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The SNO+ Experiment for Neutrinoless Double-Beta Decay

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Abstract

SNO+ is a large scale liquid scintillator based experiment located 2 km underground in a mine near Sudbury, Ontario, Canada. The detector is reusing the Sudbury Neutrino Observatory facility to investigate the Majorana nature of neutrinos through the search for neutrinoless double-beta decay of ^{130}Te. In the double-beta phase about 0.3% natural tellurium will be loaded in the 780 tonnes of liquid scintillator. This corresponds to nearly 800 kg of ^{130}Te. After several years of data taking, it is expected to reach a sensitivity on the effective Majorana neutrino mass below 100 meV. Recent development has suggested that higher loadings, up to few percent, of natural tellurium are possible by which SNO+ could approach, in the near future, the bottom of the inverted hierarchy. Additionally, designed as a general purpose neutrino experiment, SNO+ can measure reactor anti-neutrino oscillations, geo anti-neutrinos in a geologically-interesting location, solar neutrinos and watch supernova neutrinos.

A first commissioning phase with the detector filled with water will start at the end of 2014, while the double-beta decay phase is foreseen for the beginning of 2016.

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1. Introduction

SNO+ [1] is a multipurpose liquid scintillator based experiment that has the primary goal to investigate the Majorana nature of neutrinos through the search for the neutrinoless double-beta decay of ^{130}Te.

The experiment is located 2 km underground in the SNOLAB laboratory (Sudbury, Ontario, Canada). The 6080 m.w.e. shielding provided by the norite rock will greatly reduce the cosmogenic muon flux to only about 70 muons per day. SNO+ will make use the SNO (Sudbury Neutrino Observatory) infrastructure [2] where the 12 m diameter acrylic vessel will be filled with 780 tonnes of ultra-pure liquid scintillator (Linear Alkyl Benzene, LAB).

SNO+ will use a novel technique in the double-beta decay field, where a large mass of natural tellurium (2340 kg) is loaded in the scintillator. This results in about 800 kg of the double-beta decay isotope, ^{130}Te, by which it is possible to reach a sensitivity lower than 70 meV on the effective Majorana neutrino mass in 5 years of data taking.

In addition, designed as multi-purpose detector, SNO+ has the ability to measure during the double-beta phase reactor anti-neutrino oscillations, anti-neutrinos coming from the Earth and watch for supernovae neutrinos. Low-energy solar neutrinos, like *CNO*- and *pep*- (monoenergetic solar neutrino flux of 1.44 MeV) neutrinos, can be measured in a pure scintillator phase (without tellurium loading) planned after the double-beta phase.

In order to upgrade the SNO Čerenkov detector to a scintillator based one, several developments were necessary. A description of the detector, the calibration system and the developments is done in section 2. The purification system and the relevant backgrounds are described in section 3. The physics program of SNO+ is presented in section 4.

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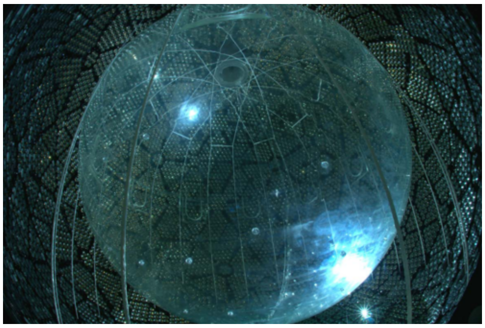

Figure 1: Hold-down rope net system. The system has been fully installed in 2012.

Figure 2: SNO+ cavity filled with water.

2. The SNO+ detector

The SNO+ detector consists of a 12 m diameter acrylic vessel (AV) sphere, 5 cm thick, that will be filled by about 780 tonnes of LAB (solvent) and 2 g/L of 2–5 diphenyloxazile (PPO, fluor). The LAB+PPO mixture has been chosen among others for its chemical compatibility with acrylic, the high light yield of about 10,000 photons/MeV, the good optical transparency, the low scattering and the fast decay time that allows an alpha–beta pulse shape discrimination. Additionally, it is possible to load heavy metals, like tellurium.

