

Solar Neutrino Experiments

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Abstract. Three solar neutrino experiments are presently collecting data: SAGE, Super-Kamiokande III and Borexino. There is also the KamLAND experiment that is operating and in the process of purifying their liquid scintillator in order to detect ^7Be solar neutrinos. The status of those experiments is described in this report. The Sudbury Neutrino Observatory recently completed taking data and the heavy water that was in the SNO detector has been returned. The transition from SNO to SNO+ has begun. SNO+, which is the SNO detector filled with liquid scintillator, aims to measure the flux of *pep* and *CNO* solar neutrinos, amongst other physics goals. The SNO+ experiment is presented here in the context of a synthesis of the results from all solar neutrino experiments. The prospects for other future solar neutrino experiments are also outlined here.

1. Solar neutrino experiments taking data

The field of solar neutrino experiments is now a mature one but one that continues to yield important results. The Chlorine experiment of Ray Davis [1] was the pioneering experiment. It was followed by Kamiokande [2], SAGE [3], Gallex [4], Super-Kamiokande [5], GNO [6] and the Sudbury Neutrino Observatory (SNO) [7]. All of these experiments measured deficits in the flux of electron neutrinos coming from the Sun compared to the predicted fluxes from the Standard Solar Model (SSM) [8]. By detecting neutral-current neutrino-deuteron interactions SNO was able to measure the ^8B solar neutrino flux in all active neutrino flavors and in doing so SNO confirmed that the total flux was significantly larger than just the electron neutrino flux (and also consistent with solar model predicted values) [9-10]. This provided conclusive evidence that electron neutrinos produced in the Sun transform to other active flavors. Results from all of these experiments are now well described by including matter-enhanced neutrino oscillations in calculating the survival probability for electron neutrinos propagating from their place of production in the Sun to respective experiments on Earth.

Of the experiments described above only SAGE and the re-built Super-Kamiokande III are still taking data. SAGE is the Russian-American Gallium Experiment. It is a radiochemical experiment that uses 50 tons of metallic gallium and that has been running (performing extractions) since 1990. By counting activity produced by neutrino capture on gallium, experiments like SAGE are sensitivity to the primary reaction *pp* solar neutrinos. At the TAUP2007 conference (for which this report is a proceedings contribution) the SAGE collaboration gave an updated result. After analyzing the results from 157 runs from their starting date of 1990 through 2006, the SAGE collaboration reported a measurement of the solar neutrino rate of $66.2^{+3.3}_{-3.2} \text{ }^{+3.5}_{-3.2}$ SNU (solar neutrino units) [11]. Their measured *pp* solar neutrino signal is in good agreement with SSM calculations which include neutrino oscillations (with the best-fit parameters) – the oscillated, calculated signal is $67.3^{+3.9}_{-3.5}$ SNU [11].

The Super-Kamiokande detector has been reconstructed; this work was completed in April 2006. The full photocathode coverage fraction of 40% has been restored. The detector tank has been filled with water since July 2006 and the current detector is referred to as SK-III. As a ^8B solar neutrino detector SK-III has a goal of measuring the upturn in the recoil electron energy spectrum at low energies. This upturn is a prediction of the best-fit oscillation survival probability calculation. In order to see this effect SK-III will need to accomplish three improvements over SK-I. These are illustrated in Figure 1.

