PROCEEDINGS OF SCIENCE

SNO+ Experiment Status

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One of the most important open questions in neutrino physics is the question of whether neutrinos are Majorana or Dirac particles. Attempts to detect the (possible) Majorana nature of neutrinos focus around the double beta decay process. Observation of neutrinoless double beta decay would prove that neutrinos are Majorana particles and also provide a measurement of the neutrino mass. A technique to load tellurium in liquid scintillator has been developed that will allow SNO+, the successor to the Sudbury Neutrino Observatory (SNO), to conduct search for neutrinoless double beta decay through the decays of the isotope ^{130}Te. Initially, tellurium will be deployed at a 0.3% loading (800 kg of ^{130}Te), with SNO+ expecting a sensitivity to an effective Majorana neutrino mass at the 100 meV level. Future, higher loading levels of tellurium are being explored. As well as investigating double-beta decay, SNO+ will serve as a general purpose neutrino experiment, with measurements of geo and reactor anti-neutrinos, sensitivity to neutrinos from a potential supernova and possible future measurements of solar neutrinos from the pep and CNO processes. The experiment is expected to begin taking data with a water-filled commissioning phase in late 2013 and the liquid scintillator double-beta phase in late 2014.

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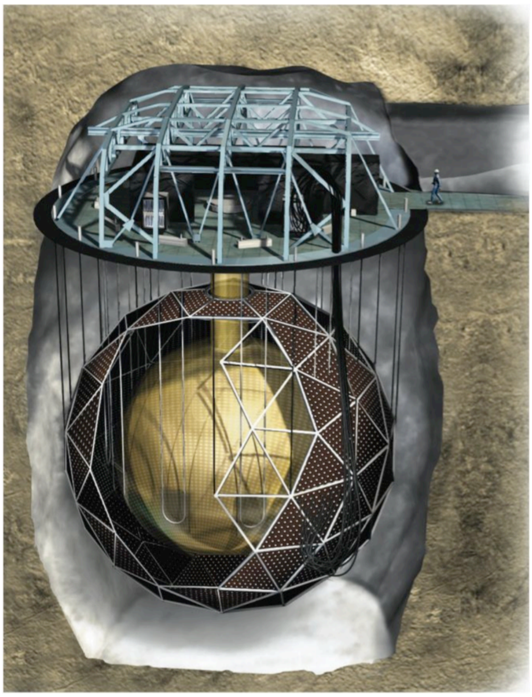

Figure 1: Artistic view of the SNO+ detector showing the acrylic vessel and PMT support structure.

1. The SNO+ experiment

SNO+ is a multipurpose liquid scintillator neutrino experiment that will operate 2 km underground, at the SNOLAB facility near Sudbury, Canada. As the successsor to the SNO experiment [1], SNO+ will inherit much of its experimental infrastructure from its precursor, however, through the use of liquid scintillator in place of D_2O, SNO+ will operate with a significantly lower energy threshold.

SNO+ (shown in figure 1) consists of a 6 m radius acrylic vessel, in which 780 tonnes linear alkyl-benzene (LAB) liquid scintillator will be deployed. Surrounding the acrylic vessel will be 7 kTonnes of UPW shielding, within which sits a 12 m diameter structure holding approximately 9500 inward facing Hamamatsu R1408 8 inch photo-multiplier tubes (PMTs). A small number ($<$100) of outward facing PMTs will be used to monitor the outer region of the UPW shielding.

The transition from a Cerenkov experiment (SNO) to a liquid scintillator experiment (SNO+) necessitates a number of major upgrades, modifications and additions to the experiment. LAB was chosen as the SNO+ liquid scintillator was because it is compatible with acrylic and has a high scintillation light yield of approximately 10000 photons/MeV. The LAB will be deployed with 2 g/litre of 2,5-diphenyloxazole, which will act as a fluor. In order to meet stringent background requirements, a new purification system that will process the liquid scintillator is being installed in the underground SNOLAB facility. Target background U and Th levels in the LAB are comparible to the levels observed by the Borexino experiment [2].

