The SNO+ experiment: current status and future prospects.

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SNO+ is a multi-purpose neutrino experiment whose main physics goal is the search for the neutrinoless double-beta ($0\nu\beta\beta$) decay of ^{130}Te. With an initial loading of 0.5% (by weight) of natural tellurium SNO+ is expected to reach a sensitivity on the $0\nu\beta\beta$ lifetime of the order of 10^{26} years at 90% C.L. in a 5-year run. Along with the $0\nu\beta\beta$ decay search, SNO+ has the capability to measure the low energy solar neutrinos, like pep and CNO neutrinos. It has also an extraordinary opportunity to do the first measurement of the supernova ν_x energy spectrum.

1 Introduction

The SNO+ experiment is reusing the Sudbury Neutrino Observatory detector which is located at a depth of 2 km in the Vale's Creighton mine in Sudbury, Canada. The deep underground location, the large volume, and the high radio-purity of the materials used allows SNO+ to explore several neutrino physics topics.

The primary goal of SNO+ is the search for the Dirac or Majorana nature of the neutrinos via searching for the neutrinoless double-beta ($0\nu\beta\beta$) decay of ^{130}Te. The neutrinoless double-beta decay is an extremely rare nuclear process that can only happen if neutrinos are their own antiparticles, i.e. they have a Majorana mass component. With an initial loading of 0.5% of tellurium by weight, SNO+ aims to reach a sensitivity on the effective Majorana neutrino mass smaller than 100 meV, exploring the top of the inverted hierarchy region in five years.

The low energy threshold of the SNO+ experiment, the deep underground location and the high radiopurity allows the measurement of the low-energy solar neutrinos, like *pep*, ^{8}B, and CNO neutrinos. The measurement of the *pep* neutrino flux and of the spectral shape of the ^{8}B-neutrinos will shed like on oscillation models, while the measurement of the CNO neutrino flux can solve the solar metallicity problem.

Along with these goals SNO+ can measure antineutrinos from nuclear reactors and the Earth's crust and mantle, can watch for neutrinos and antineutrinos from core collapse supernovae, and has the potential to search for exotics physics, like invisible nucleon decay, and axion-like particles.

This article is structured as follows. In Section 2 the SNO+ detector is described together with the most recent upgrades, and the liquid scintillator and tellurium purification processes. In Section 3 the physics goals, the expected phases of the experiment and the run plan is presented. In Sections 4 to 6 the physics program of SNO+ is described: the neutrinoless double-beta decay search (Section 4), the measurement of low energy solar neutrinos (Section 5), and the watch for supernova neutrinos and antineutrinos (Section 6). The conclusion will follow at the end.

2 The SNO+ Experiment

The SNO+ experiment is located at a depth of 5890 ± 94 m.w.e. in the SNOLAB underground laboratory [1]. The flat overburden provides a shield against the cosmic muons, reducing the muon flux to 63 muons per day passing through a 8.3 m radius circular area. SNO+ will reuse the SNO detector infrastructure [2, 3] which consists of a spherical acrylic vessel of 12 m diameter and 5.5 cm thickness suspended in a cavity excavated in the rock via a system of high purity ropes. The vessel will be filled by about 780 tonnes of liquid scintillator and is viewed by 9300 8 inch PMTs placed on a geodesic stainless steel structure (PSUP) of 19 m diameter. Each PMT is equipped with a light concentrator for an overall coverage of 54%. The volume between the acrylic vessel and the PSUP and the one outside the PSUP is filled with high purity water to shield against the radioactivity coming from the rock and the PMTs. Due to the lower density of the liquid scintillator (LS) contained in the acrylic vessel compared to the one of the surrounding water a new system of high purity ropes has been installed on the top of the vessel and anchored to the cavity floor to offset the LS buoyancy [4].

