BNL-71097-2003-CP

Recent SNO Results

Minfang Yeh

Brookhaven National Laboratory, Chemistry Department-555
Upton, NY 11973-5000

Abstract. Solar Neutrinos from the decay of ^{8}B have been detected at the Sudbury Neutrino Observatory (SNO) by charged current (CC) and neutral current (NC) interactions on deuterium and elastic scattering (ES) of electrons. The SNO data indicate that with the assumption of undistorted ^{8}B shape, the flux for ν_e is $\phi_e = 1.76^{+0.05}_{-0.05}$(stat.)$^{+0.09}_{-0.09}$(syst.) $\times$ 10^6 cm^{-2}s^{-1} for a kinetic energy threshold of 5 MeV. The non-ν_e flux is $\phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}$(stat.)$^{+0.48}_{-0.45}$(syst.) $\times$ 10^6 cm^{-2}s^{-1}. This provides strong evidence for solar ν_e flavor transformation. The day and night solar neutrino energy spectra and rates have also been measured. For CC events, the ν_e asymmetry is 14.0% $\pm$ 6.3% $^{+1.5}_{-1.4}$%. By additionally constraining the total (NC) flux of active neutrinos to have no asymmetry, the ν_e asymmetry becomes 7.0% $\pm$ 4.9% $^{+1.3}_{-1.2}$%. A global solar neutrino analysis strongly favors the Large Mixing Angle (LMA) solution in a two-flavor neutrino oscillation model.

INTRODUCTION

SNO is a water Cherenkov detector that was designed to search for definitive evidence of ^{8}B neutrino interactions as they occur in real time with kinetic energy threshold of 5 MeV. It is situated in a specially constructed underground clean area, at the 6010-m level of the Creighton mine near Sudbury, Ontario, Canada. The detector contains 1000 metric tons of ultra-pure heavy water, D_2O, in a 12-meter wide transparent plastic acrylic vessel (AV), surrounded by 7000 metric tons of ultra-pure light water, H_2O, which acts as shielding. In the H_2O, 9456 20-cm photomultiplier tubes (PMTs) surround and view the AV, detecting the Cherenkov light produced in the D_2O by neutrino interactions and thus measuring the neutrino energy spectra and fluxes.

The D_2O makes SNO unique among neutrino detectors, since deuterium can observe all three active neutrino flavors ($x = e, \mu, \tau$) via the reactions:

$$\nu_e + d \rightarrow p + p + e^- \quad \text{(CC)}$$

$$\nu_x + d \rightarrow p + n + e^- \quad \text{(NC)}$$

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \text{(ES)}$$

The charged current (CC) reaction, with a Q value of 1.44 MeV, provides good measurement of the ν_e energy spectrum, but weak directional sensitivity *(1-1/3cos(θ_{sun}))*. The neutral current (NC) reaction with a Q value of 2.2 MeV measures the total ^8B ν flux from the sun by detecting the Cherenkov photons resulting from the 6.25-MeV γ ray from neutron capture on deuterium. This reaction has equal cross section for all active ν types. The elastic scattering (ES) reaction is sensitive to all flavors as well, but with less sensitivity to ν_μ and ν_τ. Compared to the CC and NC reactions, ES has a smaller neutrino cross-section, but shows strong directional sensitivity.

Ability to detect these three reactions simultaneously allows SNO to determine the electron and non-electron active neutrino components of the solar neutrino flux. The flux ratios of ϕ^{CC} to ϕ^{NC} or ϕ^{ES} represent the direct indication of neutrino flavor transformation. In term of matter enhanced, two-flavor oscillations, the MSW effect implies that the neutrinos can change flavor as they propagate through the Earth, which leads to an asymmetric neutrino flux between day and night, ϕ_D and ϕ_N. In this paper. the CC, NC, and ES results from the first phase of the SNO experiment (pure D_2O only) are presented. The MSW plots and allowed mixing parameters using day and night neutrino energy spectra only and with additional constraints from other experimental data are shown. The second and third phases of the SNO experiment will also be discussed.

