SNO+ status and plans for double beta decay search and other neutrino studies

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Abstract. SNO+ is a multi-purpose Neutrino Physics experiment, succeeding to the Sudbury Neutrino Observatory by replacing heavy water with liquid scintillator, which can also be loaded with large quantities of double-beta decaying isotope.

The scientific goals of SNO+ are the search for neutrinoless double-beta decay, the study of solar neutrinos and of anti-neutrinos from nuclear reactors and the Earth's natural radioactivity, as well as supernovae neutrinos.

The installation of the detector at SNOLAB is being completed and commissioning has already started with a dry run. The detector will soon be filled with water and, later, with scintillator.

Here we highlight the main detector developments and address the several Physics analysis being prepared for the several planned SNO+ runs.

1. The SNO+ experiment and its detector

SNO+ re-uses the hardware of the Sudbury Neutrino Observatory detector (see figure 1 and ref. [1] for a global view), located at a depth of 6000 meter water equivalent in SNOLAB, Canada. The active medium changed from heavy water in SNO to a specially designed liquid scintillator in SNO+, allowing for measurements below a 1 MeV threshold. The energy and position of each event are reconstructed from the signals of an array of around 9500 PMTs overseeing the isotropic fluorescence light and depend on the precise optical characteristics of the several media.

A new rope system holding the spherical acrylic vessel that separates the active volume from the outside water shielding is already in place, and its capacity to now accommodate a positive buoyancy, is being tested as the detector is filled with water. Also new purification, calibration and monitoring systems are needed to ensure higher levels of radio purity to match the lower energy threshold. The water purification system is an upgrade of the one used in SNO, the scintillator purification is designed to match the goal of 10^{-17} g/g U/Th, as achieved by Borexino; in addition also the loading material for the double beta phases must be purified though to a lower level. A new system is being prepared for the insertion of well known sources in different positions inside the active volume, in order to providing an end-to-end calibration of all the reconstruction and analysis chain. These include alpha, beta, gamma and neutron sources at different energies and also a powerful laser light source for PMT and optical calibration.

In order to allow for an effective monitoring of the detector characteristics with reduced access to the active volume, direct light sources are located in the outer volume and crossing the inner sphere. In this case an array of more than 100 optical fibers carry LED light signals down to the PMT support structure, in short pulses that can be used during normal data-taking. Large
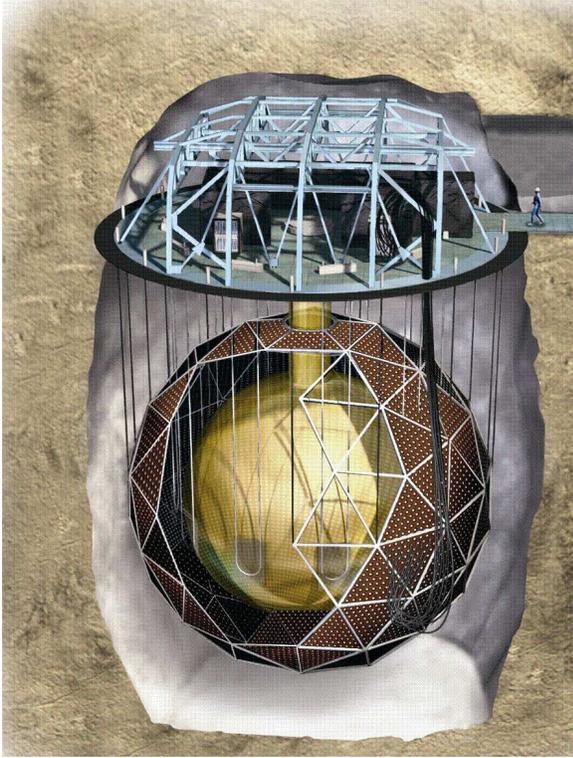
Figure 1. The SNO+ detector consists of a 12 meter diameter inner sphere, where the active volume is held by a 5 cm thick acrylic vessel; and a 60% optical coverage given by 9500 PMTs placed in a 17 meter diameter geodesical structure, with inside and outside shielding by pure water.

aperture fibers allow the calibration and synchronization of the PMTs viewing the same signals, and a partial overlap allows the coverage of the full sphere. Small aperture fibers are used to monitor light attenuation and scattering of the scintillator as a function of time. Part of this system has been installed from the ground and tested in air with the detector empty, the rest will be installed by both during the present water fill, as PMT repairs are also being done.

The experiment will be divided in different phases. Pure liquid scintillator might allow for the measurement of all the solar neutrino lines, depending on the background conditions to be measured in-situ. In order to search for neutrinoless double beta decay, less dependent on low energy backgrounds, loading with specific isotopes is being explored. High intensity Supernovae signals and easily tagged anti-neutrino signals can be identified in all the phases of the experiment.