2.1 Liquid scintillator

The SNO+ liquid scintillator consists of linear alkylbenzene (LAB) as a solvent and 2 g/L of 2,5-diphenyloxazole (PPO) as a fluor. The LAB+PPO mixture has been selected among others due to its chemical compatibility with the acrylic vessel, its high light yield of more than 10000 photons per MeV, its transparency and good optical properties (long attenuation and scattering lengths), its linear response in energy, and its long term stability. Additionally, the fast decay time allows to discriminate between alpha-like and beta-like signals.

Despite the high purity levels available directly from the manufacturer, a further purification of the liquid scintillator is necessary in order to achieve a U- and Th-chain radiopurity close to the one of Borexino and KamLAND, i.e. less than 10^{-17} g/g$_{LAB}$ [5]. The scintillator purification plant of SNO+ is fully described in [6, 7]. Heavy metals and optical impurities are removed by a multi-stage distillation and high temperature flash vacuum distillation. Gases and residual water are then removed by a N_2/steam gas stripping process. Once the SNO+ detector is filled with LAB+PPO the mixture can be further purified in-situ by recirculating the scintillator (about four days for the entire volume) through a rotating-stage liquid-liquid extraction column and metal scavengers. The liquid scintillator purification plant has been fully installed at the SNOLAB depth and is currently undergoing commissioning.

2.2 Te-loading

To search for the $0\nu\beta\beta$ decay SNO+ will load tellurium into the liquid scintillator. The SNO+ collaboration has developed a new technique to load several tonnes of tellurium into LAB maintaining a high light emission level and good optical properties. In the initial phase SNO+ will load 3.9 tonnes of natural tellurium (a concentration of 0.5% by weight) by forming an organometallic compound of tellurium and butanediol which is soluble in LAB scintillator. A secondary wavelength shifter (bis-MSB) is added to better match the PMT quantum efficiency. The currently predicted light yield in SNO+ for the 0.5% Te-loaded cocktail is 390 Nhits (detected photoelectron hits) per MeV of energy.

The purification technique for tellurium is described in [8]. It has been designed to remove both the U- and Th-chain impurities and the isotopes produced by cosmogenic neutron and proton activation of the material during handling and storage on the earth's surface. The purification plant for tellurium consists of two stages. Both the stages are expected to happen underground. A first double-pass acid recrystallization (Stage I) reduces the U/Th and cosmogenic-induced isotope level of a factor larger than 10^4. In the second purification stage (Stage II) tellurium is dissolved in water at 80° C and left to cool to recrystallize without further rinsing. This stage will further reduce the impurity level of a factor larger than 100.

2.3 Detector Upgrades

In addition to the installation of the hold-down rope system several detector upgrades have been done in the latest years. The read-out boards and the data acquisition system of SNO have been upgraded with a higher bandwidth one to cope with the higher rate and lower energy events expected in SNO+. The trigger system has been improved for a more flexible calibration interface. The electronics and the trigger system have been tested in runs with the detector empty and partially filled with water. A new calibration hardware has been designed which consists of a set of radioactive sources (beta, gamma, alpha and neutron) and a set of optical sources. The optical calibration system consists of deployable sources and a fixed external system of optical fibers attached to the PSUP as described [9]. The SNO cover gas system, a sealed system of bags filled with high-purity nitrogen that shields the detector against the radon contained in the mine air, has been upgraded for a radon reduction of about 10^5.

3 Physics Goals and Run Plan

The main goal of the SNO+ experiment is the search for the $0\nu\beta\beta$ decay of ^{130}Te. However, due to the deep underground location and the high purity of the materials used, SNO+ has the potential to explore other physics topics: the measurement of the low energy *pep* and CNO neutrino flux, the measurement of the spectral shape of the ^{8}B-neutrinos, the watch for supernova (SN) neutrinos and antineutrinos, and the measurement of antineutrinos produced in nuclear reactors and in the Earth's crust and mantle.

Currently, there are planned three main phases for the experiment. During the initial phase the detector will be filled with about 905 tonnes of ultra-pure water (1, *water phase*). This phase will start by the end of 2016 and last for a few months. In this phase the detector performance and the PMT response will be checked. At the same time SNO+ will search for exotic physics events, like the invisible nucleon decay, and will watch for SN-neutrinos.

