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SNO+ present status and prospects

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SNO+ present status and prospects

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Abstract. SNO+ has been taking data for one year, as a pure water Cherenkov detector, while preparing for filling with scintillator and then loading 3900 kg of Tellurium to search for neutrinoless double beta decay. This contribution reviews the present results and status of SNO+, focusing on how the water commissioning phase extends the capabilities of previous Cherenkov detectors, and on the results that the present data provides for neutrino and other low background physics.

1. Introduction

The ultimate goal of the SNO+ experiment [1] is the search of neutrinoless double beta decay. The existence of this decay, violating lepton number conservation, would indicate that neutrinos are Majorana particles. This would provide an indication of the absolute neutrino mass scale, since the decay rate is proportional to an effective neutrino mass, depending on the mixing matrix parameters and mass eigenvalues.

The strategy of SNO+ is to load more than a thousand kilograms of a known double beta isotope in a large volume liquid scintillator detector, with very low background level, and a high optical coverage surrounding it. SNO+ is sensitive also to other low energy physics and is an observatory for solar, geo and supernova neutrinos. Detector commissioning is planned into three experimental phases, in which the active medium is changed, and different physics goals can be achieved.

The next sections describe the SNO+ detector and the experimental phases foreseen, first physics results of the water phase and, lastly, the next steps and prospects for the neutrinoless double beta decay search.

2. SNO+ detector and 3 physics phases

SNO+ reuses the infrastructure of the SNO experiment (see Figure 1). It is installed 2092 m underground at SNOLAB, Canada, in an experimental hall filled with pure water for shielding; $\sim$9300 PMTs view the liquid active medium, housed in a transparent spherical acrylic vessel that held 1 kiloton of heavy water in SNO and will hold 780 Ton of scintillator in SNO+. It is the active medium inside the acrylic vessel that defines the experimental phase.

Changing from the SNO heavy water target to SNO+ liquid scintillator required some changes: hold-down ropes were installed to compensate for the lower density of the scintillator (0.86 g/cm^3), and the existing hold-up ropes were replaced with radio-pure material ones, as required for a low energy measurement; fixed optical calibration sources [2] were installed to allow monitoring with less intrusion, and the electronics and DAQ were upgraded to deal with higher rates.

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New purification and recirculation systems were needed. Underground facilities for the distillation and purification of the liquid scintillator[1] are in place; a telluric acid purification plant has been constructed and another is being built to synthetise the butanediol that allows its mixing in the scintillator; 3.8 tonnes of telluric acid are already underground, cooling down from its cosmogenic activation when at surface.

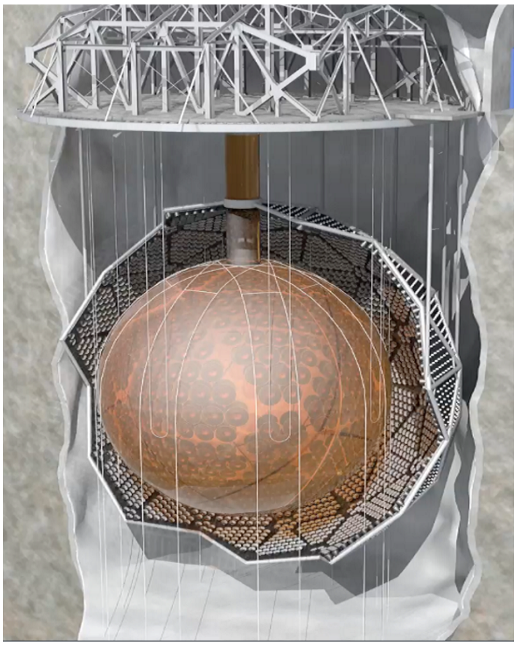

Figure 1. 3D sketch of SNO+ detector: the 12 m diameter acrylic vessel (shown in transparent color) is held by a system of ropes (white) at the center, and viewed by the $\sim$ 9300 PMTs held in a 18 m diameter geodesic structure. Each PMT has a light concentrator of 27 cm diameter, providing a large effective photo coverage of $\sim$54%. The detector is located in a cavity excavated in the rock and filled with 7 kTon of water. The electronics are placed above this cavity; the detector is accessed through the "neck", and extra guide tubes around it for the external water.

Three SNO+ phases are planned, with different commissioning as well as physics goals:

- **the water phase:** a pure water Cherenkov detector, allows to measure events occurring both inside and outside the acrylic vessel, with directional information, and to characterize the optical properties of the outer water and PMT response.
- **the scintillator phase:** a pure liquid scintillator detector, with much lower energy threshold, which allows to characterize the optical properties and backgrounds of the scintillator, in the absence of the double beta decay isotope.
- **the Tellurium phase:** the liquid scintillator is loaded with tellurium and the two neutrino double beta decay becomes the main signal, above which the neutrinoless decay must be searched for; a 5 year data taking is planned.

