

Solar neutrino experiments: recent results and future prospects

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Abstract. Recent results from the SNO and Borexino solar neutrino experiments have pushed the observation of solar neutrinos to lower energies. Borexino's measurement of the rate of ^7Be solar neutrinos demonstrates that the survival probability for solar neutrinos below 1 MeV is larger than for the ^8B solar neutrinos, consistent with our expectation for neutrino propagation affected by matter. On the other hand, by looking at lower energy ^8B solar neutrinos, SNO (and also Borexino) do not see the predicted rise in the survival probability and there is even a hint that the survival probability drops to a lower value. Future solar neutrino experiments, in particular the SNO+ experiment, will look at this question by making precision measurements of the survival probability of the pep solar neutrinos (1.44 MeV energy).

1. Introduction

We have learned much about neutrino oscillations from solar neutrino experiments. In addition to uncovering that neutrinos change flavour, and that this is strongly affected by propagating through dense matter, we have been able to constrain neutrino oscillation parameters using global fits of the data from all solar neutrino experiments and the KamLAND reactor neutrino experiment [1]. Recent results from SNO and Borexino continue to refine our knowledge and may be pointing to new, sub-dominant effects that need to be understood.

2. SNO low energy threshold analysis

The recent publication from the SNO collaboration [2] reports on the lowering of the analysis threshold from 5 MeV down to 3.5 MeV. This analysis, dubbed LETA (Low Energy Threshold Analysis), featured a joint analysis of the data from SNO Phase I (pure D_2O) and Phase II (NaCl salt added). The combined analysis of the two data sets leads to more than just the simple statistical combination of the results since neutrino signals, backgrounds, and detector parameters in one phase help to constrain their extraction in the other phase, and vice versa. Additionally, systematic uncertainties were reduced and several improvements in simulations and analysis helped to lower uncertainties. The SNO LETA results were extracted with two different (one novel) signal extraction techniques and the SNO LETA paper featured a three-neutrino analysis, also new for SNO. These details are not reported here; only the spectrum results will be described.

Figure 1 shows the signals and backgrounds as extracted from the Phase II data. This figure shows the essence of the SNO low threshold analysis. By looking at energies in the SNO detector less than 5 MeV, backgrounds from internal and external radioactivity start to dominate but it is

possible to extract the neutrino signal content provided there is a detailed understanding of these backgrounds and their distributions. It should be noted that more than just energy distributions were used to characterize backgrounds during signal extraction. Radial position distributions are important (especially for external backgrounds coming from radioactivity outside the SNO heavy water volume), as are event isotropy, and the angular correlation to the Sun's direction.

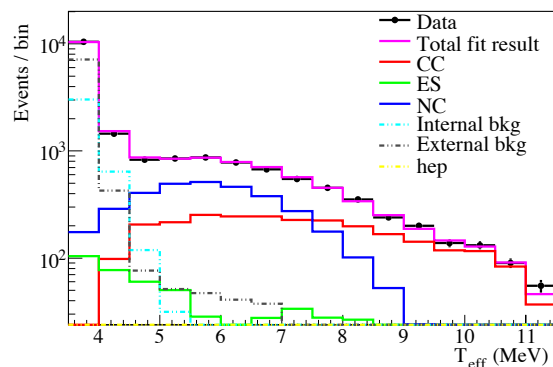


Figure 1. Energy distributions of signals and backgrounds used during signal extraction. SNO Phase II data are plotted here.

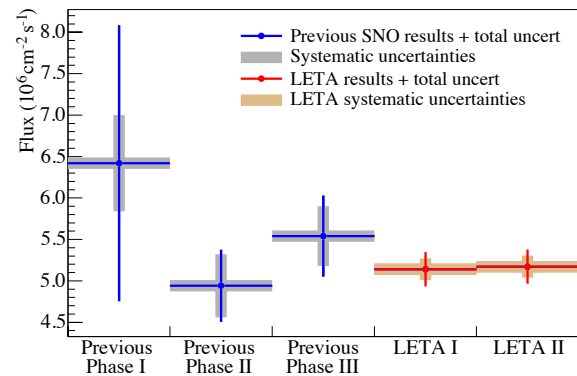


Figure 2. Measurements of the total active ^8B solar neutrino flux (neutral-current events) from all phases of SNO and the new analysis.

The addition of neutrino data at lower energies offers improved statistics for the neutral-current events and provides a look at neutrino survival probabilities at lower energies not previously explored by SNO, using the charged-current events. Figure 2 shows the improvement in SNO's neutral-current measurement. This is the measured flux of ^8B solar neutrinos of all (active) flavours. The two signal extraction techniques used in SNO LETA are seen in Figure 2 to agree with each other.