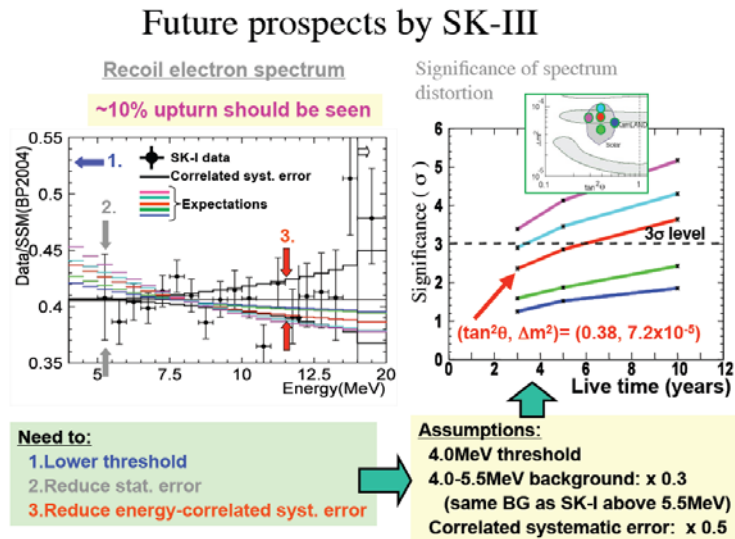


Figure 1. The SK-III goal to demonstrate the upturn in the recoil electron spectrum is shown above [12].

SK-III plans to lower the analysis threshold to 4.0 MeV from the 5.0 MeV used previously. This may require backgrounds in the detector to be reduced. The energy-correlated systematic uncertainties will need to be reduced. Finally statistical errors will be reduced – the plan is for a 10-year run (or longer). By accomplishing these improvements a detection of the spectrum distortion at the 3σ level or greater could be achieved.

SK-III has analyzed 97 live-days of data collected in 2007. The solar neutrino data in SK-III are consistent with previous SK-I results and were reported at the TAUP2007 conference. Noteworthy is the fact that in the central-top region of the detector backgrounds are lower than in SK-I (within the 5.0-5.5 MeV bin); this result is reproduced in Figure 2. By continuing to purify the water in the detector, the SK-III collaboration anticipates that this low background region will be enlarged.

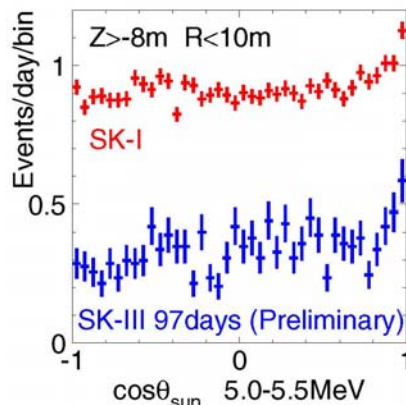


Figure 2. Preliminary data from SK-III illustrating lower backgrounds [12].

In addition to SAGE and Super-Kamiokande III a new solar neutrino experiment is currently taking data. The Borexino experiment was constructed in the late 90's-early 2000's and began taking data in 2007. The Borexino detector contains 300 tons of pseudocumene-based liquid scintillator and detects the scintillation light produced by neutrino-electron scattering. Since scintillator is used as the detection medium (as opposed to water Čerenkov) the high light yield enables detection of the ^7Be solar neutrinos with energy 0.86 MeV. In order to detect events at these low energies considerable care is needed, and was taken, in the construction of the Borexino experiment and in the purification of the liquid scintillator in order to eliminate backgrounds from natural radioactivity.

The first results from Borexino were presented in August 2007. The experiment successfully detected ^7Be solar neutrinos and determined their rate: $47 \pm 7 \pm 12$ counts/day/100 tons [13]. This rate is consistent with the theoretically predicted event rate including oscillations of 49 ± 4 counts/day, and less than the SSM unoscillated rate which would be 75 ± 4 counts/day [13]. The Borexino results are consistent with other solar neutrino experimental results and the model for oscillations that those data imply. Figure 3 shows the energy spectrum of events in Borexino after a pulse-shape discrimination cut has removed alpha backgrounds from ^{210}Po (other cuts also were applied). The recoil edge spectral feature expected from ^7Be solar neutrinos is clearly visible. Backgrounds in this energy region are low compared to the signal.