RESULTS FROM THE FIRST PHASE OF SNO

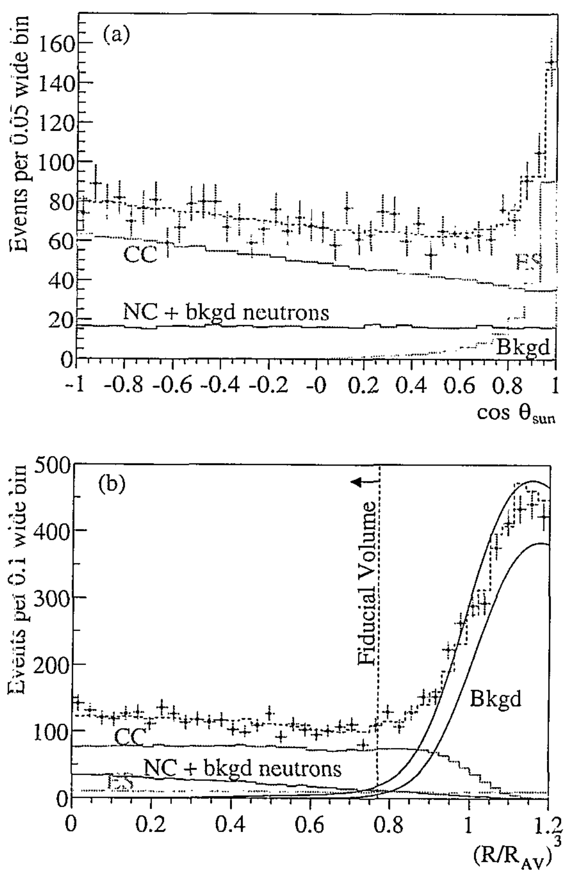
Three operational phases were planned at the beginning of the SNO experiment. First, to run the detector with pure D_2O only. In all likelihood, at the end of this operation, the solar neutrino problem will be solved with clear evidence either of new neutrino properties, i.e., that neutrinos have mass and the capability of undergoing flavor transformations traveling from sun to the earth, or of new astrophysical processes that require the standard solar model to be modified. The charged current (CC) reaction is sensitive only to ν_e. The neutral current (NC) interactions of all three active flavors of neutrinos, *e*, μ, and τ, break the deuteron into a proton and a neutron, so that the rate of neutron production gives the sensitivity to measure the total ^8B solar ν flux. The probability of detecting free neutrons from NC can be enhanced by neutron capture on ^{35}Cl, as compared to neutron capture on deuterium. The second phase of the SNO experiment, to add 2% (w/w) of salt (NaCl) into the pure D_2O, began in the summer of 2001. In the final, third phase, an array of ^3He-filled proportional counters will be installed in the AV to directly measure the neutrons from NC, after removal of the dissolved salt from the D_2O.

The data reported here have a total of 306.4 live days, representing the entire first phase of the SNO experiment, in which only pure D_2O was present in the detector. The details of analysis procedures were described in [1] and an example of the data reduction steps is shown in Table 1.

TABLE (1). Data Reduction Steps

Analysis Step	Number of Events
Total	450,188,649
NHIT 100	191,312,560
Analysis Threshold	10,088,842
Data Cleaning	7,805,238
High Level Cuts	3,418,439
Fiducial Volume	67,343
Energy Threshold	3,440
Mu Follower	2,981
Frati Follower	2,928

After the background cuts were applied, the remaining events, which were classified as neutrino events, were decomposed into the CC, NC, and ES signals in terms of their different probabilities in the (1) volume-weighted radial distribution $(R/R_{AV})^3$, where $R_{AV} = 600$ cm, (2) angular distribution of the cosine of the angle between the direction of each event and the position of the sun ($\cos(\theta)_{sun}$), and (3) kinetic energy distribution (T_{eff}). The data recorded for the pure D_2O phase at $T_{eff} \geq 5$ MeV and $R \leq 550$ cm are shown in Figures 1(a), (b), and (c). The extended maximum-likelihood method used in the signal decomposition yields $1967.7^{+61.9}_{-60.9}$ CC events, $263.6^{+26.4}_{-25.6}$ ES events, and $576.5^{+49.5}_{-48.9}$ NC events, where only statistical uncertainties are given.