The water phase will be followed by a *pure liquid scintillator phase* (2) where the detector is filled with about 780 tonnes of LAB+PPO. Also this phase will last few months. The physics topics covered are the measurement of the low energy solar neutrinos, the watch for SN neutrinos, and the measurement for reactor and geo- antineutrinos. This phase will be also used to measure the liquid scintillator background and verify the optics model.

Tellurium will be loaded into the detector starting from the end of 2017 with the beginning of the data taking expected for the summer of 2018. The *double-beta decay phase* (3) will last

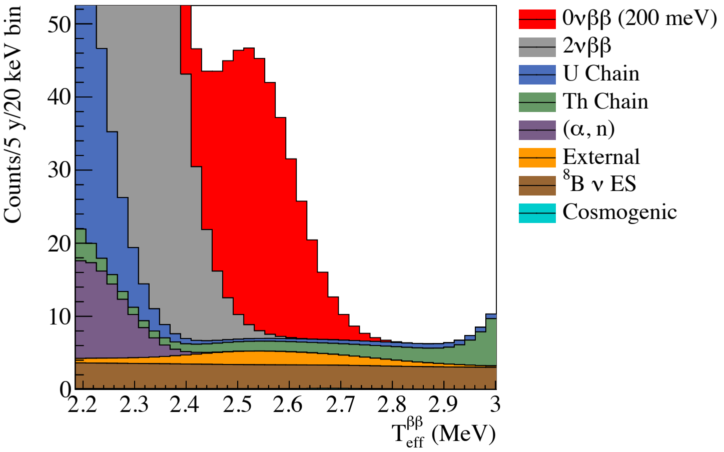

Figure 1: Energy spectrum plot (stacked) of all backgrounds and an hypothetical $0\nu\beta\beta$ signal coresponding to $m_{\beta\beta} = 200\,\mathrm{meV}$. The plot is shown for 5 years live-time, 0.5% Te-loading and a light yield of 390 Nhits/MeV. A fiducial volume of 20% has been applied. External backgrounds are further reduced by a factor of two, while ^{214}BiPo and ^{212}BiPo are reduced by >99.99% and 98%, respectively. $T_{\beta\beta}$ is the effective kinetic energy.

about 5 years. Simultaneously to the $0\nu\beta\beta$ search the detector will be live for a potential SN, and the geo- and reactor antineutrinos can be observed.

4 ^{130}Te neutrinoless double-beta decay search

The observation of the $0\nu\beta\beta$ decay would demonstrate lepton number violation, and shed light on the ordering of the neutrino masses, both intriguing open questions in the neutrino research area. The $0\nu\beta\beta$ decay is a nuclear process in which two neutrons are converted into two protons and two electrons without the emission of the neutrinos. It can be seen as two simultaneous β-decays in which the neutrinos from the two weak vertices mutually annihilate. The signature of the decay is a peak at the Q-value of the reaction in the summed energy spectrum of the two electrons. The measured observable is the reaction's rate, from which it is derived the half-life of the decay. The effective Majorana neutrino mass, $m_{\beta\beta}$, is then extracted from the half-life as described in [10].

In SNO+ the search for the $0\nu\beta\beta$ decay is done by loading large amounts of ^{130}Te into the detector volume. ^{130}Te has a large isotopic abundance of 34.08%, which allows to load several tonnes of the isotope without the need of enrichment. The Q-value of the decay (2527.518 ± 0.013 keV [11]) is above many of the U- and Th-chain decays' endpoints. The half-life of the associated $2\nu\beta\beta$ decay ($7.0\pm0.9(\mathrm{stat})\pm1.1(\mathrm{syst})\times10^{20}$ yr [12]), one of the main irreducible backgrounds in the $0\nu\beta\beta$ decay search, is among the longest of all the $0\nu\beta\beta$ decay candidates. Currently, loadings up to few percent (by weight) of natural tellurium in LAB have been successfully obtained with very good optical properties, high light yield and no inherent optical