The target volume is viewed by about 9500 8” PMTs, located on a geodesic stainless steel structure (PSUP) of 18 m diameter. The PMTs are equipped with reflectors for a coverage of about 54%. The PSUP and the AV are located in a cavity, excavated in the norite rock, that will be filled by about 7000 tonnes of ultra-pure water (UPW) – 1700 tonnes between the AV and the PSUP and 5400 tonnes outside the PSUP – to shield the detector from the radioactivity coming from the PMTs and the rock. The inner water volume is monitored by about 100 outward looking PMTs. The rock surface is covered by a radon seal and a Urylon liner to provide a shield against the mine air rich in radon.

Several detector upgrades have been done to make possible the transition from the heavy water Čerenkov detector to a liquid scintillator one. The main change is the rope holding system. LAB has a density of about 0.86 g/cm^3 at 12°C, which leads to a large buoyant force on the acrylic vessel from the surrounding light water. To compensate this force, and keep the AV in place, a hold-down rope system, with 40 mm diameter high-purity Tensylon ropes (low ^{40}K content), has been installed in 2012 (see figure 1). The rope system is anchored at the bottom of the cavity. To reduce the radioactivity contamination, the old hold-up rope system, has also been replaced with the new Tensylon ropes (20 mm diameter).

The inner and the outer surface of the vessel has been thoroughly washed with UPW to remove any possible dust contamination that could have deposited after the drain of the heavy water in SNO.

Further upgrades have been done in 2012 to the SNO electronics and acquisition system since a higher event rate is expected due to the lower threshold and the higher light yield. Damaged PMTs has been repaired and replaced as well.

The calibration system has been upgraded to be compatible with the scintillator. New calibration sources have been designed and are under development: AmBe(n,γ), ^{16}N(γ), ^{24}Na(γ), ^{48}Sc(γ), ^{57,60}Co(γ), ^{90}Y(β) and a ^{8}Li- based Čerenkov source. An in-situ optical calibration system based on LEDs and optical fibres have been designed and partially installed [3].

The current level of water is 20 feet from the bottom of the cavity, submerging part of the bottom PMTs (see figure 2).

The initial water phase, where the AV is filled with UPW, is planned planned to start in early 2015. In this phase the detector performance will be checked. A pure scintillator phase will follow by the end of 2015. The double-beta decay phase with 0.3% natural tellurium loading is foreseen for the beginning of 2016.

3. Purification system and backgrounds

In order to achieve the physics goals of SNO+ it is necessary to reach high purity levels for the different components of the scintillator cocktail. The background target values for the pure liquid scintillator are $1.6\cdot10^{-17}$ g_{238U}/g_{LAB}, corresponding to about 13 counts per day (cpd) of ^{214}Bi, and $6.8\cdot10^{-18}$ g_{232Th}/g_{LAB}, corresponding to about 2 cpd for ^{228}Ac. To reach these values a purification system for the liquid scintillator is

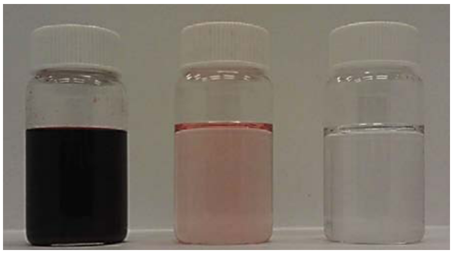

Figure 3: Scintillator spiked with Co to test the purification efficiency. The sample on the left is the original spiked sample. The one in the center is after the first purification pass based on nitric acid recrystalization. The sample on the right is after the second purification pass. The reduction factor on ^{60}Co is larger than $3{\cdot}10^4$. The purification process has the advantage to also improve the optical properties of the scintillator.

currently under installation in the underground laboratory. The system consists of a multi-stage distillation to remove heavy metals and a high temperature flash vacuum distillation in order to reach both a high radiopurity and optical clarity for LAB and PPO. In a second stage PPO is added to LAB, and the mixture is further purified by a N_2/water vapour gas stripping process which will remove gases such as Rn, Ar, Kr, and oxygen. Water extraction, metal-scavenging and microfiltration will further improve the purity level. A detailed description of the SNO+ scintillator purification plant can be found in [4].