2. Double Beta Decay

There are only a few isotopes which undergo double beta decays, with simultaneous emission of two electrons and two anti-neutrinos. If the neutrinos are Majorana particles, an extra decay mode can exist in which the two electrons carry all the energy (Q) and no neutrinos are emitted. The neutrinoless double beta decay rate would be proportional to an effective neutrino mass depending on the mass-mixing parameters and Majorana phases. For each isotope it would depend also on phase-space parameters and on the nuclear matrix elements, different from the two-neutrino decay.

We have searched for those double beta decay isotopes which can be dissolved in liquid scintillator, without changing its optical characteristics too much. In fact, liquid scintillator experiments have in general a worse energy resolution than other detector types, but have the advantage of dealing with high quantities in a low background environment. A per-mil loading of a given isotope corresponds to hundreds of kilograms, hard to get in other detector types.

SNO+ has concentrated in two isotopes [1]:

- ^{150}Nd has a high Q value of 3.2 MeV, for which a high energy resolution can be achieved and the main background comes from two-neutrino decay. The two neutrino decay has been measured[3] to be 9×10^{18} years to the ground state, with an extra mode with 10^{20} years. The neutrinoless decay has been calculated as $3 \times 10^{23}/M_{\beta\beta}^2$ years/$(meV)^2$. The natural abundance of the isotope is of only 5.6%, and although enrichment is possible it is nowadays difficult to find.

- ^{130}Te has a lower Q of 2.6 MeV, but a much higher natural abundance of 33%, allowing for a more effective loading. The main background is also of two neutrino decay mode, but with a lifetime measured[4] to be large, of 7×10^{20} years. The neutrinoless decay was calculatedto be $4 \times 10^{23}/M_{\beta\beta}^2$ years/$(meV)^2$, under the same framework [5].
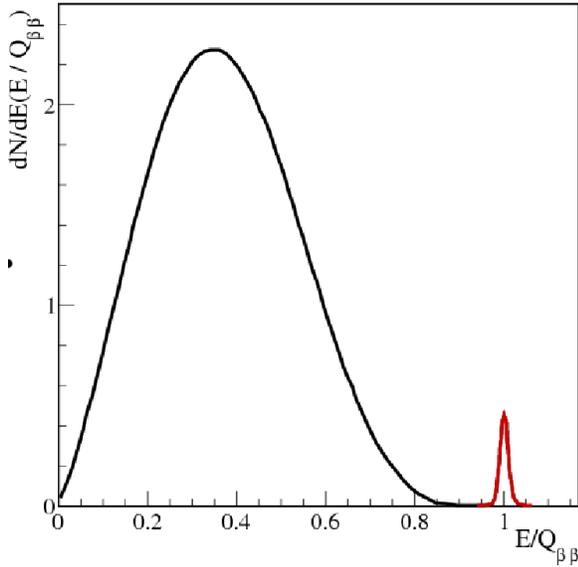
Figure 2. Schematic representation of the expected double beta spectrum. For each isotope, the integral of the continuous curve will be inversely proportional to the $2\nu\beta\beta$ half-life and the peak at Q to the $0\nu\beta\beta$ lifetime.

The two-neutrino decay will be the main background, not only due to the spill-over due to finite energy resolution but also to pile-up events which are reconstructed as a single high energy decay. Both energy and position resolution are fundamental for their treatment. In addition, radiopurity of the loaded scintillator, and namely the cosmogenic activation of some of the isotopes, must be taken into account. ^{214}Bi and ^{208}Tl decays sit in similar energy windows but can be reduced with $\alpha - \beta$ tagging[?]. Solar ^8B neutrinos are an irreducible background, but their energy spectrum is known as is the rate (which can also be measured again as the high energy tail is visible), while all other solar neutrinos will be buried below the beta decay signals.

Preliminary testsindicate the possibility to use ^{130}Te with a 0.3% loading in the first phase of the experiment, which should reach a sensitivity down to 100 meV of effective mass. If the loading can be increased SNO+ could become sensitive to all of the degenerate and even inverted hierarchy mass scenarios.

3. Solar Neutrinos
The oscillation of solar neutrinos was established by SNO which also measured the total ^8B neutrino flux to be consistent with solar models[6]. In fact, the experimental result is more

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[1] Another liquid scintillator experiment, KamLAND[2], used ^{136}Xe (with $Q = 2.5$ MeV and enriched from a natural abundance of 10%), and experienced problems with unexpected backgrounds.

precise than the model predictions, but lays in between two predictions - according to low or high solar metalicity. The goal of the new generation experiments is now to measure the other solar neutrino lines to increase the sensitivity to both oscillation parameters and solar models.

Table 1. Summary of Solar Neutrino Measurements, indicating for each line the main uncertainty source in the model, the existing measurements and the expected precision after a SNO+ solar phase of 1 or 3 years. Notice that hep neutrinos, with a very low cross-section are not included, that the pp rate is estimated from a global oscillation fit and that for ^7Be, there are two lines with a fixed ratio, but only one has been measured.

