PROCEEDINGS OF SCIENCE

Status of the SNO+ Experiment

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SNO+ is an upcoming multipurpose neutrino experiment in its final phase of construction. It is the successor of the Sudbury Neutrino Observatory, located in the world's deepest operating underground laboratory SNOLAB in the Vale Canada Ltd. Creighton Mine. About 6000 m.w.e. overburden, the replacement of SNO's heavy water with liquid scintillator, elaborate scintillator purification techniques and the use of ultra–clean materials shift the detector threshold to low energies and provide ultra low backgrounds. For this reason SNO+ is, in the pure scintillator phase, capable of observing low–energy solar neutrinos, with particular interest in CNO and pep neutrinos, geo neutrinos, reactor neutrinos and possibly supernova neutrinos. In the neodymium–loaded phase SNO+ will primarily search for the neutrinoless double beta decay of ^{150}Nd. In this paper the general set–up, the main detector developments and the physics goals of SNO+ are summarized.

The XIth International Conference on Heavy Quarks and Leptons,
June 11-15, 2012
Prague, Czech Republic

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PoS(HQL 2012)025

1. Introduction

The Sudbury Neutrino Observatory was the deepest multi-tonne underground detector of its time. With the ability to not only detect electron neutrinos but also muon and tau neutrinos, SNO solved the long–standing solar neutrino problem [1]. SNO+ is the follow–up experiment of SNO, replacing the kilotonne of heavy water with $\sim$780 t of liquid scintillator and taking advantage of the already existing SNO infrastructure. However, due to the conversion from a Cherenkov detector into a scintillator detector, several developments are needed to be able to achieve the physics goals of the experiment.

The unique location of SNO+ 2 km underground, the high radiopurity of the used materials and the purified liquid scintillator allow the experiment to address various open questions in neutrino and astroparticle physics like the Majorana or Dirac character of neutrinos, the nature of neutrino oscillations and the chemical abundances in the Sun and the Earth.

More precisely, the strong suppression of the cosmic muon flux due to the vast rock shielding reduces cosmogenic backgrounds to a level that allows a precision measurement of the solar pep neutrino flux. Depending on the U and Th background levels and the purity of the liquid scintillator a CNO and pp flux measurement may also be possible.

At the search for neutrinoless double beta decay, the high mass of liquid scintillator loaded with an intial concentration of 0.1% Nd will provide 43.7 kg of the double beta decay isotope ^{150}Nd. An increase of the concentration during data taking is planned to further improve the sensitivity despite an enhanced light absorption due to Nd.

Additionally to the measurements mentioned above, SNO+ can in case of a supernova provide important information to help understanding the physical processes within a core–collapse.

The detector design and the completed and ongoing developments are described in section 2 and the main physics program is presented in section 3 carried out in the two different phases as given in section 4.

2. Detector Developments

The SNO+ detector is installed in a barrel–shaped 34 m deep and 22 m wide cavity, which is sealed against the ingress of radon with an Urylon radon liner. The center of the detector is formed by a 12 m diameter acrylic vessel (AV) of 5 cm thickness which will contain about 780 t of liquid scintillator. The AV is connected to the deck area via a cylindrical neck and is surrounded by a photomultiplier support structure (PSUP), a 17.8 m diameter geodesic stainless steel frame holding more than 9000 8“–PMTs. This configuration yields a solid angle coverage of about 54%. The entire volume outside the AV is filled with 7.4 kt of ultra–pure water.

The solvent chosen for the liquid scintillator is linear alkylbenzene (LAB) as it satisfies the different requirements of the experiment. This solvent is chemically compatible with acrylic, low in toxicity and environmentally safe. It has a comparatively high flash point of 130° C and a high purity is achievable. Furthermore, LAB is readily available as it is a standard component in the production of detergents. SNO+ LAB will be delivered from the Petresa plant in Bécancour, Quebec, since Petresa performs purification steps that other producers skip and provides in this way the purest and most transparent LAB of all tested by SNO+. As fluor 2,5-Diphenyloxazole (PPO) will be used in a concentration of 2 g/L. This value is the optimal compromise between light yield and self–absorption and reaches a light yield of 10,000 photons/MeV. Different decay times for electrons e and alpha–particles α permit a proper α/e separation [2].