In the neutrinoless double-beta decay phase, natural tellurium will be loaded in the form of telluric acid into the liquid scintillator using water and a surfactant. The added components will worsen the purity levels introducing new sources of U and Th. The target levels for the resulting scintillator cocktail (TeLS) are $2.5{\cdot}10^{-15}\ g_{238U}/g_{TeLS}$ and $3{\cdot}10^{-16}\ g_{232Th}/g_{TeLS}$. The purification system for the surfactant and the telluric acid is currently under development.

The telluric acid will be purified using a two-stage purification procedure developed by the collaboration [5]. The first stage of the procedure consists of a two-passes purification on surface using nitric acid recrystallization and ethanol rinse. The purification process not only removes Th and U contamination but also possible cosmogenically produced isotopes while handling and storing the tellurium on surface. The cosmogenic isotopes produced by proton and neutron activation of natural tellurium that are a background for double-beta decay searches in liquid scintillator based experiments are discussed in [6]. Production rates have been calculated for isotopes with Q-value larger than 2 MeV and $T_{1/2}$ larger than 20 days. A total of 21 nuclides have been identified as potential background candidates. In order to reduce the cosmogenic background to a negligible level a purification factor of 10^4, followed by 3–6 months of cooling down, would be necessary. The purification procedure for telluric acid in [5] has been verified with many spike tests. A reduction factor of about 100 in a single pass has been achieved. For Co a overall reduction in two steps of a factor larger than $3{\cdot}10^4$ has been reached. In figure 3 the Co-spiked sample is shown after each purification step. Besides the radiopurification a good optical clarity is reached as well.

After the first-stage purification on surface, a few hours could pass before tellurium is carried underground. During this period cosmogenically induced short lived isotopes can be produced in the purified sample. A two passes purification underground, with a total reduction factor of 100, has been designed and bench top tested to further remove these nuclides. Telluric acid is dissolved in water at 80°C and cooled to recrystallise without rinsing. The process keeps 50% of tellurium, while the fraction that remains in solution is recycled in the surface plant for recovery.

For tellurium that has been exposed to the cosmic flux at sea level for one year, has undergone the purification on surface and underground with additionally 6 months of cooling down, a total of less than one event per year of cosmogenic background is expected in the region-of-interest (ROI).

Other backgrounds that fall in the ROI and need further mitigation techniques are ^{214}Bi–Po and ^{210}Tl from the U chain, ^{212}Bi–Po and ^{208}Tl from the Th chain and the external ^{214}Bi and ^{208}Tl.

The internal ^{214}Bi (Q-value of 3.27 MeV) can be efficiently identified by the delayed coincidence with the ^{214}Po-alpha decay (E_α=7.7 MeV, $T_{1/2}$=164μs). The total efficiency depends on the coincidence time window selected for the decay. However, in 0.2% of the cases the alpha event will happen in the same SNO+ trigger window of 450 ns. In this case the beta and the alpha energy sum up and are seen as a single event (pile-up). Using the time distribution of the light detected by the PMTs a rejection factor larger than 50 can be achieved. The total rejection for the ^{214}BiPo background is >25000.

Additionally, ^{214}Bi alpha-decays to ^{210}Tl (Q-value of 5.49 MeV, $T_{1/2}$=1.3 min) in 0.021% of the cases. A coincidence tagging technique is under development.

From the Th chain the main backgrounds are from the ^{212}Bi–Po decay and the ^{208}Tl-decay. ^{212}Bi beta-decays (Q-value of 2.25 MeV) to ^{212}Po which then alpha decays with a 300 ns half-life. In 66% of the cases the Bi and Po will decay in the same SNO+ trigger window. Due to the alpha quenching of about a factor 10, they pile-up in the ROI of neutrinoless double-beta decay study. Also in this case the in-window background can be reduced by a factor 50 using the PMT timing. Inter-window decays are reduced by the delayed coincidence tagging. An overall rejection of > 70 has been currently achieved. A tagging technique for ^{208}Tl ($T_{1/2}$ = 3.05 min) using the delayed coincidence between the ^{212}Bi-alpha decay and the ^{208}Tl beta-decay is under development.

