Status and prospects of the SNO+ experiment

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Abstract. The SNO+ experiment is located at the SNOLAB underground laboratory and will employ 780 tons of liquid scintillator loaded, in its initial phase, with 800 kg of $^{130}$Te (0.3% by mass) for a low-background and high-isotope-mass search for neutrino-less double beta decay. SNO+ reuses the acrylic vessel and PMT array of the SNO detector, but several experimental upgrades and adaptations were necessary to allow for the use of liquid scintillator. The SNO+ technique allows a staged approach, and extensive R&D is ongoing to increase the loadings and improve the purification of Tellurium. The very good conditions of background and low energy threshold allow SNO+ to also have other physics topics in its program, including geo- and reactor neutrinos, Supernova and solar neutrinos. This talk will describe the main advantages and challenges of the SNO+ approach for the double-beta decay program, the current status of the experiment and its sensitivity prospects.

1. Introduction

SNO+[1] is the successor of the Sudbury Neutrino Observatory (SNO)[2], reusing its 9500 photomultipliers (PMTs) and acrylic vessel (AV). The usage of liquid scintillator loaded with 0.3% of Tellurium, will permit the search for the neutrinoless double beta decay ($0\nu\beta\beta$) of $^{130}$Te. The discovery of this decay would prove that neutrinos are of Majorana type, and allow to measure the effective Majorana mass. With an excellent ability to reject backgrounds, SNO+ aims at reaching a sensitivity about 80 meV, covering all the neutrino degenerate mass cases and probing the next region: the inverted mass hierarchy.

The liquid scintillator technique has several advantages over other types of $0\nu\beta\beta$ experiments: the scintillator and the Tellurium compound can be purified; the high scintillator mass allows fiducialization and an almost elimination of external backgrounds; fast timing properties allow the rejection of time-correlated backgrounds from the natural radioactive chains of Uranium and Thorium.

The experiment is currently being installed at SNOLAB, Canada. This article describes the main recent developments related to the experiment in Section 2, and the expected backgrounds and sensitivity in Section 3.
2. Developments and construction

2.1. Tellurium-loaded scintillator

The scintillator of SNO+ will be composed of linear alkyl-benzene (LAB) with 2 g/L of PPO as primary fluor. An innovative technique was developed to load telluric acid into LAB at percent levels, while maintaining a low optical attenuation and with tolerable losses on light emission[3]. The telluric acid is not soluble directly in LAB, so it is first mixed in water, and a surfactant is used to load the water into LAB. Samples of scintillator mixed in this way have been shown to be stable for over 2 years. Concentrations of up to 5% of Tellurium (by mass) have been achieved. The choice for the initial SNO+ ($0\nu\beta\beta$) phase will be a concentration of 0.3% which, given the high mass of scintillator and the high natural abundance of $^{130}\text{Te}$, corresponds to 800 kg of isotope.

2.2. Scintillator purification systems

The scintillator will be purified with a combination of distillation, water extraction and steam/N$_2$ stripping. The installation of the scintillator plant has been completed. The system has been leak-checked with He, and passivated with citric acid. The next major steps are its commissioning with water and after that, with scintillator.

Purification of the telluric acid is also necessary due to its activation by cosmic rays, that produces isotope, namely $^{60}\text{Co}$, $^{110m}\text{Ag}$, $^{88}\text{Y}$ and $^{22}\text{Na}$, that have long enough half-lives and whose decay energy overlaps the ($0\nu\beta\beta$) energy region-of-interest (ROI). A purification method was developed[4], that involves dissolving the acid in water, forcing re-crystallization with nitric acid, pumping away the liquid and rinsing. In addition to improving the optical properties, this method has been shown to be very effective in removing $^{60}\text{Co}$, with efficiencies of $10^2$-$10^3$ per

\footnote{on behalf of the SNO+ collaboration.}
pass, and $10^6$ for two passes. A full scale plant has been designed and will be installed in 2016, underground to avoid the build-up of more radioactive isotopes after purification.