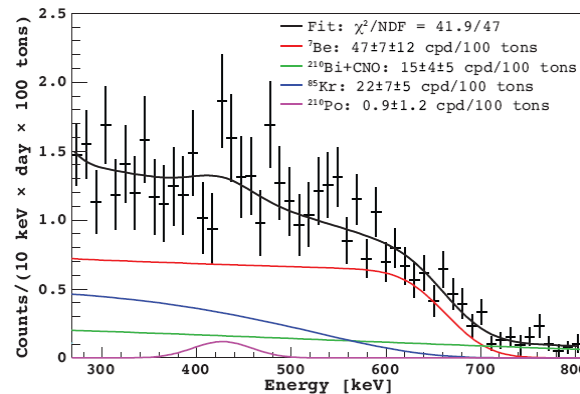


Figure 3. Detection of ^7Be solar neutrinos by observing the recoil electron energy spectrum in Borexino [13].

2. Solar neutrino experiments in transition

The KamLAND experiment has been measuring neutrino oscillation parameters by detecting reactor antineutrinos. KamLAND is a large, low background liquid scintillator detector and it would also be capable of detecting ^7Be solar neutrinos like Borexino; however singles backgrounds in KamLAND are observed to be too high by a factor of $\sim 10^5$. These backgrounds are due to ^{85}Kr and ^{210}Pb contamination in the scintillator and they prevent the observation of ^7Be solar neutrinos.

In order to enable the experiment to detect solar neutrinos the KamLAND collaboration built a scintillator purification system. The system uses the techniques of distillation and nitrogen stripping to remove backgrounds from Pb and Kr respectively. The first purification campaign was completed in July 2007. The total quantity of liquid scintillator that was processed was 1699 m^3 (KamLAND contains about 1000 tons of scintillator). Figure 4 shows some data taken during this purification campaign and it can be seen that the purified scintillator re-introduced in the detector (on top) has a lower background. After completing the first purification campaign, the result was that backgrounds had been reduced but not yet by the desired amount. This might have been due to mixing of purified scintillator inside the KamLAND detector after it was re-introduced.

Another experiment that is in transition is the Sudbury Neutrino Observatory. The SNO experiment had 1000 tons of heavy water and detected both charged-current (CC) and neutral-current (NC) neutrino interactions with deuterons in the ultra-pure D_2O . SNO ran in three phases; each phase detected the neutrons produced by neutral-current events differently. The third and final phase of SNO

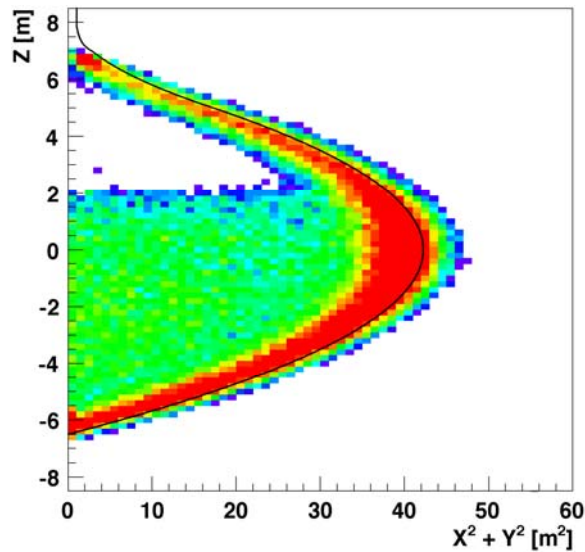


Figure 4. Snapshot of events in the KamLAND detector during the first liquid scintillator purification campaign [14]. The number of events in the top of the detector is much lower showing that the purified scintillator re-introduced in the detector (on top) had much lower backgrounds.

included the deployment of ^3He proportional counters distributed in an array inside the heavy water volume. This phase took data from November 2004 until November 2006. The dedicated neutron counters detected NC events in a separate detector subsystem whereas in the previous two phases of SNO neutrons produced capture gamma rays that interacted to produce Čerenkov light detected by photomultiplier tubes. These signals had then to be separated from the Čerenkov light from CC events. The third phase of SNO thus had the potential to break correlations between CC and NC rate measurements, thereby reducing systematic uncertainties.