3. SNO+ water phase – a low energy Cherenkov detector

SNO+ started taking data in May 2017. The detector is operated from underground or remote control rooms (in addition to SNOLAB, several others are already operating in Canada, USA and Europe). The water phase allowed the commissioning of water circulation and assay systems, and of the electronics, trigger and DAQ. It served to exercise the data processing and data cleaning methods, along with the detailed run-by-run detector simulations. A reasonable fraction of the time was dedicated to calibrations: in addition to forced electronic triggers and fixed optical sources, deployable optical and radioactive sources were used to scan the inner and outer water volumes.

[1] The liquid scintillator of SNO+ consists of an aromatic hydrocarbon, linear alkylbenzene (LAB), as a solvent, and 2,5-diphenyloxazole (PPO) as a fluor in a concentration of 2 g/L.

IOP Conf. Series: Journal of Physics: Conf. Series **1137** (2019) 012053 doi:10.1088/1742-6596/1137/1/012053

The main optical calibration relies on a diffuser laser-ball, run at different wavelengths from multiple position. The results are translated to a full optical model, separating the properties of the external water and acrylic vessel from the ones of the liquid scintillator, which will be measured in later phases. This calibration has confirmed the expected degradation of the PMT response at large incidence angle, due to the aging of the light concentrators.

A 3D scan was also done with a ^{16}N source, using a 6.1 MeV γ to directly measure the resolutions of the physical quantities used in further analysis: position (based on PMT hit timing), energy (based on the number of PMT hits and detector optical properties), and direction (from the Cherenkov cone reconstruction). This calibration provided a validation of the full simulation model, and the systematic uncertainties of the event reconstruction.

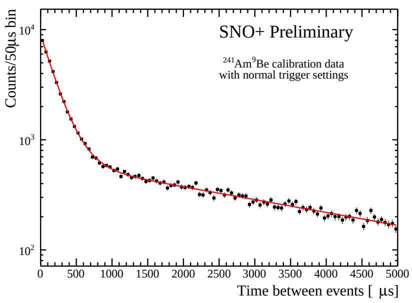

Figure 2. Time difference between following events in an AmBe calibration run (see text). The distribution is fitted with a two exponential function, for measuring the true and random coincidence rates simultaneously, and to extract the neutron capture time constant.

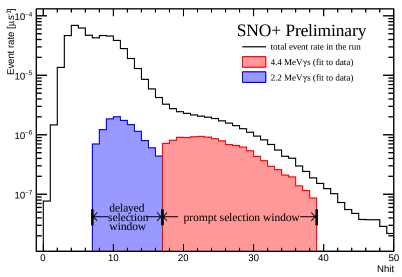

Figure 3. Distribution of hit PMT numbers for the same calibration run, with the AmBe at detector center. The colored regions show the signals of the 2.2 MeV and 4.4 MeV γs, from the statistical analyses of coincidences; the line shows the full distribution for single events.

In September, the triggers were adjusted and the thresholds lowered to unprecedented values of 1 MeV. The calibration was extended to lower energies, using an AmBe source, which provides time coincidence pairs of a prompt 4.4 MeV γ (from Carbon deexcitation at source) and a delayed 2.2 MeV γ (from neutron capture in free hydrogen after thermalization in the water).

Figure 2 shows the time difference between following events selected after basic data cleaning for a one hour calibration run, requiring only a minimum of 17 PMT hits for the prompt event and 7 for the delayed event. By fitting two exponentials, we extract the true and random coincidence rates and the neutron capture time constant of $208.1 \pm 2.1 \mu$s.

By varying the PMT hit thresholds, the full distributions corresponding to the 2.2 MeV and 4.4 MeV γs can be obtained statistically under a large background (figure 3). Using this data analysis, independently of simulation, we determined that the efficiency for detecting the capture of a neutron produced at the center of the detector is larger than 46%.

The delayed coincidence of a neutron capture after a positron is the signature that allows to tag anti-neutrino inverse beta decay interactions, and the low energy thresholds achieved may be used to measure reactor anti-neutrinos for the first time in a pure water Cherenkov detector.

4. Water phase physics results

The main physics goal defined for the SNO+ water phase was the search for invisible nucleon decays of ^{16}O, resulting on deexcitation γs of 6 to 7 MeV. SNO+ is expected to improve the

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current limits for both neutron and proton decays [3, 4]. The search is conducted in a blind analysis, and the results are expected soon after the end of this phase. They represent a full test of the water Cherenkov capabilities, using all the analysis variables, namely energy (E), position ($\vec{r}$, to define a fiducial volume and limit external backgrounds), direction ($\vec{u}$, to identify the origin of backgrounds and solar neutrinos) and an isotropy parameter, that distinguishes single β Cherenkov rings from ^{241}Bi decays, and multiple γ rings from ^{208}Tl decays.

The contribution from internal water backgrounds is measured in a 4.3 m radius fiducial volume, for 4 MeV$< E <$ 5.6 MeV. Assuming secular equilibrium, these are limited to less than 2.8 x 10^{-14} g/g of Thorium, at a confidence level of 95%, and $[5.4 \pm 0.7(\mathrm{stat}) \pm 2.9(\mathrm{syst})] \times 10^{-14}$ g/g of Uranium, in agreement with the targets set for the water phase.