LAB has a density of 0.86 g/cm^3, therefore the SNO+ acrylic vessel will experience a very large buoyant force. To compensate for this up-force a hold-down rope net has been installed over the acrylic vessel, anchoring the vessel to the SNO+ cavity floor. The rope net, which is made from tensylon, is connected to the cavity floor via turn buckles at 20 locations.

The use of liquid scintillator will lead to significantly lower energy thresholds in SNO+ compared to SNO (10s of keV as compared to MeV, although the detector will operate with a threshold above 100 keV) along with a much higher light yield as a function of energy. The effect of this will be greatly increased event and data rates during operation. To prepare for this new readout electronics, trigger and DAQ have all been designed and installed; a maximum data-taking rate of 450 Mbit/s is now possible.

A new in-situ optical calibration system has been designed and partly installed, this system uses a combination of LED and LASER light sources to inject light via over 100 injection points distributed on the PMT support structure. With ns scale time profiles, these systems will be used to both calibrate channel timing and gains while also providing monitoring of the optical properties of the various media within the detector. As such, there will be a much reduced need for deployed light sources. Meanwhile, a new system for deployed calibration sources that is compatible with LAB has been developed, along with an array of calibration sources that have either been inherited and upgraded from SNO or have been designed specifically for SNO+.

SNO+ will operate in a number of distinct phases. Initially, the detector will operate with ultrapure water (UPW) deployed in the interaction volume. A search for forbidden modes of nucleon decay will be conducted during this period, along with the commissioning of new and upgraded calibration systems. The UPW will then be replaced with 780 tonnes of LAB liquid scintillator and, soon afterwards, a double beta-decay isotope (^{130}Te) will be deployed, at a loading of 0.3% natural Te (approximately 800 kg of ^{130}Te). The primary goal of this period will be a search for neutrinoless double beta decay ($0\nu\beta\beta$), however, concurrent searches for geo and reactor antineutrinos will be conducted, and the experiment will also be sensitive to neutrinos from a potential Galactic supernova. Following the initial $0\nu\beta\beta$ search, there is the potential for operation phases with pure LAB, during which measurements solar neutrinos from the pp and CNO processes would be made, and also a phase with higher loading of ^{130}Te for a more sensitive search for $0\nu\beta\beta$.

2. Physics goals

2.1 $0\nu\beta\beta$

The possible Majorana nature of the neutrino is seen as one of the most promising avenues for the study of beyond Standard Model physics; a large number of $0\nu\beta\beta$ experiments are currently operating or under construction. Liquid scintillator experiments offer a number of advantages in the search for $0\nu\beta\beta$. Such experiments are constructed with low background tolerances, lending themselves to searches for small signals. The typical large scale of liquid scintillator experiments means that large quantities of $\beta\beta$ isotope can be deployed at low cost to the light yield of the experiment and also allows for both self shielding and fiducialisation to further reduce backgrounds. SNO+ in particular among liquid scintillator experiments is well placed to make a competitive measurement of $\beta\beta$, since the 2 km rock overburden results in 100 μ per m^2 per year: a flux that is orders of magnitude lower than most other $0\nu\beta\beta$ experiments.

SNO+ intends to deploy natural Telurium in LAB at a 0.3% loading, giving 780 kg of ^{130}Te. Previously, SNO+ had considered deploying Nd, however, following a near 2-year period of assess-