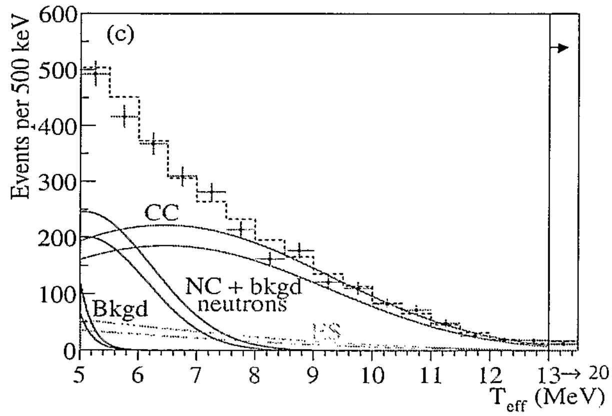


FIGURE 1. (a) Distribution of cos θ_{sun} for $R \leq 550$ cm. (b) Distribution of the Volume Weighted Radial Variable $(R/R_{AV})^3$. (c) Kinetic Energy Distribution for $T_{eff} \geq 5$ MeV. Also shown are the Monte Carlo predictions for CC, ES, and NC + background neutron events, scaled to the fit results, and the calculated spectrum of Cherenkov background (Bkgd) events. The dashed lines represent the sums of the components, and the bands show $\pm$ 1σ uncertainties. Crosses are the data points. All distributions are for events with $T_{eff} \geq 5$ MeV.

Following the event decomposition process, the resulting measured ^{8}B ν flux, with the assumption of the standard ^{8}B spectral shape, is for each reaction in SNO (in units of 10^6 cm^{-2}s^{-1}):

$$\phi_{CC}^{SNO} = 1.76^{+0.05}_{-0.05}\,(\text{stat.})^{+0.09}_{-0.09}\,(\text{syst.})$$

$$\phi_{ES}^{SNO} = 2.39^{+0.24}_{-0.23}\,(\text{stat.})^{+0.12}_{-0.12}\,(\text{syst.})$$

$$\phi_{NC}^{SNO} = 5.09^{+0.44}_{-0.43}\,(\text{stat.})^{+0.46}_{-0.43}\,(\text{syst.})$$

The ratios of ϕ^{CC} to ϕ^{NC} or ϕ^{CC} to ϕ^{ES} are the direct indications of neutrino flavor transformation. On the other hand, the measured NC neutrino flux can also be decomposed into electron (ϕ_e) and non-electron ($\phi_{\mu\tau}$) components:

$$\phi_{e}^{SNO} = 1.76^{+0.05}_{-0.05}\,(\text{stat.})^{+0.09}_{-0.09}\,(\text{syst.})$$

$$\phi_{\mu\tau}^{SNO} = 3.41^{+0.45}_{-0.45}\,(\text{stat.})^{+0.48}_{-0.45}\,(\text{syst.})$$

Combing the statistical and systematic uncertainties $\phi_{\mu\tau}$ is $3.41^{+0.66}_{-0.64}$, which is 5.3σ above zero, also providing strong evidence for flavor transformation. The total active ^{8}B ν flux measured from the NC reaction, $\phi_{NC} = 5.09^{+0.44}_{-0.43}\,(\text{stat.})^{+0.46}_{-0.43}\,(\text{syst.})$, is in good agreement with the standard solar model prediction of $\phi_{SSM} = 5.05^{+1.01}_{-0.81}$.

IS DAY EQUAL TO NIGHT?

One of the favored explanations for the flavor transformations of neutrinos traveling from sun to earth is the flavor mixing model. Depending on the mixing parameters, effects caused by neutrino interactions with the matter of the Earth (MSW effect) are expected, such as the distortion of the neutrino energy spectra, and the asymmetry of the observed events as a function of the solar zenith angle. The flux asymmetry ratio of day (ϕ_D) and night (ϕ_N), which is a function of neutrino energy, path length and electron density of earth, and oscillation parameters, provides a sensitive tool, in addition to spectral distortions, for exploring the MSW allowed neutrino mixing parameters.