However, changing the active medium within the AV from heavy water to liquid scintillator raises new demands to the detector. In contrast to heavy water, the used liquid scintillator has a lower density (0.86 g/cm^3) than the surrounding light water shielding and will be subjected to buoyancy. An additional rope–net system anchoring the vessel to the cavity floor is necessary. The installation has been successfully completed at the beginning of this year using high purity Tensylon as rope material. To match the background target levels of SNO+, the rope material of the former hanging system was replaced by Tensylon as well.

Additionally, the AV itself has to be as free from radioactivity as possible. The vessel has been exposed to mine air, which is laden with radon, for several years. To remove daughters of ^{222}Rn having been implanted into the acrylic and causing a diffuse background, the inner surface of the AV will be cleaned and polished. To avoid new infiltration of radon, the neck will be closed by a radon–tight glove box after cleaning.

Electronics and data acquisition are upgraded including a redesigned trigger system and an increased data rate capacity to meet the one to two orders of magnitude higher light yield compared to heavy water. Some boards and several dead PMTs have been repaired or replaced and dead electronic channels have been re–mapped.

2.1 Calibration

The calibration and monitoring program must provide an extensive understanding of the energy response, position dependencies, the optical response and the long term stability of the detector response while minimizing the risk of contamination. To cover an energy range of about (0.1–10) MeV, various radioactive sources are under development with special interest in the ^{57}Co source (around the detector threshold) and the ^{48}Sc source (at the double beta decay endpoint of ^{150}Nd). The ^{8}Li source will be used as absolute optical calibration source. It is designed to only produce Cherenkov light in order to break down the degeneracy between scintillator and PMT plus reflector response. The position of a deployed source will be determined with a system of six cameras installed all over the PSUP, improving the accuracy from ±5 cm, given by the source manipulation system, to ±1.5 cm at the center of the detector. Moreover, the camera system will monitor the shift of the AV during the full course of SNO+.

While SNO deployed for optical calibrations the so–called laseball monthly, a quasi isotropic light source using laser light injection into a spherical diffuser, the access to the AV has to be reduced for SNO+ as much as possible to avoid the insertion of contaminants. Therefore the ELLIE system (Embedded LED Light Injection Entity) was newly designed. It consists of 120 optic fibres fixed onto the nodes of the PSUP with the light being injected from the deck area. This way, the optical and electronic response of the PMTs, and the optical response in all media can be monitored quasi continiously from outside the AV and the use of the laseball can be minimized. All ELLIE fibers that can be put into postion from the cavity bottom have been installed this year.

2.2 Scintillator Purification

An elaborate system of different scintillator purification techniques is underway, mainly following the successful approach of the Borexino experiment. To reach the target levels of 10^{-17} g/g of ^{238}U and 10^{-18} g/g of ^{232}Th that were achieved by Borexino [3], a highly concentrated master solution with 120 g/L PPO is prepared in batches and prepurified in a first step. The concentrated PPO solution and LAB are distilled in parallel before blending the scintillator in order to remove heavy metals and to improve UV transparency. In a further purification step, volatile contaminants of the scintillator like Rn, Kr, Ar and O_2 are removed in a N_2/steam stripping process. At a throughput speed of 19 L/min the AV is filled within 12 weeks with scintillator by replacing the ultra–pure water inside the vessel. While the detector is operating it will be possible to repurify the scintillator in a recirculation process at 150 L/min within 4 days. Water extraction will remove elements like Ra, K and Bi and metal scavenging will further remove Ra and Bi and other elements like Pb. Within the recirculation, steam stripping will be repeated and the scintillator will pass through microfiltration.

