PROCEEDINGS OF SCIENCE

Status of the SNO+ experiment

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The SNO+ experiment has multiple physics goals among which the search for neutrinoless double-beta decay, the study of solar neutrinos, measurements of anti-neutrinos from nuclear reactors and the Earth's natural radioactivity, as well as the ability to detect supernova neutrinos. Located in the SNOLAB underground physics laboratory (Canada) it will re-use the SNO detector equipped with ∼9300 PMTs and looking at a 12 m diameter spherical volume. The detector will be filled with 780 tonnes of liquid scintillator to which ^{nat}Te at 0.3% loading will be added. The commissioning of the detector at SNOLAB has started, and data with air and partial water fill have been taken. A short phase with the detector completely filled with water is expected to start at the end of the year, before running the detector with scintillator in 2016. The main detector developments and technical challenges inherent to this large volume liquid scintillator and low-energy experiment are presented. In addition, the status of the detector which is in its commissioning phase and the detector and physics plans for the water phase will be described. Finally, the neutrinoless double-beta decay sensitivity and physics goals that SNO+ aims to achieve in phases with different loadings will be given.

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1. The SNO+ experiment

The SNO+ collaboration has about ninety members from twenty three different institutes located in six different countries. Located 2 km (6000 m.w.e.) underground in the Creighton mine (Sudbury, Ontario, Canada), the SNO+ [1] detector will replace SNO's heavy water target by 780 tonnes of liquid scintillator loaded with different amount of double-beta isotope. A new hold-down rope system has been installed on the 5 cm thickness and 12 m diameter acrylic vessel (AV) to compensate for the buoyancy of the liquid scintillator. About 9300 inward looking photo-multipliers (PMTs) installed on a 17.8 m diameter support structure (PSUP) surrounding the AV are collecting light with 54% photo-cathode coverage. An amount of 7 kt of ultra-pure water provides shielding from radioactivity coming from the cavity rocks (norite + gabbro) and the PMTs array. The detector has been upgraded with a new data-acquisition (DAQ) system and readout cards. New calibration systems have also been implemented. SNO+ has several physics goals among which the search for Majorana neutrinos, measurements of low-energy solar neutrinos from the *pep* reaction, the CNO cycle and the ^{8}B branch, anti-neutrinos from nearby nuclear reactors and from the Earth [2], supernova signal observation and search for exotics physics such as invisible nucleon decay (IND) modes and axion-like particles (ALP). It will run several phases dedicated to different part of the physics program as summarized in Table 1.

	$0\nu\beta\beta$	solar ν	reactor and geo $\overline{\nu}$	supernova ν	exotics
water				X	IND, ALP
pure scintillator I			X	X	
loading I (0.3% ^{nat}Te)	X		X	X	ALP
pure scintillator II		X	X	X	
loading II ($>$ 0.3% ^{nat}Te)	X		X	X	ALP

Table 1: Physics program of the different SNO+ phases

2. SNO+ status

2.1 Scintillator mixture and isotope selection

The choice of Linear alkylbenzene (LAB) as a solvent with 2,5-diphenyloxazole (PPO) in a concentration of 2 g/L as a fluor for the SNO+ liquid scintillator was motivated by LAB properties such as its long time stability, its compatibility with acrylic, its good optical properties (high attenuation length) and linear response in energy, as well as its high flash point and low toxicity. In addition, it can be produced at large scale with high radio-purity.
The choice of ^{130}Te as isotope are motivated by its high natural abundance (34.08%), its high half-life $T_{1/2}^{2\nu\beta\beta}$ = 7.0×10^{20} yr, and the absence of inherent absorption lines. At 0.3% ^{nat}Te loading between 200 and 300 photoelectron hits (Nhits) are detected per MeV depending on the wavelength shifter chosen. However, due to its low end-point ($Q_{\beta\beta}$ = 2.53 MeV), efficient background reduction techniques need to be used.
An innovative loading technique has been developed which involves the dissolution of telluric acid $Te(OH)_6$ in water and its combination with LAB with the help of a surfactant. For loading phase I

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the total quantity of ^{130}Te represents an amount of 800 kg. Higher loading, with concentration up to 5% ^{nat}Te are under study and good transparency has been achieved so far [3].

2.2 Rope tensioning and water level

In addition to the SNO PSUP hold-up rope system, a hold-down net has been installed over the AV and anchored to the cavity floor to compensate for the 130 T of added buyoancy due to the liquid scintillator. The rope tensioning system will be tested with the detector filled with water up to the equator. It will involve tensioning the hold-down net to 284 000 lb (total load of liquid scintillator) by floating the AV filled to the equator and hold the tension for two weeks. A partial rope tensioning test has been already performed when the cavity water level was at the AV bottom. An 80 000 lb load was applied to the rope net and it successfully confirmed the anchors adjustment. The water level at the time of the presentation was lowered down to 20 ft (18 ft below equator) for cavity liner inspection which are still on-going at the moment in an attempt to identify potential leaks.

