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Neutrinoless double-beta decay search with SNO+

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SNO+ is a large multi-purpose liquid scintillator based experiment, with the main physics goal of searching for the neutrinoless double-beta decay of ^{130}Te. Additional physics topics include the measurement of solar neutrinos, antineutrinos from reactors and the Earth, supernova neutrinos and the search for other rare events. Since April 2022, the experiment is taking data with liquid scintillator and a 2.2 g/L PPO concentration, allowing the study of all radioactive backgrounds prior to the tellurium loading. In a first phase, 3900 kg of natural tellurium (0.5%) will be added to the scintillator for a predicted sensitivity of about 2×10^{26} years (90% C.L.) with 3 years of livetime. Higher tellurium loading will follow for predicted sensitivities above 10^{27} years (3% loading).

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1. Introduction

SNO+ is a multi-purpose neutrino experiment located at a depth of 6000 m.w.e. in a mine in Sudbury, Canada. The primary goal is the search for the neutrinoless double-beta decay using ^{130}Te, among the most promising isotopes considering its high natural abundance of 34.1%, that doesn't require enrichment, and the high Q-value of 2.53 MeV, which is above the majority of the U and Th-chain gammas.

The detector consists of a 6 m acrylic vessel (AV) viewed by about 9300 photomultiplier tubes (PMTs) located on a geodesic stainless steel structure (PSUP) of 8.5 m radius. The vessel and the PSUP are placed in a cavity excavated in the rock, filled with about 7 ktonnes of ultra-pure water, which acts as a shield against the external radiation. Furthermore, a radon impermeable plastic is covering the cavity walls to reduce radon ingress. In autumn 2018, for additional protection, a nitrogen cover gas blanket was added across the entire detector resulting in a reduction of radon by several orders of magnitude compared to mine air [1]. During the course of SNO+ data taking, the AV will be filled by three major target materials: 905 t of ultra-pure water (2017 - 2019), about 780 t of high purity liquid scintillator (Linear Alkyl Benzene, LAB) with 2.2 g/L of PPO (primary fluor) and few mg/L of BisMSB (wavelength shifter) (2022 - 2024), and an initial 3.9 t of natural tellurium (0.5% by weight) [2], which will be loaded into LAB starting from early 2025. Higher tellurium loading for enhanced sensitivities will follow.

This article will focus on SNO+ current status, its purity measurements, and the major mitigation techniques adopted to reduce the radioactive backgrounds for a sensitivity of $T^{0\nu}_{1/2} > 2 \times 10^{26}$ yrs (90% C.L.) with 3 years of data taking.

2. SNO+ status

As of April 2021, the SNO+ detector was filled with about 780 t of LAB and an initial PPO concentration of 0.6 g/L. This period was followed by a PPO loading campaign, which was concluded a year later (April 2022) with the final 2.2 g/L concentration [3]. From July 2023 the scintillator cocktail further includes 0.5 kg (0.5 mg/L) of bisMSB, a wavelength shifter that has the goal of boosting the light output in preparation of the tellurium loaded phase, which resulted in a light increase of a factor 1.5. The first component of the Te-cocktail, a stabilizer (DDA), is expected to be added in 2024, while the first Tellurium is planned to be loaded in early 2025.

SNO+ has four purification plants operating underground: one for water (in common with SNOLAB), one for scintillator and two for the tellurium cocktail. The scintillator purification plant [3] has reached a purity of $(5.3\pm0.1)\times10^{-17}$ g/g in U-chain and of $(5.7\pm0.3)\times10^{-17}$ g/g in Th-chain (4 m fiducial radius), well below the purity requirements for the neutrinoless double-beta decay phase. The SNOLAB water purification plant allowed to reach a water purity of the order of 10^{-15} g/g in U [4], while the telluric acid purification plant is expected to give a reduction factor better that 10^4 for cosmogenic induced isotopes. A first test of the fully installed underground telluric acid purification plant, with about 200 kg of tellurium, is expected to happen by the end of

2023. Samples will be collected and sent for external ICP-MS measurements (U and Th).
Additionally, SNO+ can perform online recirculation of the external/internal water and the scintillator. Extensive QA campaigns are also performed before, during and after filling/loading to always cross check the optical clarity of the target material.