Other internal backgrounds that contribute in the ROI are the ^{8}B neutrino elastic scattering and the ^{130}Te double-beta decay.

External backgrounds also contribute in the ROI by the 2.6 MeV gamma decays (^{208}Tl and ^{214}Bi). A total rejection of a factor 2 is obtained using the PMT timing and a fiducial volume cut of 20%.

4. The physics program of SNO+

4.1. Neutrinoless double-beta decay search with ^{130}Te

The search for the Majorana nature of neutrinos is one of the most interesting and active searches in modern neutrino physics. It has the potential to explain the nature of neutrino mass and shed light on the absolute scale of their masses. The only known method to explore the nature of neutrinos is the Double-Beta-Decay (DBD). The DBD is a nuclear process where the Z number changes of 2 units while the atomic mass, A, doesn't change. It can only happen if the single double-beta decay is forbidden or strongly suppressed. If neutrinos are Majorana the decay can proceed without the emission of the 2 neutrinos, with only the two electrons in the final state. This results in a peak at the Q-value of the reaction in the double electron spectrum. The quantity measured is the half-life of the decay, which is related to the effective Majorana neutrino mass by the nuclear matrix element and phase-space factor.

Among the several experiments searching for the neutrinoless double-beta decay, SNO+ will use a novel technique in the field, where a large mass of the double-beta decay isotope is loaded directly in the scintillator. The low energy resolution of SNO+, compared to solid state detectors, will be compensated by a large mass (high loading), a very low background environment and by the developed background rejection techniques (see section 3).

The SNO+ experiment has initially investigate the use of natural Nd (^{150}Nd) as candidate. However, following the suggestion outlined in [7] and nearly two years of investigation and development by the entire collaboration, in 2013 it has been decided to use natural tellurium (^{130}Te). The advantages of the use of ^{130}Te (Q-value of 2.53 MeV) are the followings:

- high natural abundance of 34.08%, the highest among the neutrinoless double-beta decay candidates;
- factor 100 lower $2\nu\beta\beta$ decay rate than Nd ($T_{1/2}$ = $7.0 \cdot 10^{20}$ y [8]), which decreases the background in the ROI;
- no inherent atomic absorption line in the region where the PMTs are sensitive (350 nm–500 nm);
- relative low cost;
- possibility to increase the loading up to 5% still achieving a high light yield.

A method for loading high concentration of tellurium in the scintillator has been developed by the SNO+ collaboration. Telluric acid will be added to the scintillator with the help of water, a surfactant and wavelength shifter. Due to the degradation of the optical properties increasing the amount of tellurium dissolved, a good compromise between the loading level, stability and light output must be found. With the current developed cocktail a light yield of 200 pe/MeV has been reached. Currently, the collaboration is investigating the use of a different wavelength shifter to increase the light yield to 300 pe/MeV. The estimated energy spectrum for a 0.3% natural Te loading, 200 pe/MeV, five years of running within a fiducial volume cut of 3.5 m (20%) is shown in figure 4. The plot is obtained with >99.99% and >98% ^{214}Bi–Po and ^{212}Bi–Po tagging efficiencies, as described in section 3. The external backgrounds are also reduced by a factor two. The total background in the ROI (-0.5σ to $+1.5\sigma$ inside the fiducial volume) is about 18.6 events/yr. With this background level and 5 years of measurement, SNO+ can set a limit (90% C.L.) on the half-life of ^{130}Te of $T_{1/2} > 9 \cdot 10^{25}$ yr, which corresponds to a limit on the effective Majorana neutrino mass of m_{ee} <67 meV [9][10]. For reference in figure 4, the effective neutrinoless double-beta decay signal for a 200 meV Majorana mass is shown.

4.2. Reactor- and geo- antineutrinos

Reactor anti-neutrino oscillations were seen for the first time by KamLAND experiment [11]. With only 3 main reactors close to SNO+ location, Bruce at 240 km, Pickering at 340 km, and Darlington at 360 km, the total expected flux is a factor 5 smaller than the one measured by KamLAND. However, the position of the three reactors creates two effective distinct baselines, raising a clear 3 peaks feature in the energy spectrum. SNO+ has hence the potential to make a competitive constraint on Δm^2_{12} despite the lower flux.