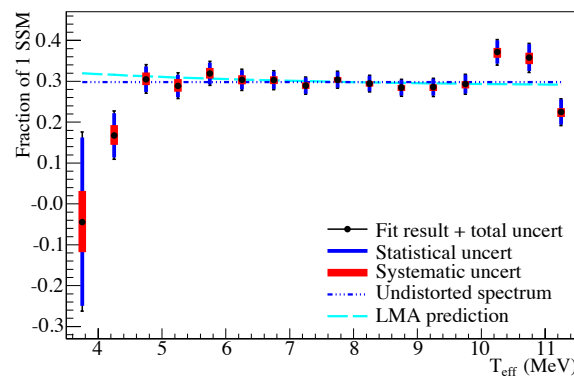


Figure 3. Spectrum of charged-current events from the SNO low energy threshold analysis. The expectation for the best-fit LMA survival probability is shown overlaid.

In Figure 3, the energy spectrum of charged-current events in SNO is shown. The data points at lower energies are not observed to increase as expected for the best-fit LMA oscillations; rather, they appear to be lower than even the undistorted ^8B neutrino spectrum (though the statistical significance is small). It should be noted that each charged-current signal energy bin was extracted independently; however, background energy spectra were used in the extraction

thereby introducing correlations between bins. Thus, any apparent disagreement with the LMA spectrum shape is likely to be less significant than one might naively assume by looking at this figure.

3. Borexino

The Borexino experiment has detected ^7Be solar neutrinos, in real time. The Borexino detector contains roughly 300 tonnes of liquid scintillator (fiducial volume 100 tonnes). Neutrino-electron scattering produces a recoil edge from the monoenergetic ^7Be solar neutrinos of energy 0.86 MeV. The recoil electron spectrum from Borexino's 2008 publication [3] is shown in Figure 4. The rate of ^7Be solar neutrinos detected by Borexino is consistent with neutrino oscillations with the current best-fit LMA parameters and a survival probability of about 0.56. In comparison, the survival probability for ^8B solar neutrinos at energies above 5 MeV is measured by SNO (using the CC/NC ratio) to be around 0.3.

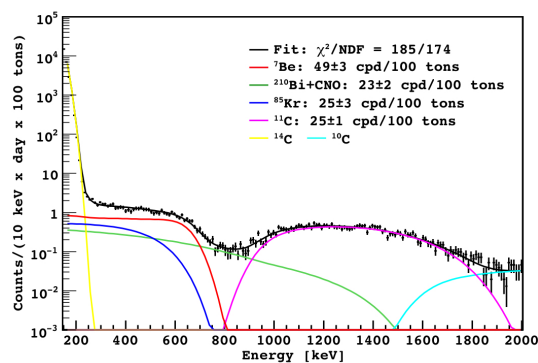


Figure 4. Recoil electron energy spectrum as measured by Borexino. ^7Be solar neutrinos produce the edge feature in the spectrum.

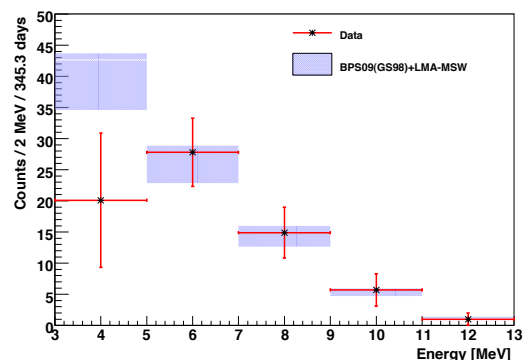


Figure 5. Borexino measurement of ^8B solar neutrinos and comparison to oscillation models.

The Borexino experiment has also detected ^8B solar neutrinos (again by observing neutrino-electron scattering) [4]. This measurement involved subtracting backgrounds, like SNO LETA, and ends up with large uncertainties. Uncertainties are larger also because of limited statistics (Borexino is a smaller detector than SNO and neutrino-electron scattering cross sections are lower than neutrino-deuteron). Borexino's extracted ^8B spectrum is shown in Figure 5. The observation of ^8B solar neutrinos in a liquid scintillator detector is interesting. One sees that the lowest energy data point is also, curiously, lower than expectations as in the SNO LETA results.

It should be noted too that the Super-Kamiokande experiment also sees a ^8B solar neutrino spectrum that is “flat”, meaning consistent with the undistorted spectrum [5]. An objective of future measurements of lower energy solar neutrinos will be to examine whether these observations described above are possibly indicative of any new physics or that it is just chance occurrence that all experiments have data at lower energies that suggest a flatter spectrum or even a dip before the survival probability rises at lower energies still. Several sub-dominant oscillation ideas are consistent with just such an observation, such as the possibility of non-standard neutrino interactions [6].