One important aspect of this event-by-event separation for neutrons (NC signal) is how it might also reduce the uncertainties that affect the measurement of the CC spectral shape. Figure 5 shows the SNO extracted energy spectrum for charged-current neutrino-deuteron events. The large systematic uncertainties at low energy are dominated by the uncertainties related to the separation of CC and NC events in the previous two phases of SNO; but with the event-by-event separation of the third phase the CC-NC correlations reduce to ~ 0 . This will aid in the observation of the predicted upturn in the spectrum at low energies in the data from SNO's third phase.

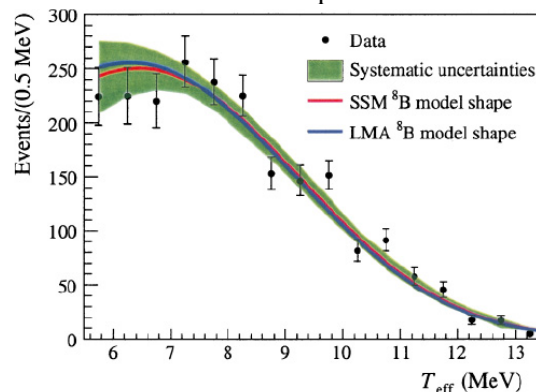


Figure 5. SNO CC energy spectrum extracted from the data from the salt phase [10].

Analysis of data from SNO's NCD (neutral current detectors) phase is taking place. There are also ongoing analyses of past SNO data and there will ultimately be a combined, three-phase analysis. For the near term there are two main analysis efforts. The first blind analysis of the data from SNO's

neutron counters is being completed. With the aim of reducing the total uncertainty in SNO's NC measurement down to the $\sim 5\%$ level, a careful understand of the backgrounds in the neutron counters and their uncertainties is required. The second major effort taking place is the lowering of the analysis threshold. Improvements in energy estimators have been developed and they lead to better energy resolution in SNO (and even better understanding of the response function). The result is that tails from low energy backgrounds are smaller. Combining these improvements with improved characterization of these backgrounds allows the analysis threshold to be decreased from 5.5 MeV (electron kinetic energy) down to 4.0 MeV or lower. Figure 6 shows simulated data with a lowered analysis threshold. Backgrounds from Bi (uranium chain) and Tl (thorium chain) will be fitted in this analysis along with neutrino signals.

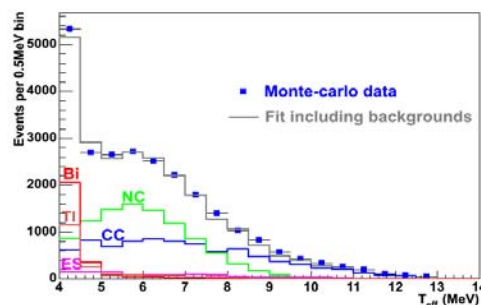


Figure 6. Simulation of a lower energy threshold analysis of SNO data. CC, NC and ES are signals from charged-current, neutral-current and elastic scattering while Bi and Tl are backgrounds.

The SNO experiment stopped taking data at the end of November 2006. The ^3He neutron counters were removed by the middle of January 2007 and heavy water removal began in late January 2007. The heavy water that was used by the SNO experiment was borrowed from Atomic Energy of Canada, Limited. On May 28, 2007 the last drops of heavy water were taken out of the SNO acrylic vessel and that event marked the end of the SNO experiment.

There are plans to fill the SNO detector with a liquid scintillator now that the heavy water has been removed. This project is called SNO+ and involves a subset of the SNO collaboration and new collaborators. A liquid scintillator that uses linear alkylbenzene (LAB) as the solvent has been developed by SNO+. It is chemically mild and is compatible with acrylic undiluted, thus has high light yield. LAB is safer and cheaper than pseudocumene. With an LAB-based scintillator in the SNO+ detector, the Monte Carlo simulated light yield in SNO+ is 900-1200 photoelectrons/MeV, depending on the concentration of fluor (e.g. PPO) used.