3. Physics Program

3.1 Geo Neutrinos

Geo neutrinos, electron anti–neutrinos coming from the naturally occuring beta decays of ^{235}U, ^{238}U, ^{232}Th and ^{40}K in the Earth, provide an efficient probe for the chemical abundances of the respective elements in the Earth's crust and mantle. Seismology gives no information about the chemical composition and different authors of Bulk Silicate Earth (BSE) models propose different abundances [4]. Also heat flow within the Earth is an open question. Different models (e.g. cosmochemical, geochemical, geophysical) expect a different heating power and different contributions from heat sources. Geo neutrinos can help benchmarking the radioactive power in the heat flow of the Earth as the radiogenic heat is in a well–fixed ratio with the electron anti–neutrino flux.

The signal of geo neutrinos in a liquid scintillator detector is given by the deposited energy of the positron coming from an inverse beta decay. However, electron anti–neutrinos are also produced by nuclear reactors leading to the same signal. The ratio of reactor background to geo neutrino signal in SNO+ is about 1.1 and the peak of the reactor neutrino spectrum lies slightly above the maximum kinetic geo neutrino energy of 3.3 MeV, making SNO+ sensitive to geo neutrinos.

At the location of SNO+, geo neutrinos are mainly coming from two reservoirs, the mantle and an old, thick continental crust. Moreover, the very local region is extensively studied due to the vast mining activities near Sudbury. Hence, by subtracting the well–known crust component from the SNO+ geo neutrino signal the deep Earth (i.e. the mantle) component can be inferred. This turns SNO+ into an important pillar in a worldwide multi–site measurement with other low energy neutrino experiments.

3.2 Reactor Neutrinos

The expected electron anti–neutrino flux from nuclear reactors at SNOLAB is only about 20% of the flux through the KamLAND detector. On the other hand, because of the small number of relevant reactors in the reach of SNO+, only two baselines are considerably contributing to the oscillated energy spectrum of reactor neutrinos. This leads to distinct peaks in the spectrum being more easily identified with the referring oscillation minima. The enhanced resolution of the oscillation pattern increases the sensitivity to Δm^2_{21} despite low statistics.

3.3 Supernova Neutrinos

With the observation of the SN 1987A, the Kamiokande and IMB Cherenkov experiments provided important information about the mechanisms of a supernova burst. Liquid scintillator detectors are sensitive to both, charged and neutral currents, and have in total a larger variety of reactions. Therein the golden channel for SN neutrino detection of all flavours is the neutral current neutrino–proton scattering, as it is the only channel providing spectral information for all neutrino flavours. Besides offering with new detection channels new information about supernovae, SNO+ will participate in the Supernova Early Warning System SNEWS as SNO did.

3.4 Solar Neutrinos

After the precision measurement of the ^{8}B neutrino flux at high energies ($\geq 3.5\,$MeV) by SNO [5] and the ^{7}Be flux at low energies (0.862 MeV) by Borexino [6] the next target precision measurement is the pep neutrino flux in the energy region in between. This region is of particular interest since the survival probability as a function of energy shows a different behaviour in this transition region assuming the MSW model on the one hand and several models beyond the Standard Model (e.g. sterile neutrinos or mass varying neutrinos) on the other hand. The pep reaction within the pp solar fusion chain produces monoenergetic neutrinos with 1.44 MeV and the flux is with an uncertainty of 1.5% very well predicted by Standard Solar Models (SSM) being basically constrained by the Sun's luminosity. This makes pep neutrinos a sensitive probe for new physics and helps to further constrain the MSW oscillation parameters.

