Neutrino Physics with SNO+

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SNO+ is a multi-purpose neutrino experiment that will leverage the large US- (amongst others) capital investment in SNO, re-using the detector and replacing the heavy water target with liquid scintillator (LS) to allow lower operating threshold and improved energy resolution. As part of the "New Standard Model Initiative" the NSAC long-range plan of 2007 made "a targeted program of experiments to investigate neutrino properties and fundamental symmetries" one of 4 key objectives. SNO+ meets many goals of this program, $0\nu\beta\beta$ being foremost amongst them, and as the only fully-funded new solar neutrino experiment, SNO+ is the only experiment capable of answering many of the questions laid out in the relevant section of the proposed "Weak Probes of Astrophysics". SNO+ will also be sensitive to reactor νs, geo-νs, and supernova νs, all of which feature in the plan.

A primary physics goal of SNO+ is to use the existing Sudbury Observatory (SNO) detector to search for the neutrinoless double beta decay of ^{150}Nd. ^{150}Nd has the highest Q-value of double beta decay candidates with reasonable natural abundances, which has two consequences: the rate for $0\nu\beta\beta$ is proportional to Q^5 thereby requiring a lower lifetime sensitivity for detection, and it places the region-of-interest above most potential radioactive backgrounds.

Isotope loading in LS is a fine balance between event rate and light yield. Nd dissolved in LS absorbs scintillation light, requiring a careful optimization: too little Nd and the source is too weak; too much Nd and the energy resolution of the detector becomes too broad to separate the signal from background. Recent work has indicated that the optimum concentration of natural Nd in solution is $\sim$0.3%. At this concentration we anticipate a sensitivity to the effective neutrino mass $\langle m_{\beta\beta}\rangle$ of 120 meV at 90% C.L. in a three year run. The sensitivity calculation uses the Interacting Boson Model 2 matrix elements, which accommodate the nonspherical shape of the Nd nucleus. The irreducible background from $2\nu\beta\beta$ is the dominant background and requires a minimum energy resolution to be resolved from a signal peak. For the large Q-value of 3.37 MeV the only other significant backgrounds are from ^{208}Tl, and ^{8}B solar neutrinos. The shapes and strengths of each of these backgrounds can be constrained by a combination of *in-situ* and *ex-situ* measurements, precision calibrations, and simulation. To increase sensitivity further, SNO+ will need to find a way to load more isotope without an accompanying loss of light. Funding for four US institutions has recently been secured from the NSF to investigate more advanced techniques for loading metals into LS. We will determine whether an alternative technique might allow an increased Nd loading fraction, or whether an alternative isotope is optimal, thus increasing our sensitivity.

SNO+ will detect low-energy solar νs in a separate phase. The vacuum-matter transition region in solar neutrino oscillation is particularly susceptible to new physics effects, such as sterile νs or non-standard interactions, and can be directly probed with *pep* solar νs, which are a line source at 1.4 MeV. SNO+ will achieve $< 10\%$ precision with one year of data, enough to differentiate between models. SNO+ also aims for a $\sim 15\%$ observation of CNO νs, from the sub-dominant CN fusion cycle in the Sun, to resolve current uncertainty in solar heavy-element abundance. The world's first direct measurement of *pp* νs, primary products of solar fusion, would let us test the so-called "Luminosity Constraint", which assumes that the solar fusion reactions are the sole source of both the νs and electromagnetic power; this tests the presence of additional energy loss or generation mechanisms.

SNO+ will also be sensitive to reactor antineutrinos primarily from two nearby reactors at baselines of ~ 200 km, which is in the solar regime of neutrino oscillation, similar to KamLAND. Although the flux is lower, the very similar baselines of the two reactors means that SNO+ will be able to observe the minima in the oscillation spectrum, thus increasing the sensitivity to Δm^2_{12} dramatically, to something roughly comparable to KamLAND. SNO+ will also detect geoneutrinos, complimentary to existing measurements by KamLAND, in Japan, and Borexino in the Gran Sasso Lab in Italy: observations in multiple geographical locations are necessary in order to distinguish different models for heat production in the Earth. Since reactor antineutrinos form a direct background to this measurement, the low reactor flux is an advantage. SNO+ will continually monitor for supernovae neutrinos, and during the light-water phase will improve existing limits on invisible modes of nucleon decay by an order of magnitude by searching for the 6–7 MeV γ from nucleon decay in ^{16}O.

US institutions play a major leadership role in SNO+. J. Klein is the outgoing Executive Committee (EC) chair, and many other EC members are at US institutions. G. D. Orebi Gann is the Physics Analysis Coordinator, and many Working Group leaders are based in the US, leading efforts ranging from electronics & DAQ development to instrumental-background rejection and solar neutrino analysis.

SNO+ uses linear alkyl benzene (LAB), which has been developed in efforts led by M. Yeh at BNL. LAB has a high flash point and low toxicity and, critical for SNO+, is chemically compatible with the acrylic of our vessel. The high light yield ($\sim 10,000$ photons / MeV) is critical for energy resolution, and the LS decay time allows us to achieve α-β separation of $> 99.9\%$, critical for tagging radioactive backgrounds. Along with collaborators at SNOLAB, BNL has developed an extensive multistage purification program aimed at minimizing all potential sources of contamination in the LAB, including N_2 and steam stripping, metal scavenging, and microfiltration.

Another major US responsibility is the upgrades to electronics and DAQ. U. Penn was responsible for designing the original SNO electronics; although the front end is fast, the readout speed had to be increased in order to handle the high data rates from LS. U. Penn has completed design and construction of 19 new custom crate-readout boards, which provide local intelligence in each crate to autonomously push data to a central switch via TCP/IP, increasing the readout speed to more than 100 times that of SNO. A new analog trigger card has reduced power dissipation and a larger dynamic range, as well as new features such as automatic retriggering for events with a significant fraction of late light. A digitizer board has been installed to digitize the analog trigger sums, and a new interface board is being developed to interface with calibration systems. The newly installed electronics and upgraded DAQ system were stress tested in March 2012, when we applied high voltage to the PMTs, with no target in the vessel, to benchmark the status of the detector. The US is also heavily involved in both calibration and analysis efforts.

What major scientific discoveries have occurred in your research area since the 2007 LRP? KamLAND-Zen and EXO-200 have produced limits on $0\nu\beta\beta$ on ^{136}Xe, motivating the need for searches with other isotopes.

What compelling and unique science is to be done in the next 5 years?

March 2013	H_2O data	invisible modes of nucleon decay
March 2014	LS data	solar neutrino, reactor antineutrino & geoneutrino results
Sept 2014-2017	$0\nu\beta\beta$ data	120 meV sensitivity in 3 years; additional reactor & geoneutrino data

What science would you expect to pursue in the program in 2020 and beyond? SNO+ has the potential to cover the inverted hierarchy region at extremely low cost relative to other $0\nu\beta\beta$ experiments. Further R&D is necessary into alternative isotope loading techniques, and alternative isotope possibilities, in order to mitigate the limitation imposed by absorption.

What is the international context, and how does it affect your vision? SNO+ is an international collaboration, with participants in the US, Canada, the UK, and Europe. We are competitive with concurrent $0\nu\beta\beta$ experiments, and have the potential to lead the field in solar neutrino physics.