The density of LAB is similar to that of mineral oil and is 0.86 g/cm^3 . With water surrounding the scintillator-filled acrylic vessel, the mechanics in SNO+ need to be reversed from SNO. Whereas the heavy water vessel was held up in SNO, the buoyant scintillator vessel needs to be held down in SNO+. A preliminary engineering evaluation has found feasible solutions for this hold down, likely to be based upon a rope net deployed over the upper hemisphere of the SNO+ acrylic vessel, with hold-down ropes penetrating the photomultiplier support structure and anchored to the cavity floor.

SNO+ aims to detect *pep* and *CNO* solar neutrinos. SNO+ will also detect geo and reactor antineutrinos, serve as a monitor for supernova neutrinos and, with the addition of Nd, plans to search for neutrinoless double beta decay in a separate running phase. This discussion will only focus on the solar neutrino capabilities. The flux of *pep* solar neutrinos is fundamental and related to the flux of *pp* solar neutrinos; it is calculated to $\pm 1.5\%$ uncertainty in the Standard Solar Model [8]. The cross section for neutrino-electron scattering has negligible uncertainty. A measurement of the rate of *pep* solar neutrino interactions can thus be used to determine the survival probability (for $E_\nu = 1.44 \text{ MeV}$) precisely. It is also interesting to detect ^7Be solar neutrinos; but with a solar model uncertainty in the ^7Be flux of $\pm 10\%$, the determination of the survival probability necessarily includes this uncertainty.

Detecting the *pep* solar neutrinos and measuring their survival probability, with precision, is interesting from the point of view of new neutrino physics. The presence of phenomena such as non-standard interactions [15] or mass-varying neutrinos [16] might manifest itself as a different survival probability at the transition between vacuum dominance and matter dominance, in the oscillation of solar neutrinos. The transition region is at neutrino energies between 1-2 MeV. Measuring the survival probability of *pep* solar neutrinos has good sensitivity to new physics.

Detecting the *CNO* neutrinos would be interesting as it could reveal information relevant to solar elemental abundances. A recent problem in solar models is the fact that helioseismology seems incompatible with low metallicity solar models. Solar model sound speeds [8] no longer agree with helioseismology when elemental abundances from [17] are used. The *CNO* neutrino fluxes depend on these abundances; differences of 50-60% in the flux result from using the older metallicity values and the newer ones. A measurement of the *CNO* fluxes would suggest which is compatible.

A background to the *pep* and *CNO* solar neutrinos is the cosmogenic production of ^{11}C . The half-life of ^{11}C is 20 minutes and that makes it difficult to veto or tag these events if the muon rate through a detector is very large. The ^{11}C background scales essentially as the muon rate. The deep location of SNO+ of 6000 mwe depth gives a muon rate that is low enough that this background is not a problem.

3. Synthesis of all solar neutrino data

Across the spectrum of solar neutrinos there have been direct and indirect observations. It is possible to synthesize all of the experimental results to examine what the present state of knowledge is of the survival probability, P_{ee} , of solar neutrinos as a function of neutrino energy.

The CC/NC ratio in SNO is a direct measurement of the average survival probability of the ^8B solar neutrinos that were detected. The mapping of detected recoil electron energy (SNO CC reaction) onto neutrino energy is direct enough (for the purpose of this study) since the response function is peaked and requires just the shift due to the reaction Q-value of 1.44 MeV.

The Chlorine experiment has contributions from ^7Be , *pep*, *CNO* and ^8B solar neutrinos; the latter is known from SNO data, and can be subtracted. The subtraction of a large component leaves the remainder with a large uncertainty; nevertheless, this gives information about the P_{ee} at intermediate energies ~ 1 MeV. The Borexino experiment has directly detected ^7Be solar neutrinos. The detection in Borexino is with the neutrino-electron scattering reaction; there is a neutral-current component in this signal for neutrinos that have oscillated to mu and tau flavor. Correcting for this gives the electron neutrino survival probability at 0.86 MeV, also at intermediate energies.