Also the endpoints of the energy spectra coming from CNO neutrinos lay in the transition region. However, they have a one order of magnitude higher model uncertainty and the summed CNO neutrino spectrum is nearly degenerate with the unavoidable ^{210}Bi beta decay spectrum. Still, an observation of CNO neutrinos is of importance as it can test the solar metallicity. When using the metallicity Z gained from early photospheric absorption line analyses as input parameter, Solar Models can reproduce helioseismology data. A re–analysis of the lines with a 3D model of the photosphere instead of the former 1D model improved the consistency of line sources and the line shapes but led to a significant reduction of Z. Sound speed profiles now produced with SSMs using the reduced metallicity are however no longer in good agreement with helioseismology. This controversy raises the fundamental question whether elements are homogeneously distributed in stars. CNO neutrino flux expectations depend directly on Z and differ by more than 30% using SSMs with low or high metallicity. Accordingly, a strong limit on the fluxes can help to determine the metallicity in the solar core, the production region of the neutrinos.

The main background to the pep signal and a contribution to the background of the CNO signal in liquid scintillator comes from the decays of cosmogenically produced ^{11}C. A sophisticated coincidence cut can partly reduce this background but is strongly limitted by signal acceptance [7]. SNO+ has, due to its uniquely deep location, a muon rate that produces a ^{11}C background that is already below the pep signal without any cuts (see figure 1). Together with the high scintillator mass resulting in high statistics SNO+, will be able to perform a precision measurement of the pep neutrino flux. Concerning a CNO observation additional cuts on ^{11}C will improve its feasibility.

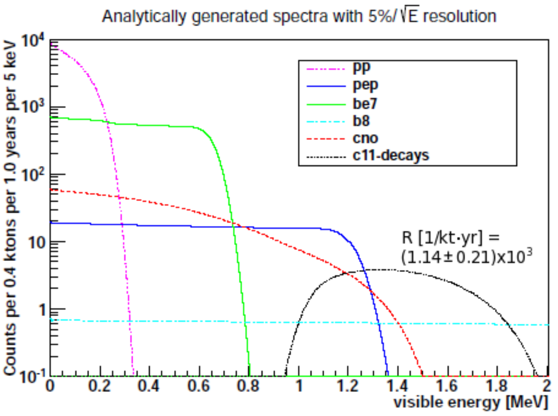

Figure 1: Expected electron recoil spectrum of the ^{11}C background (extrapolated from KamLAND data [9]) compared to the pep and CNO solar neutrino signal for the SNO+ experiment. One year data taking, 50% fiducial volume and a resolution of $5\%/\sqrt{E}$ are assumed. Further backgrounds are not shown.

3.5 Double Beta Decay Search

^{150}Nd as candidate for the neutrinoless double beta decay ($0\nu\beta\beta$) search entails several advantages. It has with 3.371 MeV the second largest Q–value, placing the signal above most of the natural radioactivity spectrum and yielding a high phase–space factor. The latter results in one of the highest calculated $0\nu\beta\beta$ rates for the same effective neutrino mass $m_{\beta\beta}$. Furthermore, Nd has a high natural abundance of 5.6% and LAB could be succesfully loaded with Nd staying stable for several years. With an initial concentration of 0.1% (corresponding to 43.7 kg of ^{150}Nd), optical measurements led to an expected energy resolution of 6.4% (FWHM) at the Q–value. Increasing the concentration during operation will gradually increase the decay rate and thus raise the sensitivity to $m_{\beta\beta}$ at the price of a reduced resolution of 9.0% (FWHM) at the final value of 0.3% loading (corresponding to 131 kg of ^{150}Nd). Backgrounds include the $2\nu\beta\beta$ decay, ^{214}Bi, ^{208}Tl and ^{8}B solar neutrinos. The ^{8}B spectrum at these energies is very well known from the SNO measurement and Bi and Tl can be efficiently tagged decreasing the referring levels by 99.9% and 90.0% respectively. Further backgrounds are inserted by Nd itself. Neutron and proton activation of the Nd samples creates long–lived isotopes, such as ^{144}Nd, ^{176}Lu and ^{138}La, which can pile up to background events despite low Q–values due to high decay rates. Comprehensive Monte Carlo studies revealed a pileup rejection efficiency at the double beta decay endpoint of $>99\%$ with a signal acceptance of $>90\%$. Figure 2 shows the expected neutrino mass sensitivity as a function of time for 0.1% and 0.3% loading assuming 80% effective livetime, a fiducial volume of 50% and the mentioned background reduction efficiencies. The IBM-2 nuclear matrix element was used for the calculation.

