Background analysis for the SNO+ experiment

V. Lozza for the SNO+ Collaboration
Laboratório de Instrumentação e Física Experimental de Partículas Lisboa, Av. Prof. Gama Pinto 2, 1649-003 Lisbon, Portugal
E-mail: vlozza@lip.pt

Abstract. 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. The first of the three SNO+ phases started in May 2017, with the detector filled with ultra-pure water. The deep underground location (6000 m.w.e.) and the low background levels allowed new physics searches, together with the measurement of the $^8$B solar neutrino flux in the 5-15 MeV energy range. Recently, SNO+ has began the transition to the scintillator phase. The double-beta decay phase is expected to start in early 2020, when the ultra-pure liquid scintillator will be loaded with 3.9 tonnes of natural tellurium, for a half-life sensitivity larger than $2 \times 10^{26}$ years in 5 years of data taking. This article focuses on the low background measurement of the initial water phase.

1 The SNO+ Detector
The SNO+ experiment [1] is installed 2092 m ($5890 \pm 94$ m.w.e [2]) deep underground in the SNOLAB laboratory, Sudbury, Canada. The detector is suspended in a cavern of 30.5 m height full of ultrapure water, which acts as a shield against the radioactivity from the rock. It consists of a 12 m diameter, 5.5 cm thickness, spherical acrylic vessel (AV) surrounded by 9300 PMTs, placed on a geodesic stainless steel structure (PMT Support structure, PSUP) at about 2.5 m from the vessel surface [2]. The vessel is kept in place by a high-purity hold-down and hold-up ropes system.

The data taking period of SNO+ is divided in three main phases distinguished by the medium inside the acrylic vessel.

In the first phase, started in May 2017 and ended in July 2019, the acrylic vessel was filled with 905 tonnes of ultra-pure water (water phase). This phase has been dedicated to identify the external background sources, to test the data acquisition system and the detector performance, and to measure the optical properties of the water and the acrylic vessel. The analysis of the first data set, corresponding to a live time of 114.7 days collected between May and December 2017, has been published in [3] and [4]. It resulted in a lifetime limit of the proton decay mode into invisible channels of $3.6 \times 10^{29}$ y, an improvement on the existing limit set by SNO [5], and a measurement of the $^8$B solar neutrino flux down to 5 MeV energy of $5.95^{+0.75}_{-0.71}$ (stat.) $^{+0.28}_{-0.30}$ (syst.) $\times 10^6$ cm$^{-2}$ s$^{-1}$, which is consistent with measurements from other experiments.

Currently, SNO+ has started the transition phase to full scintillator, where the 905 tonnes of water will be replaced by 780 tonnes of linear alkylbenzene (LAB), and 2 g/L of 2,5-diphenyloxazole (PPO). This phase will be used to measure the purity of the components that
Table 1. Results of the likelihood fit analysis during the first period of the water phase. Values correspond to the timebin 6 in [3]. Results are shown as fraction of nominal (f.o.n.), where the nominal external water purity is 0.21 ppt for U and 0.05 ppt for Th, the AV purity is 1 ppt in U and Th, and the rope purity is 0.23 ppb in Th.

| Source              | $^{238}$U (f.o.n.) | $^{232}$Th (f.o.n.) |
|---------------------|-------------------|---------------------|
| AV + Ropes          | $1.7 \pm 0.9^{+3.8}_{-1.7}$ | $0^{+0.1}_{-0.0}^{+1.0}_{-0.0}$ |
| External water      | $0.6 \pm 0.05^{+1.2}_{-0.4}$ | $1.9 \pm 0.1^{+5.5}_{-1.9}$ |

The main phase of the SNO+ experiment is planned to start in 2020 and has the goal to search for the $0\nu\beta\beta$-decay of $^{130}$Te. The observation of this decay will indicate that neutrinos are Majorana-like particles, i.e. they are their own antiparticles. This will help to answer some of the open questions in the modern neutrino physics field, such as if lepton number is violated and what is the ordering of the neutrino masses. For this scope about 3.9 tonnes of natural tellurium ($1.3$ tonnes $^{130}$Te) will be loaded into the detector. The measurement of reactor and geo anti-neutrinos, and solar neutrinos above 2.53 MeV (the end-point energy of $2\nu\beta\beta$-decay of $^{130}$Te) will be still possible during this phase.