External backgrounds are measured by two independent analysis which use the reconstructed event position, and either its direction or the isotropy parameter, to determine the different contributions of PMTs, external water, acrylic vessel and ropes. Both achieve results compatible with each other and with the expected levels quoted in [1]. These background sources will not change and the results are directly portable to the next phases.

Solar neutrino electron scattering signals are measured by fitting the distribution of the angle between the direction of the reconstructed events and the Sun, in a sample of 115 live days of data. The results are fully compatible with expectations for the ^{8}B fluxes including neutrino oscillations, and are given for two energy thresholds, 4.5 and 5.5 MeV (the second being almost background free), respectively:

- $\phi_{T\in[4.5,15]MeV} = (6.56^{+1.06}_{-1.01}(\mathrm{stat})^{+0.33}_{-0.58}(\mathrm{syst})).10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$;
- $\phi_{T\in[5.5,15]MeV} = (6.09^{+0.78}_{-0.73}(\mathrm{stat})^{+0.38}_{-0.46}(\mathrm{syst})).10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.

5. SNO+ double beta decay prospects

During 2018, the detector will start to be filled with liquid scintillator from the top, while the water inside the acrylic vessel is drawn from below. Data taking will continue while filling and then the scintillator phase starts. New measurements of lower energy signals, other solar neutrinos or geo anti-neutrinos, will become possible. These data will be used to determine the levels of the internal backgrounds, including previously unseen α decays, and to test the background tagging techniques. The target levels for the purification systems are 10^{-17} g/g and 10^{-18} g/g for the Uranium and Thorium, respectively, and lower for ^{40}K, ^{39}Ar and ^{85}Kr – too low to be measured previously to filling the large detector volume.

SNO+ will then proceed to its last phase, dedicated to the neutrinoless double beta decay search. Tellurium was chosen due to the high natural abundance (34%) of the ^{130}Te isotope, which has a known low rate of the two-neutrino double beta decay ($T_{1/2} = 8.2 \times 10^{20}$ years [5]) with a high end point energy (Q = 2.53 MeV). A load of 0.5% by mass in 780 tonnes of liquid scintillator provides 1330 kg of the ^{130}Te and has been shown to keep a high light yield, good transparency and a fast decay, allowing for pulse shape analysis for α/β discrimination [6].

Figure 4 shows the energy spectrum expected around the $0\nu\beta\beta$ peak. The region of interest is defined asymmetrically ([-0.5σ, 1.5σ] around the Q-value) to reduce the $2\nu\beta\beta$ end-point contribution, such that the known ^{8}B solar neutrino flux becomes the dominant background. External backgrounds, for which the levels were measured in the water phase, are reduced by a fiducial volume cut. Internal backgrounds from the Uranium and Thorium chains are to be reduced with $\alpha - \beta$ coincidence tagging of the Bi-Po decays, which will be tested during the pure scintillator phase. Internal backgrounds from cosmogenic activation of Tellurium are expected to contribute less than 1 count per year.

In the absence of signal, the expected limit for $0\nu\beta\beta$ decays is of $T_{1/2} > 1.9 \times 10^{28}$ years at 90% confidence level. The translation to neutrino parameters depends on the nuclear model used, and spans effective masses of 41-99 meV [1]. These would cover the full degenerate mass

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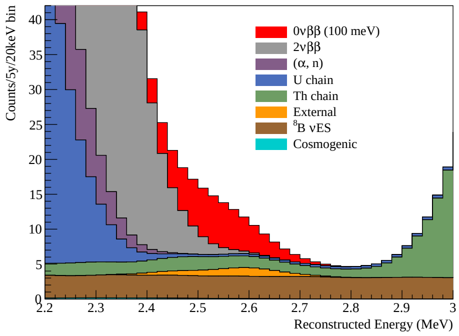

Figure 4. Simulated energy spectrum for 5 years of measurement with 0.5% Tellurium. A light yield of 390 PMT hit/MeV and a fiducial volume of 17% are assumed. Rejection factors of >99.99% for ^{214}Bi-Po and >98% for ^{212}Bi-Po are assumed. The region of interest for the $0\nu\beta\beta$ analysis is [2.49,2.65] MeV.

cases and start falling in the inverted hierarchy region. If a signal would be seen, the total Tellurium mass on SNO+ could be changed for checking it. Ongoing studies characterizing the impact of the Tellurium in the optical properties of the scintillator indicate that a 5-10 fold increase may be viable.

6. Summary

SNO+ has successfully completed its water phase, having commissioned the detector and data taking operations, verified the expected levels of external backgrounds and defined important parts of its optical model, including the time evolution of high angle PMT response. Solar neutrino ^8B fluxes have been measured, and the low energy thresholds achieved may allow the measurement of reactor anti-neutrinos for the first time in a pure water Cherenkov detector.

The next step will be the pure scintillator phase, which will check that the needed high purities are achieved, before loading the Tellurium. The loading at 0.5% per mass will provide a high sensitivity to $0\nu\beta\beta$ due to the good energy resolution, detector self-shielding, purification and particle identification capabilities. It can be increased if a signal is seen.

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