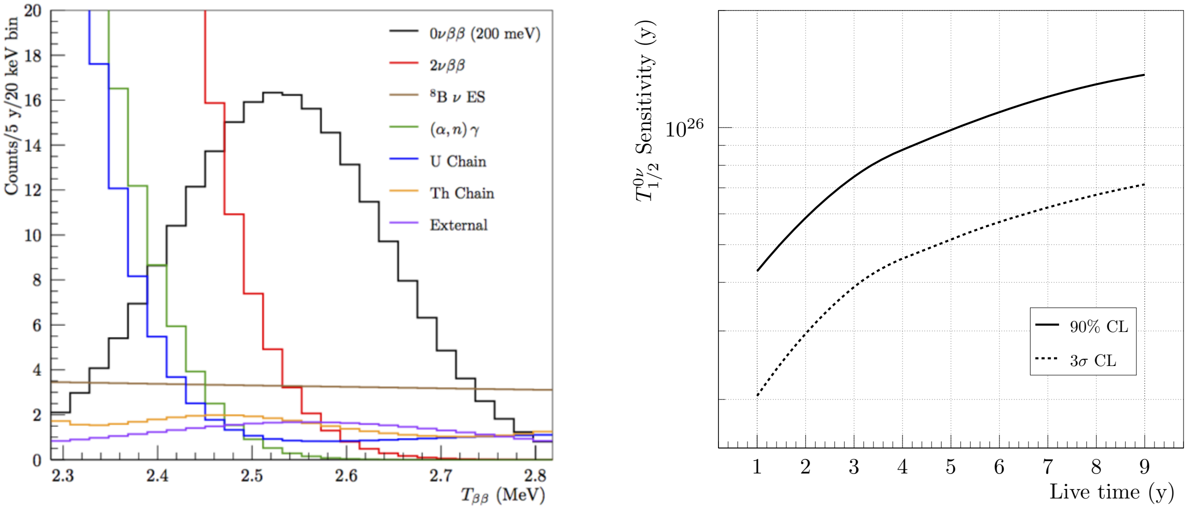

Figure 4: *Left*: Expected energy spectrum (average profiles, MC simulation) of the SNO+ backgrounds and signal for the $0\nu2\beta$-decay search. The spectrum is obtained for 5 years of running, a fiducial volume (FV) cut of 20% and 0.3% natural tellurium loading (800 kg of ^{130}Te). A >99.99% efficient tag for ^{214}Bi–Po background (U chain) has been applied. A rejection factor >70 has been applied to the ^{212}Bi–Po background (Th chain). External backgrounds are reduced of a factor two by a likelihood ratio and FV cut. The cosmogenic induced nuclides in Te have a negligible contribution after surface and underground purification. The expected $0\nu2\beta$-decay signal, for an effective Majorana neutrino mass of 200 meV, is also shown for comparison [9][10]. *Right*: ^{130}Te half-life sensitivity vs live-time for 0.3% natural tellurium loading.

The anti-neutrino signal is detected by the inverse beta decay on protons. The signal consists of two prompt photons emitted by the annihilation of the positron and which deposit an energy of E_ν-0.8 MeV in the detector and the about 200 μs delayed 2.22 MeV gamma from the thermal neutron capture on protons. The way the signal is detected allows an anti-neutrino measurement also during the double-beta decay phase.

In addition to reactor anti-neutrinos, SNO+ can contribute to the measurement of anti-neutrinos coming from the Earth crust and mantle, which will help in the understanding of the heat production of the Earth. The measurement is complementary to the one of KamLAND [12] and Borexino [13] since the Canadian Shield composition is different from the one of Italy and Japan, where Borexino and KamLAND are located.

In SNO+ about 29 geo anti-neutrinos for one year of data taking are expected [14].