2.3 PMTs and DAQ systems

SNO was equipped with 8$''$ (20 cm) Hamamatsu R1408 PMTs among which 9438 inward-looking (including 49 low-gain channels) and 91 outward-looking PMTs. Of the inward-looking PMTs, 850 were found to have base short circuit (90%) or tube failure (10%). A total of 391 PMTs has been repaired and replaced so far. However the total number of PMTs will be smaller than in SNO times due to the removal of some of them to allow for the new ropes passage and the new calibration system, thus reducing the total number of PMTs to about 9300. SNO+ increased event size (a solar neutrino event in SNO heavy water would illuminate on average 40 PMTs while a $0\nu\beta\beta$ event in SNO+ loaded scintillator will illuminate about 500 PMTs) and data rate (2-250 kB/s bandwidth in SNO compared to 2.5 MB/s in SNO+) put new requirements on the DAQ and readout cards which motivated a new design. The new DAQ software uses the University of North Carolina at Chapel Hill (United States) ORCA [4] software. A new database (using Apache couchDB [5]) was implemented together with the monitoring and slow-control systems. Airfill and partial air-water runs were taken to test the whole system. More recently, a Mock Data Challenge was performed to also test the near-line framework.

2.4 Water/scintillation systems and isotope purification

The SNO water system has been reconditioned to supply water in the AV inner volume. Re-circulation of the water inside the AV will permit an initial leach/wash of the AV walls which have been exposed to air. The system is complete and under operation and the achievable water purity is of the level of that of SNO. The water system will also serve for the scintillator mixing and purification.

The scintillator system provides multi-stage and high temperature flash vacuum distillations of the LAB and PPO separately. It is equipped with water extraction columns (to remove ^{40}K, Ra and ^{210}Pb), and N_2/steam stripping columns to remove Rn, O_2, Kr and Ar gases. Major piping and vessels installation has been done. Leak checking has been completed and cleaning and passivation is under completion at the moment.

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The isotope purification consists of a double-pass (with ethanol rinsing) purification on surface with a purification factor of 10^4. An additional purification stage underground without ethanol, allows for another factor 100 in purification. The collaboration is investigating at the moment the possibility to move the surface purification system underground.

2.5 Calibration systems

The purpose of the optical calibration systems is to measure the PMTs response on one-hand, on the other-hand to measure in-situ the optical properties of the media. Several systems have been designed for the SNO+ optical calibration: a fixed fiber-based system using LED/laser light injection located on the PMTs array, a tunable laser device that can be deployed in the detector, and a Cherenkov source that can also be deployed in the detector. It will permit the validation of the light transport models in different media. The PMTs angular response, timing and gain calibration will be measured. Attenuation length and scattering of the media will be evaluated. It will also provide monitoring of the media transparency over time and as the ^{130}Te loading concentration increases. Finally the PMTs efficiency will be measured thanks to these calibration methods. The fibers system is equipped with LEDs or laser that can send pulses at different wavelengths and different fibers angles from 106 different location points. SNO+ is equipped with a deployment system that allow the insertion of several types of sources from the top of the AV. Off-axis (in two planes) source location are achievable thanks to this system. It is a radon-tight and fully sealed system under completion at the moment. A total of 69 fibers were installed and tested. A prototype of the Cherenkov source is ready.
Several (β, γ) radioactive sources (see Table 2) are being explored in order to measure the efficiency and systematic uncertainties of event reconstruction such as on the energy, position and particle identification. All can be deployed in the detector from the top of the AV with the same deployment

Source	AmBe	^{60}Co	^{57}Co	^{24}Na	^{48}Sc	^{16}N	^{220}Rn/^{222}Rn
Radiation	n,β	γ	γ	γ	γ	γ	α,β, γ
Energy [MeV]	2.2, 4.4 (γ)	2.5 (sum)	0.122	4.1 (sum)	3.3 (sum)	6.1	various

Table 2: Calibration sources under consideration for use by the SNO+ experiment

system used for the laser and the Cherenkov source. A universal deployment/interface is under construction. It has a mechanism able to deploy all in one the sources, voltages, ropes and gas feed. A sealed interface equipped with glove box, view ports and gate valves allows for precise sources manipulation.

3. $0\nu\beta\beta$ physics sensitivity

3.1 Neutrino mass current limit

The IGEX, Heidelberg-Moscow, Cuoricino and NEMO-3 experiments have set current bounds on the effective Majorana mass $m_{\beta\beta} = \sum_i U_{ei}^2 \cdot m_i \leq$ (0.33-1.35), (0.22-0.64), (0.30-0.71) and (0.44-1.00) eV [6] respectively, depending on the nuclear matrix elements and isotope used. More recent results have lowered this limit down to (0.12-0.25) eV from KamLAND-Zen/EXO-200 [7] and (0.2-0.4) eV from GERDA I [8]. With 0.3% ^{nat}Te loading and five years of data-taking, SNO+

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will be sensitive to a mass $m_{\beta\beta}$ of 0.055-0.133 eV, depending on the method used to calculate the nuclear matrix elements. The neutrinoless double-beta decay experiments currently taking data or under commissioning at the moment hope to reach the top of the inverted hierarchy mass region by 2018.