3. Neutrinoless double-beta decay with SNO+

The loaded scintillator technique implemented by SNO+ to search for the neutrinoless double-beta decay offers several advantages:

- measure and monitor all the background components of the cocktail before and while adding tellurium (target-out). A first target-out measurement has been done during the SNO+ partial fill phase (365 t of LAB + 0.6 g/L PPO), where a total of 8 events were expected in the Region Of Interest (ROI), against only 2 events observed. Furthermore, no unexpected background was detected;

- reduce the external backgrounds by fiducialization while keeping a large mass. Furthermore, SNO+ measured the external radioactive background during the water phase, taking advantage of the directionality ($\hat{U}\cdot\hat{R}$) of the Cherenkov light, which allowed to separate the various components [5]. The measured background levels are below or within the nominal numbers. These values can be directly applied to calculate the leakage of the external backgrounds in the $0\nu\beta\beta$ ROI. For the 0.5% Te-loading, the effect is a reduction of the externals in the ROI of a factor of 2, with respect of what originally assumed;

- increase the loading with time while keeping a high light yield for a good energy resolution. Currently, SNO+ foresees a light output of 460 PMT hits per MeV of deposited energy with the 0.5% Te-loading.

With an initial loading of natural tellurium of 0.5%, SNO+ expects to reach a sensitivity of 2×10^{26} years in an optimized fiducial volume and ROI with 3 years of data taking, touching the top of the inverted ordering region. With the future 3% loading and 10 yrs of data taking, SNO+ is expected to reach a sensitivity above 10^{27} years, exploring the inverted ordering region.
In order to reach this goal, in addition to the above mentioned implementations, SNO+ is developing the following mitigation techniques:

U and Th-chain background: The fast coincidences between Bi-beta and Po-alpha decays and the in-window classifiers allows to reject the majority of ^{214}Bi-Po and ^{212}Bi-Po decays falling in the ROI;

Cosmogenics: In addition to purification, SNO+ tellurium has been underground since 2015. Multi-site classifiers are also developed to reduce this contribution to less than 1 event/yr in the ROI;

(α,n) events: The major source is from ^{210}Po αs reacting with ^{13}C atoms. The current ^{210}Po rate is 30 Hz, more than a factor 3 smaller than in partial fill. The proton recoil from scattered neutrons and the neutron capture on protons (2.2 MeV γ) can produce events with energies

in or near the $0\nu\beta\beta$ ROI. Delayed coincidence tagging allow to reduce these events similarly to what done for the U and Th-chain backgrounds;

^{8}B solar neutrinos: by separating the Cherenkov and the scintillator light components, SNO+ might be able to reduce this source of background. ^{8}B solar neutrinos, in fact, have a strong directionality, towards the Sun, which is not present in the $0\nu\beta\beta$ signal or other backgrounds. A promising event-by-event direction reconstruction has been succesfully demonstrated in SNO+ scintillator with the 0.6 g/L PPO concentration for events with energy larger than 5 MeV [6].

4. Conclusions

SNO+ has successfully completed the scintillator loading, taking data with 2.2 g/L PPO as of April 2022. Initial measurements of the scintillator purity, done in 2020 (0.6 g/L PPO) and 2022 (2.2 g/L PPO), show consistent results, with U and Th-chain levels below the requirements for the neutrinoless double-beta decay phase. Furthermore, a first target out analysis has shown that the background level in the ROI is consistent within the expectations. Test of the tellurium purification plant is planned for later this year, with the tellurium loading foreseen to start in 2025.

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