As for the surfactant, a combination of underground synthesis of some components, and underground purification, will be used. The collaboration is currently optimising the full scale design. Another purification plant supplies ultra-pure water (UPW) both for the cavity and detector fill, but also for the production and purification of the scintillator cocktail.

2.3. Detector and electronics upgrades

In order to "transform" SNO into a low energy liquid scintillator experiment, several detector changes and upgrades were required.

The low density of LAB (0.86) imposes a significant buoyancy load on the AV. In order to compensate that, the AV is held down by a system of ropes bolted to the experimental cavity floor. Figure 1 shows a photo of the AV with its rope system, and also the ladder used during the cleaning of its internal surface. The cavity and the AV have started to be filled with UPW. By letting the cavity water level go above the AV water level, an upwards mechanical load of 80 000 lb was applied to the AV. This allowed a successful test of the hold-down rope system. The filling of the AV and cavity had to be stopped due to the presence of a significant leak in the cavity. The water level was lowered, repairs were made to the cavity wall liner, and currently the cavity is being filled again.

The stringent background constraints of SNO+ impose a maximum level on the allowed Radon content in the scintillator of a factor of 5 orders of magnitude lower than that of the mine air. The AV must then be fully sealed, but this poses a mechanical problem, since there can be significant pressure swings in the mine air. In order to compensate those variations, while keeping the AV sealed, a cover gas system including low Radon emanation flexible bags, that take up the pressure variations, was installed and will be coupled to the AV.

Calibration systems also face these stringent requirements. The calibration source internal deployment system was re-designed as a fully sealed system, with more stringent material selection, but following the same working principle as the system used in SNO[2]. In addition, a new system based on optical fibers illuminated by LEDs and lasers was built for SNO+. A large set of PMMA fibers illuminates the full detector for the calibration of PMT array[5]. Figure 2 shows the accumulated hits on the PMT array from a set of calibration pulses sent by one of these fibers. Further sets of quartz optical fibers are used to measure and monitor the scintillator’s optical properties.

At the end of the SNO data-taking, the number of PMTs that stopped working was under 10%. Most of these failures were due to base short circuits, that can be repaired. Of these, about half of them have already been repaired and replaced, with more to follow as the cavity water fill will allow access to further parts of the detector. The central electronics cards for SNO+ are completely new, in order to handle the higher currents from scintillation events, and time correlations. New crate readout interfaces also allow a higher data rate with respect to SNO. In addition, a new Data Acquisition system and new monitoring tools are also used in SNO+. The detector and its electronics have undergone full tests in air-fill and partial water-fill data runs.

3. Expected backgrounds and sensitivity

3.1. Expected backgrounds

The sensitivity of SNO+ to the neutrinoless double beta decay of $^{130}\text{Te}$ is crucially dependent on the mitigation and constraints on a number of backgrounds. These can come from radioactive contaminants of the scintillator cocktail – some caused by cosmic ray activation – and of the detector materials external to the scintillator, but also from the two-neutrino decay mode of $^{130}\text{Te}$ and from the elastic scattering of $^8\text{B}$ solar neutrinos.
Mainly due to the presence of water in the scintillator mixture, Uranium and Thorium chain isotopes are present at high levels, and beta decays from $^{214}$Bi and $^{212}$Bi cause events close to the 2.53 MeV Q-value of $^{130}$Te. Due to their short half-lives, these appear in coincidence with the $^{214}$Po and $^{212}$Po $\alpha$ decays and can be tagged using time correlations. For decays in different trigger windows the rejection efficiency is 100%, and in the same window, a rejection factor is expected to be a factor of 50.

Gammas from external radioactivity (in the AV, water, PMTs, ropes) can travel long distances into the scintillator volume. Since $^{208}$Tl emits gammas with 2.614 MeV, close to the Q-value, the rejection of these external backgrounds requires a stringent fiducial cut based on position reconstruction, with 20% of the full AV volume used as a signal region.

