Physics capabilities of the SNO+ experiment

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Abstract. SNO+ will soon enter its first phase of physics data-taking. The Canadian-based detector forms part of the SNOLAB underground facility, in a Sudbury nickel mine; its location providing more than two kilometres of rock overburden. We present an overview of the SNO+ experiment and its physics capabilities. Our primary goal is the search for neutrinoless double-beta decay, where our expected sensitivity would place an upper limit of $1.9 \times 10^{26}$ y, at 90\% CL, on the half-life of neutrinoless double-beta decay in $^{130}$Te. We also intend to build on the success of SNO by studying the solar neutrino spectrum. In the unloaded scintillator phase SNO+ has the ability to make precision measurements of the fluxes of low-energy pep neutrinos and neutrinos from the CNO cycle. Other physics goals include: determining the spectrum of reactor antineutrinos, to further constrain $\Delta m_{23}^2$; detecting neutrinos produced by a galactic supernova and investigating certain modes of nucleon decay.

1. Introduction

In these proceedings, we describe the physics capabilities of SNO+ grouped by the phase of data taking. The detector comprises a 12 m diameter acrylic vessel, which we will fill with ultra-pure water, during the water phase, 780 tonnes of liquid scintillator, during the unloaded scintillator phase and for the double-beta phase, we will load the scintillator with tellurium.

2. Water phase physics

The primary physics goal of the water phase is investigating certain invisible modes of nucleon decay, where a proton or neutron in the nucleus, decays to some undetected final state. An example, is the proposed interaction $n \rightarrow 3\nu$. SNO+ has potential sensitivity to nucleon decays in $^{16}$O. Were a neutron to decay, it would leave an excited $^{15}$O nucleus, which de-excites via a 6.18 MeV photon 44\% of the time. The excited nucleus for a proton decay, would be $^{15}$N, emitting a 6.32 MeV photon 41\% of the time [1].

SNO+ expects to improve on existing limits, from SNO [2] and KamLAND [3], since ultra-pure water has reduced neutral current backgrounds compared to D\textsubscript{2}O and $^{16}$O has a more favourable branching ratio than $^{12}$C. Using a Poisson counting method, the 90\% confidence lower-limits, on the neutron and proton lifetimes are: $\tau_n = 1.25 \times 10^{30}$ y and $\tau_p = 1.38 \times 10^{30}$ y. These are a factor of two improvement on the KamLAND limits, with one month of data-taking.
Table 1. Expected precision of flux measurements, for a global fit to the solar neutrino spectrum

| ν source | 6 months data | 12 months data |
|----------|--------------|----------------|
| ⁸B       | 10.0%        | 7.1%           |
| ⁷Be      | 5.1%         | 3.3%           |
| pep      | 13%          | 8.9%           |
| CNO + ²¹⁰Bi | 6.5%     | 4.4%           |

3. Unloaded scintillator phase

The key physics goal in the unloaded scintillator phase, is to build on the success of SNO in probing the solar neutrino spectrum. SNO+ hopes to make the first precision measurement of the CNO cycle, which could help solve the disparity in the level of heavy ions (metals) predicted by 3D modelling and the results of helioseismic measurements—the so called solar metallicity problem. Through a combined measurement of the pep flux and the ⁸B spectrum from 1 MeV to 5 MeV, SNO+ can probe the νe survival probability, in the important transition region between vacuum oscillations and the presence of matter effects. If levels of ¹⁴C are low enough, SNO+ can measure the pp flux, which would test the solar luminosity constraint. Table 1 shows estimates of the precision to which SNO+ can measure the flux of each of the solar neutrino signals with one year of data and fig. 1 shows the visible energy spectrum, including key backgrounds, scaled to their target levels.

With both loaded and unloaded scintillator, SNO+ can study reactor neutrinos. Three nuclear reactors surround SNO+: Bruce, 240 km away, and Pickering and Darlington at 350 km baselines. Other reactors in continental North America also contribute to the reactor neutrino spectrum. By measuring the combined, oscillated spectrum, based on seven years of data, SNO+ can measure Δm² to 0.2 × 10⁻⁵ eV² [4], a similar precision to KamLAND [5].

Geoneutrinos, share the decay signature of reactor neutrinos (inverse β-decay), where one can tag events by the characteristic delayed 2.22 MeV γ as a hydrogen atom captures the neutron. We record the energy the corresponding positron deposits in the scintillator. The detector should have the required sensitivity to separate out contributions from the uranium and thorium chain decays, in both the crust and mantle. Inverse β-decay is also one of the channels SNO+ can use to probe supernova neutrinos. For an example supernova at 10 kpc, SNO+ would expect a...
burst of more than 500 neutrino events in less than 10s. The detector is part of the supernova early warning system (SNEWS).

4. Double-beta phase
The key question we hope to address here is whether massive neutrinos are Dirac or Majorana particles. J. Schecter and J. W. F. Valle showed that, by forming an effective operator for neutrinoless double-beta decay ($0\nu2\beta$), any physics mechanism producing the net result $(A,Z) \rightarrow (A,Z + 2) + 2e^-$ (in a nucleus with mass number $A$ and $Z$ protons), will develop a nonzero Majorana mass for the neutrino \[6\]. For $^{130}$Te it is more energetically favourable to decay via two simultaneous $\beta$-emissions. Its high natural abundance and long measured lifetime for two neutrino double-beta decay make it a good probe of $0\nu2\beta$. SNO+ will use a novel loading technique using telluric acid and 1,2-butandiol. With the Te-Diol method, we expect to be able to load 0.5% natural tellurium, by mass.

We estimate a Feldman-Cousins, 90% confidence limit, on the lifetime of $0\nu2\beta$, via light Majorana-neutrino exchange, as $T^{0\nu2\beta}_{1/2} \geq 1.96 \times 10^{26}$ y, with five years of data, corresponding to an effective Majorana-neutrino mass in the range 38 meV to 92 meV. The range accounts for uncertainty in the nuclear matrix element. Figure 2, shows the stacked histogram spectral plot, in the energy region of interest, with an example signal of a 200 meV Majorana neutrino.

![Figure 2. Stacked histogram spectral plot, for 0.5% loading using the Te-diol method (390 hits/MeV). Includes the main background contributions and an example signal scaled to $m_{\beta\beta} = 200$ meV.](image)

5. Conclusions
In these proceedings, we have presented the varied physics program of the SNO+ experiment, through the different phases of operation. For each physics goal, we have presented an estimate of our expected sensitivity.

References
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