4. SNO+

The SNO experiment used heavy water to detect ^8B solar neutrinos; SNO concluded taking data in November 2006 and the heavy water in the detector was returned to Atomic Energy of Canada

Limited. The SNO+ experiment is the successor to SNO; it is the existing SNO detector filled with liquid scintillator. With a liquid scintillator, the light yield in the detector will increase by a factor of about 50, allowing SNO+ to study neutrino physics at lower energies. Solar neutrinos at lower energies are interesting as precision probes of neutrino physics and also as a means of learning about solar physics, revisiting the intent of Ray Davis when he set out to detect solar neutrinos some forty years ago. The antineutrinos emitted by natural radioactivity (uranium and thorium) in the Earth can be detected by large liquid scintillator detectors. By doing so, one can assay the Earth by looking at its neutrino emission, thereby providing constraints on the radiogenic portion of Earth's heat flow and on the radiochemical composition of the Earth's mantle and crust. Nuclear power reactors in Ontario are farther from the SNO+ detector than the typical distance of reactors in Japan to the KamLAND experiment. The signal from reactor antineutrinos will still be easily detected by SNO+ and spectral features observed in KamLAND due to neutrino oscillations will be shifted to higher energy in SNO+ (L/E is a constant). This observation would demonstrate the oscillation phenomenon and provide added constraints on oscillation parameters. A large liquid scintillator detector serves as an excellent supernova neutrino monitor. All of these physics goals motivate the construction of the multi-purpose SNO+ experiment.

An additional aim of the SNO+ experiment is the search for neutrinoless double beta decay. SNO+ plans to deploy Nd-loaded liquid scintillator with a concentration of 0.1% Nd, by weight. This would correspond to about 44 kg of ^{150}Nd isotope, offering a competitive next-generation search. Though this is one of the main objectives of SNO+, the following discussion will focus on the solar neutrino prospects, and on the detection of pep solar neutrinos in particular.

4.1. *pep solar neutrinos in SNO+*

The pep solar neutrinos arise from the three-body, proton-electron-proton reaction in the Sun that produces monoenergetic electron neutrinos with energy 1.44 MeV. These neutrinos can be identified in a large, liquid scintillator detector via neutrino-electron scattering and looking for an edge feature (like a Compton edge) in the recoil electron energy spectrum. This is similar to how Borexino detects ^7Be solar neutrinos (monoenergetic $E_\nu = 0.86$ MeV). The pep solar neutrino flux is calculated in solar models to $\pm 1.5\%$ uncertainty [7] whereas the ^7Be solar neutrino flux has $\pm 10.5\%$ error [7]. By using a neutrino source with known flux and using a known cross section, a precise measure of the rate of pep solar neutrino interactions yields a measurement of the survival probability with small uncertainty. The pep solar neutrinos thus enable a precise test of neutrino oscillation parameters and of sub-dominant oscillation effects.

Backgrounds from radioactivity in the detector are extremely important at energies below 2 MeV. A liquid scintillator can be made very radio-pure because of the incompatibility of elements such as uranium, thorium and potassium with an organic liquid. Radon is ubiquitous and its backgrounds are very important. The daughter isotope of radon ^{210}Pb has a half-life of 22 years and the decays of ^{210}Bi and ^{210}Po that follow are potential backgrounds to the pep solar neutrino signal. Thus, the radon exposure history of the detector and the scintillator become important considerations too.

Techniques for purifying liquid scintillator were utilized by both Borexino and KamLAND and the SNO experiment built systems for purifying water and heavy water. The techniques for and the experience with achieving ultra-low radioactivity backgrounds will benefit the SNO+ experiment. An estimate of the levels of radioactivity that can be achieved is shown in Figure 6. This figure also shows the pep neutrino signal and the CNO solar neutrinos. The distinctive shape of the pep solar neutrinos should allow it to be extracted (using a maximum-likelihood analysis) with $\pm 5\%$ total uncertainty after 3 years of data. The CNO solar neutrino recoil energy distribution is not as distinct from background spectral shapes as the pep solar neutrinos; consequently, the measurement of the CNO solar neutrino flux will rely much more

on backgrounds targets being achieved. A statistical uncertainty of $\pm 7\%$ is the target, given the background levels simulated in Figure 6.

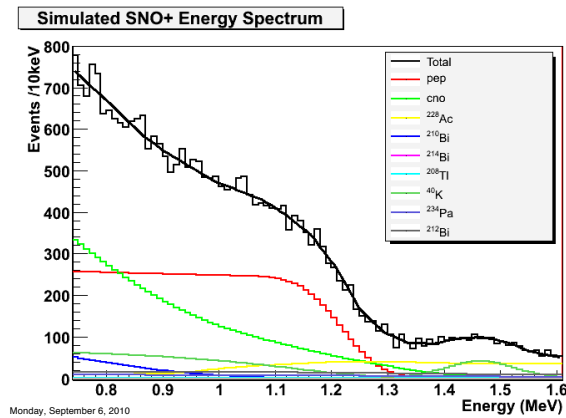


Figure 6. Expected solar neutrino signals and backgrounds in SNO+. Backgrounds were simulated at their target levels and solar neutrino signals include oscillations.