In addition, cosmic rays activate the Tellurium and surfactant while at surface, producing several isotopes, of which some have decay energy ranges overlapping the ROI and are long-lived enough to be a background for SNO+, namely $^{60}$Co, $^{110m}$Ag, $^{88}$Y and $^{22}$Na. A dedicated R&D program has shown that a strategy based on a “cool-down” period, purification and synthesis of some materials, all done underground to avoid re-activation, can reduce these backgrounds to negligible levels.

The pie chart in Fig. 3 shows the breakdown of the expected backgrounds. If the expected levels of background from radioactivity are achieved, then the dominant backgrounds will be those caused by the two-neutrino decay mode of $^{130}$Te, that can be mitigated by a choice of an asymmetric ROI around the Q-value ($[-0.5\sigma, +1.5\sigma]$), and the essentially flat spectrum of $^8$B solar neutrinos, that can be constrained by SNO and SuperKamiokande data. Mitigation of these backgrounds is however limited, essentially due to energy resolution.

3.2. Expected sensitivity

Extensive Monte Carlo simulations were carried out for all backgrounds, in order to estimate their rates and rejection efficiencies. Our baseline assumptions for the study of DBD expected sensitivity are a fiducial volume of 20%, a rejection efficiency of $> 99.99\%$ (98%) for $^{214}$Bi ($^{212}$Bi), a 0.3% Tellurium loading, and a detected scintillation light yield of 200 Nhits/MeV. In addition, the expected signal rate was calculated assuming the IBM-2 nuclear matrix element (4.03), $g_A = 1.269$ and $G = 3.68 \times 10^{-14} \text{yr}^{-1}$. 

![Figure 3. Breakdown of expected backgrounds for SNO+ in the fiducial volume (20%) and energy ROI. The total expected rate is 22 events/year.](image)

![Figure 4. Expected energy spectrum for 5 years of SNO+ data close to the ROI for the $^{130}$Te neutrinoless double beta decay search. The signal is shown assuming a Majorana neutrino mass of 200 meV.](image)
Table 1. Expected sensitivity for SNO+ on the $^{130}$Te neutrino-less double beta decay half-life and corresponding effective Majorana mass, in different scenarios. The values shown are 90% C.L. limits. From [1].

| Scenario                | $T_{1/2}^{0\nu\beta\beta}$ | $m_{0\nu\beta\beta}$     |
|------------------------|-----------------------------|---------------------------|
| 0.3 % Te, 1 yr         | $3.9\times10^{25}$ yr       | $\sim 105$ meV            |
| 0.3 % Te, 5 yrs        | $9\times10^{25}$ yr         | 55-133 meV                |
| 3 % Te, HQE PMTs, 5 yrs| $7\times10^{26}$ yr         | 19-46 meV                 |

The spectrum shown in Fig. 4 was obtained for 5 years of data-taking and assuming a Majorana mass of 200 meV. The sensitivity on the $^{130}$Te neutrino-less double beta decay half-life and corresponding effective Majorana mass have been calculated for different data-taking periods and are shown in Table 1. As mentioned in Section 2.1, SNO+ is carrying out R&D on higher loadings. A future 3% loading appears feasible and would likely be accompanied with an upgrade in the PMTs, to avoid light absorption losses. The expected sensitivity for this scenario is also shown in Fig. 4.

4. Plans and outlook
Operationally, the filling of SNO+ with Te-loaded scintillator requires an initial fill with only water, then the replacement of water by the scintillator, and only then the mixing of the isotope. These water and unloaded scintillator steps will be used also to commission and calibrate the detector and make extensive background constraint measurements.

During the Te-loaded phase, measurements of antineutrinos (from reactors and the Earth), $^8$B solar neutrinos and supernova neutrinos will also be possible. Measurements that require lower backgrounds, as low energy solar neutrinos, will not be possible during the Te phase and will likely require further background mitigation in a dedicated unloaded scintillator phase.

In terms of schedule, the water-fill phase will happen in 2016, as well as the commissioning of the scintillator plant. The unloaded and Te-loaded phases are expected to start in 2017.

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