Type	Model	Measurement	SNO+ (1yr)	SNO+ (3yr)
B-8	nuclear(14%)	CC, NC (SNO) and ES	7.5%	6.5%
pep	luminosity($\sim$1%)	ES by Borexino at 20%	9.1%	6.5% %
Be7	nuclear(7%)	ES by Borexino at 5%	4%	3%
pp	luminosity($\leq$1%)	radio-chemical	a few %?	a few %
CNO	composition(15% to 30%)	un-measured	$\sim$15%	$\leq$ 15%

In Table 1 we show the existing measurements and predictions for several solar lines from [7] together with the expected sensitivity of SNO+ after 1 and 3 years of pure liquid scintillator running. In comparison to other running experiments, namely Borexino, SNO+ has the advantage of a higher volume but mostly a deeper location. The cosmic ray muon flux at SNOLAB is 100 times smaller, which decreases the cosmogenic production of ^{11}C, whose decay represents an important background for both pep and CNO neutrinos. These are the two main targets of SNO+, for different reasons:

- pep neutrinos have a monochromatic energy of 1.44 MeV, and the solar models predict the flux with very small uncertainty. It's measurements is thus very sensitive to oscillations (and possibly also new physics) effects. The energy lays in the transition region between matter and vacuum dominated oscillation and can be used to measure oscillation parameters with very high precision.
- CNO neutrinos have not been measured yet, they are originated by three beta decays, and the total fluxes depend strongly on the parameters of solar model calculations. This measurement gives a direct probe of the solar metalicity.

The solar neutrino phase of SNO+ might be complicated due to the accumulation of radon daughters on the surface of the AV over the last few years in a significant way. If these leach into the scintillator, the purification system has the capability to remove them. However, depending on the actual leach rate, that removal might be inefficient and the ^{210}Bi levels in the scintillator too high for a pep/CNO solar neutrino measurement without further mitigation. Mitigation could include enhancing online scintillator purification, draining the detector and sanding the AV surface to remove radon daughters, or deploying a bag. $0\nu\beta\beta$ and low-energy ^8B solar neutrino are not affected by these backgrounds.

4. SuperNovae, Geo and Reactor Anti-Neutrinos
Other physics analysis will be pursued during all phases of the experiment. SNO+ is one of the neutrino detectors of the SuperNova Early Warning System (SNEWS) network, its size and energy threshold allows the measurement of hundreds of neutrinos and anti-neutrinos of all flavors in case of a Supernova explosion at 10 parsec.

Anti-neutrinos can be also detected due to a characteristic delayed coincidence signal of inverse beta decay process. In SNO+ the expected rate is of around 100 reactor anti-neutrinos a year. Sensitivity to the squared mass difference parameter becomes competitive with the existing results from KamLAND[8] after five years running because, although the flux is much smaller, a lower number of reactors gives rise to very clear oscillation pattern, as shown in figure 3.
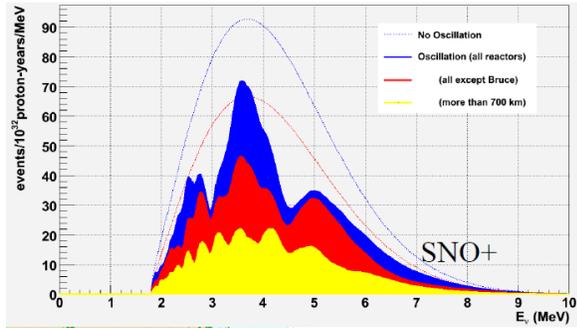
Figure 3. At SNO+, half of the reactor anti-neutrino flux comes from three nuclear power plants, one at 150 km south and two at 250 km south-east in Ontario, and present a very clear oscillation pattern. The rest of the flux is a combination of all other reactors in the world, for which the oscillation is smeared.

For energies below 2.5 MeV, half of the flux is expected to come from geo-neutrinos. Due to its location in a thick continental crust, SNO+ is expected to have an increased geo-neutrino flux compared to the two other experiments that have first measured geo-neutrinos, namely KamLAND[9] and Borexino[10]. While the low reactor rate will decrease the systematics from this background, statistical errors will be smaller because of the detector size. A full combination of the rates in different locations is needed in order to clearly separate the crust from the more interesting mantle contribution. Geo-neutrinos will finally be used to explore Earth models as was done before with Solar neutrinos[11].

5. Summary and Outlook
SNO+ is now completing the installation of the new systems in order to start data-taking in 2014. Some preliminary tests done with an empty detector have allowed early commissioning of PMT and new light calibration systems already. The detector is now being filled with water, allowing to reach the upper part of the detetor and to have first data taking in conditions similar to the latest SNO running. Water will be then replaced by pure liquid scintillator for a small commissioning phase.

In 2014, the scintillator will be loaded with 0.3% of ^{130}Te. In this first phase, neutrinoless double beta decay will be explored, with expected sensitivity to effective masses below 100 meV.

Taking into account the results and also background conditions, a second phase will be designed. It can either concentrate on adding extra Te in the detector or to unload it and do a dedicated run for solar neutrinos.

During all phases the experiment will look for Supernoave and Anti-neutrinos.

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