The live time of 306.4 days with a total number of 2928 events divides into 128.5 and 177.9 live days for day and night, respectively. The day-night flux asymmetry ratio is defined as:

$$A_x = \frac{2(\phi_N - \phi_D)}{\phi_N + \phi_D}$$

Since the CC interaction is only sensitive to ν_e and the NC interaction is equally sensitive to all neutrino flavors, the active-neutrino model predicts that $A_{CC} \neq 0$ and $A_{NC} = 0$. Because the ES interaction has non-equal cross sections between ν_e and $\nu_{\mu\tau}$, it has reduced sensitivity for determining the day-night asymmetry.

Backgrounds were subtracted separately for the day and night signals using various calibration sources. One of the calibration sources is ^{16}N, which produces 6.1-MeV γ-rays, revealed a 1.3% per year drift in the energy scale. Due to seasonal variations in the day and night live times, this energy drift can create an artificial asymmetry. The analysis can thus use this drift to assign a systematic uncertainty.

The results, using joint probability contours for A_e and A_{total} derived from the day and night rate measurements, with no additional constraints, are presented in Table 2.

TABLE (2). The Results after Signal Extraction, Assuming an Undistorted ^8B Spectrum

Signal	ϕ_D (10^6 cm^{-2}s^{-1})	ϕ_N (10^6 cm^{-2}s^{-1})	A_e (%)
CC	1.62±0.08±0.08	1.87±0.07±0.10	$+14.0 \pm 6.3^{+1.5}_{-1.4}$
ES	2.64±0.37±0.12	2.22±0.30±0.12	$-17.4 \pm 19.5^{+2.4}_{-2.2}$
NC	5.69±0.66±0.44	4.63±0.57±0.44	$-20.4 \pm 16.9^{+2.4}_{-2.5}$

By changing the variables to $\phi_{CC} = \phi_e$, $\phi_{NC} = \phi_{total} = \phi_e + \phi_{\mu\tau}$, and $\phi_{ES} = \phi_e + \varepsilon\phi_{\mu\tau}$, where ε, 0.154, is the ratio of average cross sections for $\nu_{\mu\tau}$ and ν_e above 5 MeV, and adding the constraint from the ES rate measurement, the results, A_e = $12.8\% \pm 6.2\%(stat.)^{+1.5}_{-1.4}\%(sys.)$ and A_{total} = $-24.2\% \pm 16.1\%(stat.)^{+2.4}_{-2.5}\%(sys.)$, are obtained. By forcing $A_{total} = 0$ (i.e., neutrino flavors oscillate but their total flux remains constant),

A_e is reduced to $7.0\% \pm 4.9\%(stat.)^{+1.3}_{-1.2}\%(sys.)$. The Super-Kamiokande collaboration measured $A_{ES} = 3.3\% \pm 2.2\%(stat.)^{+1.3}_{-1.2}\%(sys.)$, which included a smaller non-electron component from $\nu_{\mu\tau}$. By using the SNO total ^8B ν flux, we find that the extracted $A_e(SK) = 5.3\% \pm 3.7\%(stat.)^{+2.0}_{-1.7}\%(sys.)$, which is in good agreement with the direct measurement of SNO.

The MSW plane and neutrino flavor mixing parameters can be constructed by using the neutrino spectrum, the survival probability, and the cross sections with the two-flavor neutrino oscillation model. Three free parameters: the total ^8B neutrino flux, ϕ_x, the difference Δm^2 between the squared masses of the two neutrino mass eigenstates, and the mixing angle θ, can be fit. Figure 2(a) shows the allowed regions using only SNO day and night energy spectra with no additional experimental constraints or inputs from the solar model. By conducting a global solar data fit including information from the Cl and Ga experiments, the day and night spectra from the SK experiment, along with solar model predictions, the contours are shown in Figure 2(b), which strongly favor Large Mixing Angle (LMA) and $\tan^2\theta < 1$.