The radiochemical gallium experiments have contributions from *pp* solar neutrinos and higher energy neutrinos. One can subtract the ^8B and ^7Be contributions using SNO and Borexino data, respectively. The result gives a glimpse of the survival probability at lower energies.

This synthesis of all data is displayed in Figure 7; the calculated survival probability curve using the best-fit oscillation parameters is also shown in this figure. Also shown in this plot is a hypothetical measurement by SNO+ of the survival probability at 1.44 MeV (from *pep* neutrinos). The SNO+ error bars include estimated statistical, systematic and solar model uncertainties.

4. Future solar neutrino experiments

Several future solar neutrino experiments are being developed (in addition to SNO+ that has already been discussed). There are two noble liquid scintillation detectors under R&D. CLEAN (Cryogenic Low Energy Astrophysics with Neon) would contain 100 tons of liquid neon which is expected to have negligibly low intrinsic radioactive backgrounds. XMASS (Xenon MASSive detector) would contain 10 tons of liquid xenon which benefits from having very effective self-shielding. Both experiments would look for neutrino-electron scattering. CLEAN and XMASS plan to detect *pp* solar neutrinos; rates would be ~ 1 *pp* event/day per ton, for a 50 keV recoil electron threshold.

Two other experiments are under R&D. They are experiments that plan to use charged-current reactions to detect *pp* solar neutrinos. LENS (Low Energy Neutrino Spectroscopy) would look for neutrino capture on ^{115}In . This reaction can be tagged by subsequent gamma decays and would allow

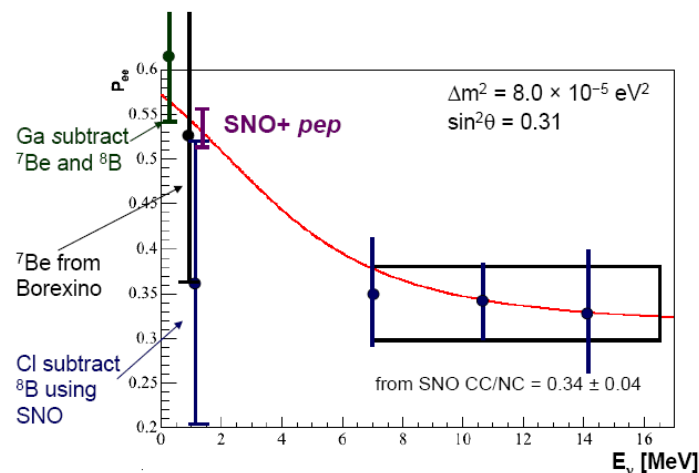


Figure 7. The survival probability for solar neutrinos as a function of energy. The data points are a synthesis of all experimental data interpreted as survival probability. The curve is the calculation using best-fit LMA oscillation parameters.

for 40 *pp* events/year per ton of indium (a rate that includes event tag efficiency). LENS would use an indium-loaded liquid scintillator deployed in a novel scintillation lattice chamber which produces event patterns that allow for discrimination from the large intrinsic ^{115}In beta decay background. MOON (Molybdenum Observatory Of Neutrinos) would look for neutrino capture on ^{100}Mo . This reaction can be tagged by a subsequent beta decay with a rate of 120 *pp* events/year per ton of ^{100}Mo isotope (9.6% natural abundance).

In summary, solar neutrinos will continue to be studied in the future. There will be further analysis of ^8B (and *hep*) solar neutrinos by SNO and further measurements by SK-III. The *pep* and *CNO* neutrinos will be detected by the planned SNO+ experiment. Borexino is measuring the flux of ^7Be solar neutrinos and KamLAND is lowering backgrounds via scintillator purification in order to detect ^7Be neutrinos also. There is R&D underway for four future *pp* solar neutrino experiments including two that would use charged-current reactions.

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