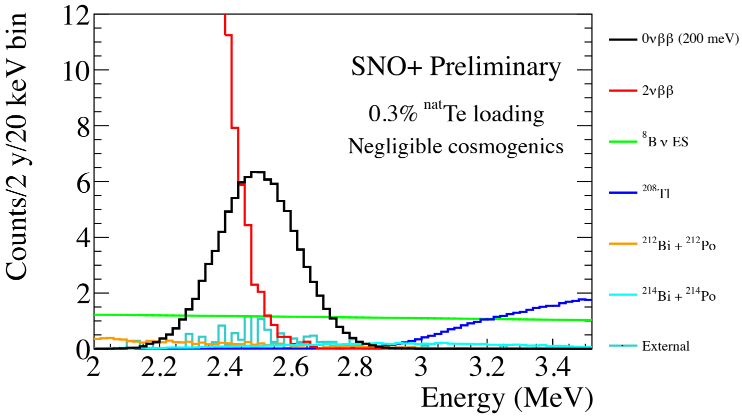

Figure 2: Monte Carlo expected background energy spectra for 2 years of running with 0.3% ^{130}Te loading, with spectrum for $0\nu\beta\beta$ signal assuming an effective Majorana mass of 200 meV for reference (assuming matrix element $M = 4.03$ and phase space factor $G = 3.69 \times 10^{-14}\text{yr}^{-1}$ [5, 6]). Spectra shown assume 20% fiducial volume cut; 99.9%, 98% and 97% efficient tag for ^{214}Bi, ^{212}Bi and ^{208}Tl respectively; negligable cosmogenic backgrounds and negligable systematic errors.

ment and development of Te loaded liquid scintillator, ^{130}Te was chosen as the favoured isotope for SNO+'s $\beta\beta$ campaign.

Te has the highest natural abundance of $\beta\beta$ isotope of all $\beta\beta$ undergoing elements, with 34% ^{130}Te (compared to ^{150}Nd in natural Nd). SNO+ collaborators have demonstrated the loading of natural Te in LAB scintillator with a high level of purification. The intrinsic light yield for the demonstrated loading is higher than for Nd, with a light yield of approximately 10^4 photons per MeV and no significant absorption lines between 350 nm and 550 nm (a frequency range over which the SNO+ PMTs are sensitive) in the Te loaded scintillator as there are for Nd loaded LAB. Meanwhile, the $2\nu\beta\beta$ which is a major background for liquid scintillator $0\nu\beta\beta$ experiments, has a 10^2 lower rate for ^{130}Te compared to ^{150}Nd, with $T^{2\nu}_{1/2}(^{130}\text{Te}) = 7.0 \times 10^{20}$ yr [3], while $T^{2\nu}_{1/2}(^{150}\text{Nd}) = 9.1 \times 10^{18}$ yr [4].

Techniques have been developed to remove backgrounds (by purification) from the LAB, Te and loading cocktail. The total level of U and Th in the scintillator cocktail is expected to be at the level of the SNO D_2O: 2.5×10^{-15} gU/g, 3.0×10^{-16} gTh/g. Purification of the Te will be conducted in a two pass process on the surface at SNOLAB, with an additional purification and cool-down period (of order 3 months) once the isotope is transported underground; the contamination of cosmogenically activated isotopes in the Te that SNO+ will use will be reduced to negligible levels. Meanwhile, analysis methods will be used to reject backgrounds from the decays of U and Th daughter nuclei via delayed coincidence tagging. Through these various techniques, SNO+ expect to be able to reach a sensitivity to $0\nu\beta\beta$ decay at the level of $<$100 meV (see figure 2); highly competitive with other $0\nu\beta\beta$ experiments.

2.2 Geo and reactor anti-neutrinos

Anti-neutrinos are observable by SNO+ through interactions via inverse beta-decay. This process can be easily tagged by liquid scintillator experiments through the delayed coincidence (typi-

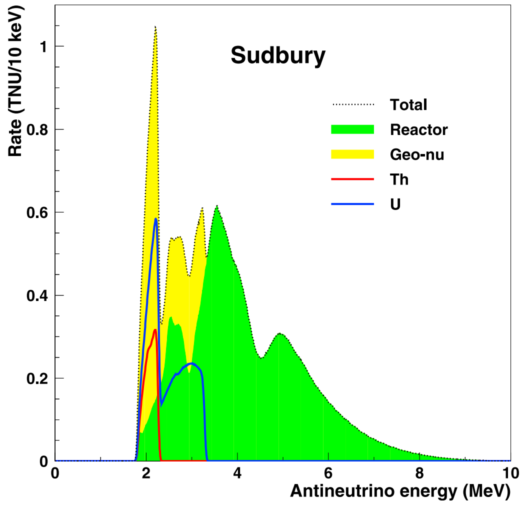

Figure 3: Expected spectra of geo (yellow) and reactor (green) anti-neutrinos in the SNO+. Figure from [9].

cally 200 μs) of signals from annihilation of the resulting e^+ and capture of the resulting neutron.