4. Phases of Operation

Liquid scintillator detectors have a comparatively poor energy resolution but have the advantage of low backgrounds due to the application of few different materials and metres of self–shielding. In addition, the high detector mass provides high statistics and in a recirculation process

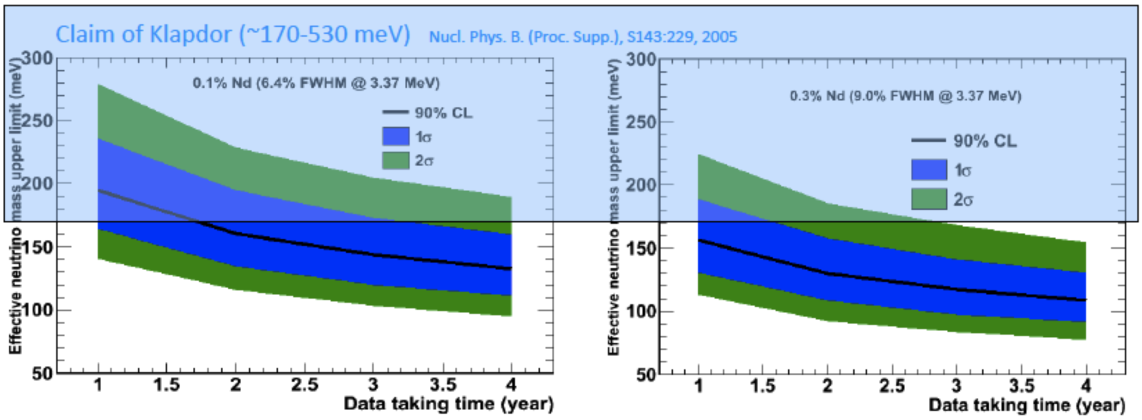

Figure 2: Time evolution of the 90% C.L. effective neutrino mass sensitivity (solid line) of SNO+ for 0.1% (left) and 0.3% (right) loading with natural Nd. The filled bands represent the 68% and 95% confidence regions. The overlaid area indicates the claimed evidence from [8].

the double beta decay isotope can be added and removed. This way SNO+ can run in two phases, a pure liquid scintillator phase and a Nd–loaded phase, enabling the extensive physics program. The pure scintillator phase is aimed at studying solar neutrinos as well as geo and reactor neutrinos whereas the Nd–phase is dedicated to the search for the neutrinoless double beta decay. However, also in the latter phase the detector will remain sensitive to geo and reactor neutrinos.

5. Timeline

The first air fill test data has been taken and data taking with the AV filled with light water will start this year. In parallel, the construction of the scintillator purification system will proceed. In 2013, the water will be replaced by liquid scintillator and as soon as enough data has been taken for a porper background model, the Nd–loaded phase will begin.

6. Conclusion

SNO+ is a multi–tonne liquid scintillator detector replacing the SNO Cherenkov detector. It is located at SNOLAB, Canada, the deepest currently active underground laboratory. The efficient rock shielding against cosmic muons and ultra low internal backgrounds permit a broad neutrino physics program. It is carried out in two phases with two major goals, namely the search for low energy solar neutrinos (e.g. pep, CNO) in the scintillator phase and the search for the neutrinoless double beta decay in the Nd–phase. Further physics goals are, amongst others, the observations of geo, reactor and supernova neutrinos. The first test data was taken this year and with the waterfill run in 2013, SNO+ will be commissioned. The liquid scintillator phase is expected to start in the same year.

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