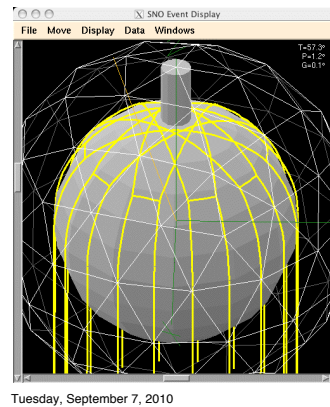


Figure 7. A graphical display of the AV hold down net to be installed over the SNO+ acrylic vessel.

In Figure 6 an important background is not shown and that's because it is, in fact, negligible in SNO+! This is the background from cosmogenic production of ^{11}C in the liquid scintillator, even while underground. The decay of ^{11}C has a 20 minute half-life so it is very difficult to veto the production of ^{11}C when many muons traverse the detector. The background signals produced by cosmogenic ^{11}C thus obscures the pep and CNO solar neutrino signals in Borexino and in KamLAND, see Figure 4; but, these backgrounds are lower in SNO+ because of the much lower muon flux at SNOLAB depths. As a result, the muon rate in SNO+ will be small enough that the production of ^{11}C will not be a background problem for the pep and CNO solar neutrinos (and any residual ^{11}C events will be more easily tagged).

4.2. SNO+ construction status

In order to convert SNO to SNO+, the following actions are needed. In SNO, the acrylic vessel contained heavy water surrounded by normal, light water and thus needed to be held up. SNO+ will have scintillator with density less than one inside the acrylic vessel which is surrounded by water. The acrylic vessel in SNO+ will thus be buoyant with an upward force equivalent to a weight of about 140 tonnes. The design and installation of a hold-down system consisting of a rope net for the SNO+ acrylic vessel is required.

The rope net for the SNO+ AV hold down will be made of Tensylon[®], a brand of ultra-high molecular weight polyethylene. This material was counted (with the Ge counter at SNOLAB) and found to meet the low U, Th and K radioactivity targets for the SNO+ detector. The SNO+ AV hold down net is illustrated in Figure 7.

For SNO+, the scintillator and its components must be procured. In order to achieve the ultra-low backgrounds required for the physics goals of the experiment, a scintillator purification system must be built (in place of the heavy water purification that was used in SNO). The three largest items (AV hold down net, scintillator procurement and scintillator purification/process systems) constitute the vast majority of the costs for the new experiment. Additional activities for SNO+ construction include a few minor upgrades that will be made:

- The cover gas system over the detector volume will be made tighter in order to lower radon backgrounds.
- The electronics/DAQ will change the manner of data transfer and this will significantly increase the data throughput capacity and the ability to handle the higher data rates that will be seen in SNO+ which are due to the greater light yield and higher event rates at lower energies.
- New calibration sources and systems will be built that will be appropriate for the new physics and new detector. These include radioactive sources as well as optical sources (an LED/fibre optical calibration system is being installed).

The main technical challenge of the SNO+ construction activities is the installation of the AV hold down net (activity currently in progress). Access to the detector cavity is only from a top hatch. This requires all equipment, materials and personnel to be lowered into the cavity using winches and harnesses. Anchor plates will be installed with bolts that will need to be drilled into the detector cavity floor. The hold down ropes are attached to the anchor plates that then support the buoyant load. The construction challenge is to accomplish all of the “dirty” work inside the SNO+ detector cavity without contaminating the detector with dust and rock that would contain more radioactivity than currently in the clean detector materials.

The SNO+ experiment is currently under construction. Construction and installation work is expected to take until 2012 at which time scintillator filling will begin and, soon after, data taking.

5. Summary

Recent results from solar neutrino experiments suggest that continued investigations of solar neutrino oscillations will be interesting and potentially an important tool for probing subdominant oscillation effects. New physics including CPT violation (solar neutrino oscillations having different parameters than reactor antineutrino oscillations) could have an effect on solar neutrino survival probabilities at lower energies. The possibility of non-standard neutrino-matter couplings would change the survival probability of solar neutrinos propagating through the Sun. Because of the greater depth, SNO+ is well-poised to detect the pep and CNO solar neutrinos and to use the pep solar neutrinos (as well as lower energy ^8B solar neutrinos) to make precise measurements of the survival probability and to test non-standard models.

References

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