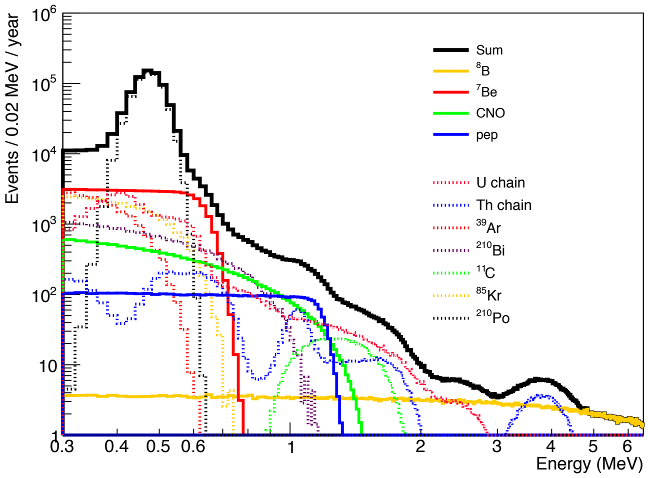

Figure 2: Expected solar neutrino fluxes and backgrounds as detected by the SNO+ experiment. The background levels are assumed to be similar to the one initially achieved by Borexino. A fiducial volume cut of 5.5 m and a light yield of 400 Nhits/MeV are assumed. The ^{214}BiPo events are rejected by 95% using delayed coincidences, while a 95% reduction is applied to the ^{210}Po and remaining ^{214}Po alpha signals. U and Th-chain backgrounds have a constrain of 7% and 25%, respectively.

absorption line in the visible wavelength range.

The expected energy spectrum for a 0.5% Te loading and a five-year live-time is shown in Figure 1. A fiducial volume (FV) cut of 3.5 m, corresponding to 20% of the total volume, has been applied. The region of interest (ROI) for the $0\nu\beta\beta$ decay search extends from -0.5σ to +1.5σ around the Gaussian signal peak. The asymmetric ROI considerably reduces the background events from the $2\nu\beta\beta$ and the low energy U- and Th-chain decays, leaving as main background contribution the ^{8}B-ν elastic scattering (irreducible flat background). ^{214}BiPo (U chain) and ^{212}BiPo (Th chain) events are rejected using a delayed coincidence tagging and, for the events happening in the same trigger window, pile-up cuts [1]. The $0\nu\beta\beta$ decay signal shown in Figure 1 corresponds to a $m_{\beta\beta} = 200\,\text{meV}$, or to a $T_{1/2}^{0\nu\beta\beta} \sim 10^{25}$ yr using IBM-2 nuclear matrix elements [13]. The expected sensitivity of SNO+ in 5 years of running is $T_{1/2}^{0\nu\beta\beta} > 1.96 \times 10^{26}$ yr at 90% CL, corresponding to a limit on the effective Majorana neutrino mass of 38 − 92 meV ($G = 3.96 \times 10^{-14}$ yr^{-1} [14] and $g_A = 1.269$), depending on the nuclear matrix elements used.

5 Low-energy Solar Neutrinos

The solar neutrino spectrum as detected by SNO+ is shown in Figure 2 together with the main background sources during the pure scintillator phase. With a liquid scintillator purity similar to the one achieved by Borexino in its Phase I [5], SNO+ can detect *pep* and CNO neutrinos with a sensitivity of few percent. Additionally, a spectral shape measurement of the ^{8}B neutrinos can be performed also during the $0\nu\beta\beta$ phase for energies above the ^{130}Te endpoint.

5.1 Pep neutrinos

The *pep* reaction in the Sun produces monoenergetic neutrinos (1.44 MeV) which have very well predicted flux (1.2% uncertainty) constrained by the Sun luminosity. A measurement of these neutrinos has the potential to probe the transition region between the vacuum oscillation (E$\leq$ 1 MeV) and the matter-enhanced oscillation (E$\geq$ 1 MeV) energy regions of the ν_e survival probability. The shape of the survival probability in the transition region is sensitive to alternate models of neutrino-matter interactions, such as flavor changing neutral currents or mass-varying neutrinos. A minimum precision of 10% is necessary to discriminate among different models. To improve the sensitivity to non standard neutrino interactions, the spectral shape of ^{8}B-νs can be used. Due to their production closer into the core of the Sun, the effect of new physics is enhanced for these neutrinos.