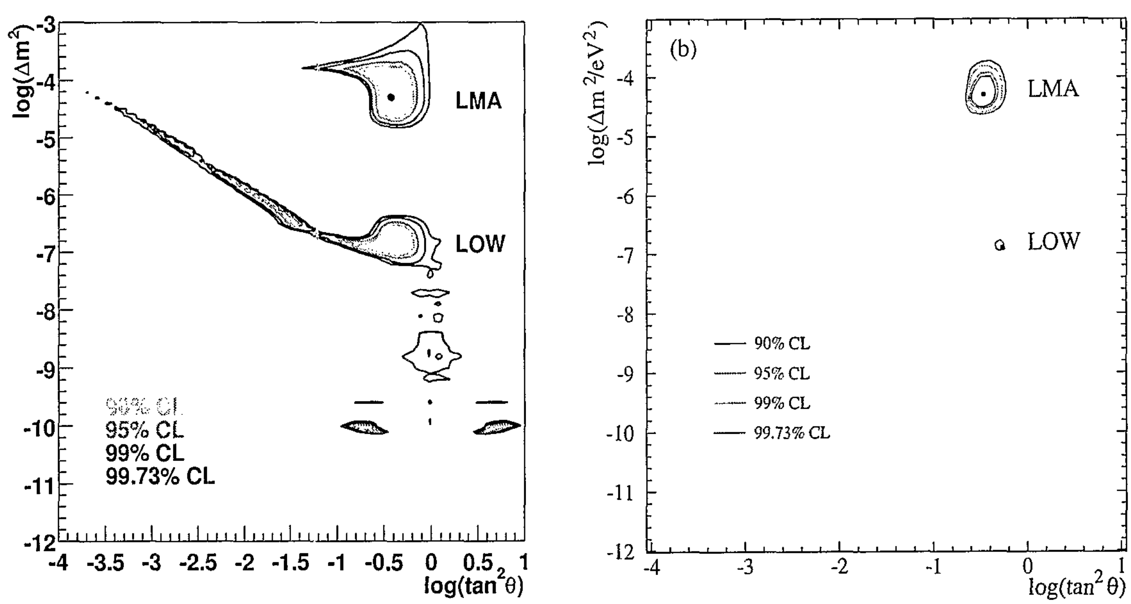


FIGURE 4. Allowed regions of the MSW plane determined by a χ^2 fit to (a) only SNO day and night energy spectra and (b) with additional experimental and solar model data. The star indicates the best fit.

FUTURE OF SNO

SNO has finished first phase operations, and has been continuing its second phase operations with the salt in the D_2O since June 2001. The neutron capture of Cl, $n + {}^{35}Cl \rightarrow {}^{36}Cl + \Sigma\gamma$, from the added salt increases the detection efficiency of free neutrons produced by neutral current interactions from 14.2% in the first phase to ~45% in the present second phase. The preparation of third phase operations that measure the produced neutrons directly by neutral current detectors (NCDs, an array of ^{3}He-filled proportional counters) is nearing completion. The NCD array will be ready for commissioning soon, and deployment is expected in mid 2003.

ACKNOWLEDGMENTS

This research was supported in Canada by NSERC, Industrial Canada, NRC, Northern Ontario Heritage Fund Corporation, INCO, AECL, and Ontario Power Generation; in the US by the Office of High-Energy and Nuclear Physics of the U.S. Department of Energy (at BNL: DE-AC02-98CH10886); and in the UK by PPARC. The strong contributions from SNO technical staff are greatly appreciated.

REFERENCES

1. Ahmad, Q. R. et al., the SNO Collaboration, Phys. Rev. Lett. 87, 071301 (2001).
2. Ahmad, Q. R. et al., the SNO Collaboration, Phys. Rev..Lett. 89, 011301 (2002).
3. Ahmad, Q. R. et al., the SNO Collaboration, Phys. Rev. Lett. 89, 011302 (2002).