2 Water phase background analysis

The analysis of the first part of the SNO+ water phase covered the period from May to December 2017. The main physics goals of this phase are the search for exotic physics, such as the nucleon decay of $^{16}$O into invisible channels, and the measurement of the $^8$B solar neutrino flux. Additionally, we aim to measure the intrinsic U and Th chain contamination in the acrylic vessel, in the hold-down rope system, in the water within the PSUP, and in the PMTs. These external sources of background are not expected to change during the lifetime of the experiment and therefore the measured purity level can be propagated in the following scintillator phases. The amount of the external contamination is the dominant factor for the choice of the fiducial volume in the double-beta decay analysis, requiring a precise measurement.

The selection of the potential radioactive background events is done using energy, position and direction. Additionally, events are classified using in time ratio (ITR) and isotropy ($\beta_{14}$). The ITR variable is obtained for each event as the ratio of PMT hit time residuals within a prompt energy window of [-2.5 ns, 5 ns] to the total PMT hit time residual, and it is used to reject events that have a too broad distribution (ITR < 0.55). The isotropy classifiers [6] helps to select events that emits light in a Cherenkov cone (-0.12 $\beta_{14}$ < 0.95) from events that emit lights more isotropically.

Two independent external background analyses have been performed during the water phase: a two-dimensional likelihood fit and a box analysis. In the first case, the $^{214}$Bi (U-chain) and $^{208}$Tl (Th chain) events were separated using the isotropy parameter, while the various sources were disentangled using the radial distribution. For example, PMT like events tend to concentrate near the support structure, while water events tend to be more uniformly distributed. A directional cut is additionally applied to separate the contamination of PMT like events. These events tend to point inward ($U \cdot R = -1$), while acrylic vessel or external water events tend to point outward, toward the PMT sphere ($U \cdot R > 0.5$). Results are shown in Table 1.

The box analysis counted the events in four analysis regions defined by radial and directional
cuts as shown in Figure 1: PMTs, AV and ropes, water within the AV, and water shielding. The number of observed events was translated into total rates using Monte Carlo simulations. Both the applied analysis methods took into account correlations between analysis regions or events type and agree with each other within uncertainties.

2.1 Systematics uncertainties
A $^{16}$N calibration source [7] has been used to calibrate the detector response in energy (scale, resolution) and position (shift, scale, resolution, angular resolution). The source has been deployed inside and outside the acrylic vessel. The acquired data have been compared to MC simulations to determine the associated systematics to be propagated in the physics analysis.

3 Conclusions
The first 114.7 days of the SNO+ water phase have been analyzed. The measurement of the external background sources (water, PMTs, acrylic and ropes) with two independent analysis methods, verified that U and Th concentrations are within the target levels.

Acknowledgments
This work is funded by EGI, GridPP, Compute Canada, CFI, STFC, NSERC, CFI, CIFAR, FCT, Deutsche Forschungsgemeinschaft, ERC, DOE, NSF, Berkeley, ASRIP, Ontario MRI, FedNor, Queens University. The author Valentina Lozza is funded by FCT, Portuguese State grant reference IF/00248/2015/CP1311/CT0001. We thank SNOLAB and Vale for their valuable support.

References
[1] M. C. Chen 2005 *Nuclear Physics B - Proceedings Supplements* **145** 65
[2] S. Andringa, *et al.*, SNO+ Coll. 2016 *Advances in High Energy Physics* **2016** 6194250
[3] M. Anderson et al., SNO+ Coll. 2019 *Phys. Rev. D* **99** 032008
[4] M. Anderson et al., SNO+ Coll. 2019 *Phys. Rev. D* **99** 012012
[5] S. N. Ahmed et al., SNO Coll. 2004 *Physical Review Letters* **92** 102004.
[6] B. Aharmim et al., SNO Coll. 2010 *Phys. Rev. C* **81** 055504
[7] M. Dragowsky et al. 2002 *Nucl. Instrum. Methods Phys. Res., Sect. A* **481** 284