With a background level similar to the one achieved in Borexino Phase I, MonteCarlo simulations suggest that, with one year of data and a 50% fiducial volume cut, the expected uncertainty on the *pep* neutrinos is 8.9% (13% in six months), while the expected uncertainty on the ^{8}B neutrinos is about 7% (10% in 6 months).

5.2 CNO Neutrinos

Recent improvements in the solar atmospheric modelling suggest a photosphere's metallicity (abundance of elements heavier than helium) about 30% lower than what was predicted by the older but quite successful model. This broke the excellent agreement between the solar model calculations and helioseismology, opening the question about the homogeneous distribution of the elements in the Sun. The prediction for the CNO neutrino flux depends linearly on the core metallicity and thus can shed light on the solar metallicity problem. Additionally, the CNO-ν flux can be further constrained by a precision measurement of the ^{8}B-ν flux as it depends on the same environmental factors.

The major background for the CNO neutrino flux measurement are the ^{210}Bi decays (Q-value = 1.16 MeV). The shape of this decay is very similar to the CNO-ν one making the discrimination difficult. The separation can be achieved by an ex-situ constraint on the ^{210}Bi decay rate or using observable different from energy. In one year of data the expected uncertainty on the CNO+^{210}Bi linked data is 4.4% (6.5% in six months). The CNO flux alone has a predicted uncertainty of 15%.

6 Supernova Neutrinos and Antineutrinos

The high radiopurity of SNO+ and its deep underground location makes it one of the most promising experiments for the detection of neutrinos from core collapse supernovae (CCSNe). CCSNe are expected to emit more than 99% of their energy via neutrinos of all flavours and type. A measurement of these fluxes is expected to shed light on the explosion mechanism. Current models estimate than about half of the neutrinos are emitted in the first second of the CCSN's burst [15].

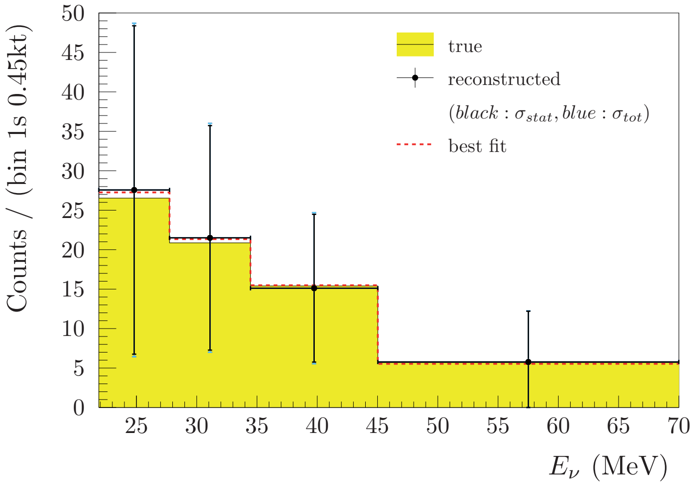

Figure 3: Supernova (SN) neutrino energy distribution for the ν-p ES interaction in the SNO+ experiment. A FV cut of 5.5 m and a detector threshold of 0.2 MeV have been applied. Shown are the true, reconstructed and best fit energy distribution of the sum of $\nu_e, \overline{\nu}_e$, and ν_x emitted in the first second of the burst for a 10 kpc away SN with a total 3×10^{53} erg energy ejected in the form of neutrinos. The uncertainties shown are statistical (black) and total (blue). The systematic uncertainty which includes the ν-p ES cross section, the number of target protons, the proton quenching parameter, the detector's energy resolution, and the spectral ν_e and $\overline{\nu}_e$ parameters, is too small to be resolved. The best fit spectrum shows excellent agreement.