4.3. *Supernova neutrino watch*

SNO+ will be part of the Supernova Early Warning System (SNEWS). Neutrinos will be detected via charge-current interactions and neutral-current interactions on ^{12}C and proton scattering. For a 10 kpc 10^{53}erg Galactic supernova > 750 events above an energy threshold of 0.2 MeV are expected from the two processes. From neutral-current interactions it would also be possible to gain information about the total flux of all neutrino flavours.

4.4. *Other physics*

During the initial water phase SNO+ will perform a search for nucleon decay. The signal is the emission of a 6 MeV gamma from the de-excitation of the residual nucleus. During 6 months of water phase data taking SNO+ can set a limit of $8.2{\cdot}10^{30}$ yr on the neutron invisible decay mode, and $9.1{\cdot}10^{30}$ yr on the proton one. The current limit set by KamLAND is $5.8{\cdot}10^{29}$ yr [15].

Due to the low energy threshold of about 200 keV SNO+ can measure low-energy solar neutrinos, like *pep* and *CNO*, during the long-term pure scintillator phase that will follow the double-beta one. A short solar neutrino data taking phase will precede the Te-phase. The *pep*-flux is of particular interest to investigate the transition between the matter-dominated and the vacuum dominated flavour transformation region. They could constrain new physics scenarios on how neutrinos couple to matter.

CNO-neutrinos, on the other hand, can shed light on the unresolved question about the solar metallicity. The recent metallicity measurements broke the excellent agreement between the Standard Solar Model and

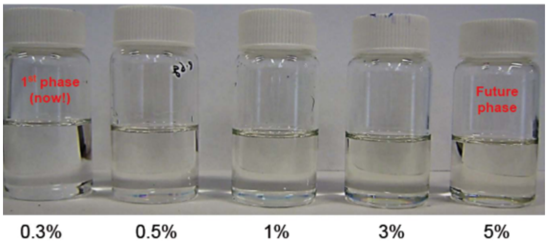

Figure 5: Test of higher tellurium loading in scintillator. From left to right the current loading (0.3%) to the heavier stable one (5%). The scintillator takes a yellowish color due to the larger fraction of surfactant.

helioseismology [16]. One of the major background for this measurement is the ^{210}Bi beta-decay as it has a shape similar the the *CNO* neutrino one.

High energy solar neutrinos, like ^{8}B-neutrinos, can be measured also during the double-beta phase. Their elastic scattering is one of the main irreducible backgrounds in the ^{130}Te ROI.

5. Future development

To increase the sensitivity to neutrinoless double-beta decay lifetime, SNO+ is testing future upgrades of the technique. Currently studies are focussed in improving the loading technique in order to reach up to 5% natural tellurium loading into scintillator. A preliminary result is shown in figure 5 for loadings from 0.3% (actual) up to 5%. All the samples have good optical transparency, slightly degradating as the loading is increased due to the higher quantity of surfactant necessary. Other future upgrades that are foreseen are larger quantum-efficiency PMTs and the use of an internal bag to reduce the external backgrounds.

6. Conclusions

The SNO+ experiment is the follow up of SNO, where the heavy water is substituted by 780 tonnes of liquid scintillator. The main aim of the experiment is the search for neutrinoless double-beta decay with ^{130}Te. With a loading of 0.3% natural tellurium, corresponding to 800 kg of ^{130}Te and 20% fiducial volume, a limit on the half-life better than $9.8{\cdot}10^{25}$ yr (90% C.L.) can be reached in 5 years of data taking. Additionally, due to the low energy threshold of few hundreds of keV, SNO+ will be able to measure at the same time as double-beta decay, geo- and reactor antineutrinos. SNO+ will be also part of the SNEWS for supernovae watch. Low energy solar neutrinos, can be measured during a pure scintillator phase planned after the double-beta phase.

Several upgrades have been made to the detector over the past years in order to make use of the SNO vessel. A new hold down rope system, with high purity ropes, has been installed in 2012. The electronics has been upgraded and broken PMTs repaired.

The purification system of SNO+ is currently being installed. The water cavity filling is ongoing with 20 feet of UPW. The filling will be completed in early 2015. The Te-loading phase is foreseen for the beginning of 2016.

Acknowledgement

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