The abundance of long-lived nuclear isotopes (^{235}U, ^{238} and ^{232}Th) in the Earth's crust and mantle, the decays of which are thought to be the main source of the Earth's internal heat generation, has a large associated uncertainty and varies significantly between different geological models [7]. The decays of these isotopes gives rise to a geo anti-neutrino flux. SNO+ is expected to observe on the order of 100 geo anti-neutrinos per year of livetime, with an example energy spectrum shown in figure 3. Such a measurement would complement measurements already made by the KamLAND experiment [8]. Moreover, because of the very well understood local crustal geology, a SNO+ measurement of the geo-neutrino flux may improve constraints on the U and Th abundances in the Earth's mantle, which cannot be surveyed by other means.

As with geo anti-neutrinos, SNO+ will observe anti-neutrinos from nuclear reactors via inverse beta-decay. A number of reactors are located within a few 100 km of Sudbury, with SNO+ expected to observe 90 reactor anti-neutrinos per year of livetime (see figure 3). An advantage of SNO+ is that it is situated close to oscillation minima for the three closest nuclear power stations, sitting near the second oscillation minimum for neutrinos from the Bruce station (240 km) and the third oscillation minimum for neutrinos from the Pickering and Darlington stations (330 km). This coincidental location means that SNO+ has the potential to make a measurement of Δm^2_{12} that is competitve with the KamLAND [10] experiment even though the expected flux of reactor anti-neutrinos will be only 20% of that at KamLAND.

2.3 Solar neutrinos

The use of liquid scintillator will allow it to make measurements of low energy solar neutrinos from the pep chain and CNO cycle. The former of these provides a means to constrain models of the transition between matter dominated and vacuum dominated neutrino oscillations, with a SNO+ measurement of the pep neutrino flux potentially improving on current Borexino result [11] due to the significantly lower background μ flux. Meanwhile, observation of CNO neutrinos would allow constraints on the solar metallicity to be inferred. Both of these measurements are dependent on prior removal of radon daughters that have accumulated on the SNO+ acrylic vessel.

2.4 Supernova neutrinos

Observation and collection of a large sample of neutrinos from a future supernova would be of great interest for a range of studies, from models of stellar core-collapse through to neutrino time-of-flight and ultra-long-baseline oscillation measurements. In the case of a Galactic supernova at 10 kpc SNO+ would observe of the order of 100 neutrinos via charge-current interactions, assuming an energy threshold of 200 keV. The observation of further supernova neutrinos via neutral current interactions (on ^{12}C and proton scattering) may be possible, with a comparible number of events expected for the same energy threshold; this opens up the possibility of making an all-flavour flux measurement. Meanwhile, a dedicated supernova trigger should allow SNO+ to become a contributor to the SuperNova Early Warning System (SNEWS), which offers a system of early alerts of supernova neutrinos to the astronomical community.

3. Conclusions and outlook

The SNO+ experiment is expected to make significant contributions to a broad range of topics in neutrino physics. In particular, the use of the $0\nu\beta\beta$ isotope ^{130}Te means that the experiment will be among the most competitive $0\nu\beta\beta$ experiments in the coming years. Within two years of livetime at 0.3% natural Te loading, SNO+ will be able to set a limit at the level of $<$100 meV on $m_{\beta\beta}$. As a result of the optical properties of the Te loaded scintillator, the potential exists for a increasing the loading levels of Te by an order magnitude, which would allow SNO+ to probe the inverted heirarchy region of Majorana neutrino masses.

SNO+ is nearing the completion of its construction phase. Data-taking will take place in three distinct phases, with an initial water-fill phase expected in early 2014, followed by scintillator fill in Q3 2014 and first Te-loaded data in early 2015.

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