3.2 Background mitigation

The largest contribution to the background signal (see Fig. 1) in the SNO+ region of interest (ROI) is the irreducible background from ^{8}B solar neutrinos elastic scattering. However it is well-known and can be normalized in the ROI using solar flux published data and neutrino oscillation mixing parameters. The second biggest irreducible background comes from the $2\nu\beta\beta$ decay from ^{130}Te itself. By using an asymmetric ROI around the $0\nu\beta\beta$ signal, one can limit the quantity of such background in the ROI. However the SNO+ limited energy resolution does not permit to reduce this background much further. External γ's from the AV, the detector ropes, the water shielding and the PMTs contribute to the background to the neutrinoless double-beta decay signal. With the help of a fiducial volume (FV) cut, and using PMTs hit time distribution cuts, one can reduce this background contribution. The dominant background from the natural ^{238}U and ^{232}Th chains are from ^{214}Bi $\rightarrow^{214}$Po and ^{212}Bi $\rightarrow^{212}$Po respectively. Coincidence-based cuts have been developed allowing a 100% rejection efficiency for events in separate trigger windows. Pile-up events can be rejected thanks to PMTs hit timing cuts with a rejection factor of 50. Cosmogenics also contribute to backgrounds falling in the FV and ROI. However using in combination purification techniques and long term underground storage, its contribution will be reduced to less than an event per year in FV and ROI. Finally (α,n) backgrounds are adding up to a small contribution as both the prompt signal and the delayed γ can fall in the FV and ROI. Coincidence-based cuts have been developed allowing to remove $>$ 99.6% of the prompt signal and 90% of the delayed events.

3.3 Phase I and higher loading sensitivity

At 0.3% ^{nat}Te loading, using a fiducial volume cut R $<$ 3.5 m (20%), assuming a rejection greater than 99.99% for ^{214}Bi $\rightarrow^{214}$Po and greater than 98% for ^{212}Bi $\rightarrow^{212}$Po, as well as a light yield of 200 Nhits/MeV, the SNO+ expected sensitivity is $T_{1/2}^{0\nu\beta\beta} > 3.9\times10^{25}$ (9.4×10^{25}) yr and $m_{\beta\beta} \leq 105$ (68) meV for 1 (5) years of data-taking. The values for the phase space factor G = 3.69×10^{-14} yr^{-1}, the axial vector coupling constant g_A = 1.269 and the IBM-2 matrix element $M_{0\nu\beta\beta}$ = 4.03 have been used in the above calculation.
Figure 2 shows a summary plot[1] of an hypothetical $0\nu\beta\beta$ signal corresponding to a mass $m_{\beta\beta}$ = 200 meV for 5 years of data-taking with respect to the corresponding background. SNO+ will run with higher ^{nat}Te loading after phase I. R&D efforts show that at 3% ^{nat}Te loading, a light yield of 150 Nhit/MeV can be achieved using perylene as second wavelength shifter. The loss of light yield can be compensated by high quantum efficiency (HQE) PMTs and PMTs concentrator improvements. In this scenario SNO+ could set a lower limit on $T_{1/2}^{0\nu\beta\beta} > 7\times10^{26}$ yr corresponding to a mass range of 19-46 meV.

[1] Backgrounds from cosmogenics after five years of data-taking become negligible thus it is not represented.

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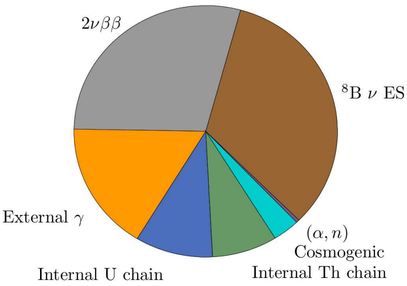

Figure 1: Pie chart of the background budget for one year of data-taking.

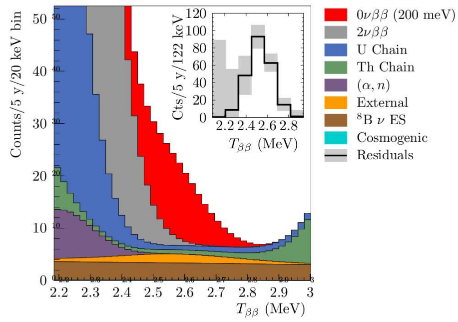

Figure 2: Backgrounds and hypothetical $0\nu\beta\beta$ signal for five years of data-taking.

4. Conclusion and outlook

The main physics goal of SNO+ is the search for $0\nu\beta\beta$ in an effective neutrino mass range at the top of the inverted hierarchy mass region. It is a multi-purpose detector able to study also low-energy solar neutrinos, reactor and geo-neutrinos, supernova neutrinos and exotics physics such as invisible nucleon decay modes and axion-like particles. The water plant is finished and under operation. The scintillator plant is undergoing final cleaning and passivation work. The source insertion and deployment mechanisms are under construction. The DAQ and data-flow systems as well as the monitoring and near-line tools are at present in benchmarking and the detector is ready to take data after full water fill. We expect the water commissioning phase to run in 2015-1016. Followed by the scintillator phase in 2016. Phase I with 0.3% ^{nat}Te loading is expected to start in 2017.

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