail of the intrinsic $2\nu\beta\beta$ mode will be minimized through an asymmetric ROI. Following this initial phase, SNO+ plans to increase the Te loading to 1.5% by weight, for an improved half-life sensitivity of $T^{0\nu}_{1/2} > 7.4 \times 10^{26}$ years (90% C.L.).

4. Summary

The SNO+ experiment has been actively acquiring data with liquid scintillator, and using it to perform neutrino measurements across a broad range of topics, search for rare events, and perform a full characterization of the liquid scintillator and detector response and of the liquid scintillator backgrounds in preparation for the Te-loaded phase. The results highlighted here are in the process of being improved by using more and newer data, as well as the use of additional analysis-based background rejection methods.

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