SNO+ has the potential to measure both the averaged energy as well as the total electromagnetic energy of the neutrinos emitted in the CCSN. The possible interaction channels during the pure liquid scintillator phase are summarized in [1]. For a 10 kpc away SN, with 3×10^{53} erg of binding energy released in form of neutrinos (equally partitioned among all six flavours and types), SNO+ expects to detect about 195 events via inverse beta decay (IBD) reactions, and about 119 events via elastic scattering (ES) on protons (for an energy threshold above 0.2 MeV) with a 5.5 m FV cut. The reconstructed energy spectrum of ν_e, $\overline{\nu}_e$, and ν_x (sum of ν_μ, $\overline{\nu}_\mu$, ν_τ, and $\overline{\nu}_\tau$) neutrinos emitted in the first second of the CCSN and detected by ν-p ES reaction is shown in Figure 3, together with the true neutrino spectrum. The reconstructed energy spectrum is obtained from the unfolded proton energy, taking into account the non-linear quenching of the proton energy and the finite detector resolution [1].

7 Conclusion and Outlook

SNO+ is a large-scale liquid scintillator experiment whose primary goal is the search for the neutrinoless double-beta decay of ^{130}Te. During the initial Te-phase about 3.9 tonnes of natural tellurium are loaded into the liquid scintillator by which SNO+ is expected to reach a sensitivity on the effective Majorana neutrino mass on the top of the inverted hierarchy region.

Additionally, due to the low energy threshold, the deep underground location and the high purity of the materials used SNO+ is also able to measure low energy solar neutrinos, like *pep* and CNO neutrinos. Furthermore, SNO+ can provide the first measurement of the spectral shape of the ν_x neutrinos ejected from a CCSN.

Several upgrades have been made to the detector in order to reuse the old SNO vessel and electronics. We expect to start the water phase data taking soon, with the tellurium loading foreseen for the end of the 2017.

Acknowledgments

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References

[1] S. Andringa, *et al.*, The SNO+ Collaboration, Advances in High Energy Physics **vol. 2016** 6194250 (2016).

[2] J. Boger et al., SNO Collaboration, Nuclear Instruments and Methods in Physics Research A **vol. 449** pp. 172–207 (2000).

[3] N. Jelley, A. B. McDonald, and R.G. H. Robertson, Annual Review of Nuclear and Particle Science **vol. 59** pp. 431–465 (2009).

[4] A. Bialek et al., Nuclear Instruments and Methods in Physics Research A **vol. 827** pp. 152 – 160 (2016).

[5] G. Alimonti et al., Borexino Collaboration, Nuclear Instruments and Methods in Physics Research A **vol. 609** pp. 58–78 (2009).

[6] R. Ford, M. Chen, O. Chkvorets, D. Hallman, and E. Vázquez-Jáuregui, AIP Conference Proceedings **vol. 1338** pp. 183–194 (2011).

[7] R. Ford for the SNO+ Collaboration, AIP Conference Proceedings **vol. 1672** 080003 (2015).

[8] S. Hans, et al., Nuclear Instruments and Methods in Physics Research A **vol. 795** pp. 132–139 (2015).

[9] R. Alves et al., Journal of Instrumentation **vol. 10** P03002 (2015).

[10] K. Zuber, Contemporary Physics **vol. 45** pp. 491–502 (2004).

[11] M. Redshaw, B. J. Mount, E. G. Myers, and F. T. Avignone III, Physical Review Letters **vol. 102** 212502 (2009).

[12] R. Arnold et al., NEMO–3 Collaboration, Physical Review Letters **vol. 107** 062504 (2011).

[13] J. Barea, J. Kotila, and F. Iachello, Physical Review C **vol. 87** 014315 (2013).

[14] J. Kotila and F. Iachello, Physical Review C **vol. 85** 034316 (2012).

[15] G. Pagliaroli, F. Vissani, M. L. Costantini, and A. Ianni, Astroparticle Physics **vol. 31** pp. 163–176 (2009).