SOLAR NEUTRINO RESULTS FROM THE SUDBURY NEUTRINO OBSERVATORY

JOSHUA R. KLEIN, FOR THE SNO COLLABORATION
Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA
19104-6396

We describe here the measurement of the flux of neutrinos created by the decay of solar $^8$B by the Sudbury Neutrino Observatory (SNO). The neutrinos were detected via the charged current (CC) reaction on deuterium and by the elastic scattering (ES) of electrons. The CC reaction is sensitive exclusively to $\nu_e$'s, while the ES reaction also has a small sensitivity to $\nu_\mu$'s and $\nu_\tau$'s. The flux of $\nu_e$'s from $^8$B decay measured by the CC reaction rate is $\phi_{CC}(\nu_e) = 1.75 \pm 0.07$ (stat.)$^{+0.12}_{-0.11}$ (sys.) $\pm 0.05$ (theor.) $\times 10^6$ cm$^{-2}$s$^{-1}$. Assuming no flavor transformation, the flux inferred from the ES reaction rate is $\phi_{ES}(\nu_e) = 2.39 \pm 0.34$ (stat.)$^{+0.16}_{-0.14}$ (sys.) $\times 10^6$ cm$^{-2}$s$^{-1}$. Comparison of $\phi_{CC}(\nu_e)$ to the Super-Kamiokande Collaboration’s precision value of $\phi_{ES}(\nu_e)$ yields a 3.3$\sigma$ difference, assuming the systematic uncertainties are normally distributed, providing evidence that there is a non-electron flavor active neutrino component in the solar flux. The total flux of active $^8$B neutrinos is thus determined to be $5.44 \pm 0.99 \times 10^6$ cm$^{-2}$s$^{-1}$, in close agreement with the predictions of solar models.

1 Introduction

Over thirty years of solar neutrino experiments have demonstrated that the flux of neutrinos from all sources within the Sun is significantly smaller than predicted by models of the Sun's energy generating mechanisms. The deficit is not only universally observed but has an energy dependence which makes it hard to attribute to astrophysical sources: the data are consistent with a negligible flux of neutrinos from solar $^7$Be, though neutrinos from $^8$B (a product of solar $^7$Be reactions) are observed. A natural explanation for the observations is that neutrinos born as $\nu_e$'s change flavor on their way to the Earth, thus producing an apparent deficit in experiments detecting primarily $\nu_e$'s. Neutrino oscillations—either in vacuum or matter—provide a mechanism both for the flavor change and the observed energy variations.

While these deficit measurements argue strongly for neutrino flavor change through oscillation, a far more compelling demonstration would not resort to model predictions at all but look for non-$\nu_e$ flavors coming from the Sun. The Sudbury Neutrino Observatory (SNO) was designed to do just that: provide direct evidence of solar neutrino flavor change through the inclusive appearance of non-electron neutrino flavors from the Sun. We present here the first solar neutrino results from SNO, which have also been described in an earlier publication.

2 SNO Detector

SNO is an imaging water Cerenkov detector, which uses heavy water (D$_2$O) as both the interaction and detection medium. Figure 1 shows a diagram of the detector. SNO is located ~2 km (6020 k.w.e.) underground in INCO Ltd.’s Creighton Mine, deep enough that the rate of cosmic ray muons passing through the entire active volume is just 3/hour.

The 1000 tons of heavy water is contained in a 12 m diameter transparent acrylic vessel, and is surrounded by 2 ktons of light water shielding. The Cerenkov light produced by neutrinos and radioactive backgrounds is detected by an array of 9500 8 inch photomultiplier tubes (PMTs), supported by a stainless steel geodesic sphere. Each PMT is surrounded by a light concen-
For Publisher’s use

trator, which increases the photocathode coverage to nearly $\sim 55\%$. The front-end discriminator thresholds are set to fire on 1/4 of a photoelectron of charge. Outside the PMT support sphere is another 7 ktons of light water shielding.

The detector is also equipped with a flexible calibration system, capable of placing sources almost everywhere in either the $x - z$ or $y - z$ plane. The sources that can be deployed include a diffuse multi-wavelength laser for measurements of optical parameters and PMT timing, a $^{16}$N source which provides a triggered sample of 6.13 MeV $\gamma$’s, and a $^3$Li source delivering $\beta$’s with an endpoint near 14 MeV. In addition, high energy (19.8 MeV) $\gamma$’s are provided by a $^3$H($p, \gamma$)$^4$He (‘pT’) source and neutrons by a Cf source. Some of the sources can also be deployed on vertical axes within the light water volume between the acrylic vessel and PMT support sphere.

3 SNO Reactions

SNO can provide direct evidence of solar neutrino flavor change through comparisons of the interaction rates of three different processes:

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

The first reaction, the elastic scattering (ES) of electrons, has been used to detect solar neutrinos in other water Cerenkov experiments. It has the great advantage that the recoil electron direction is strongly correlated with the direction of the incident neutrino (and hence the direction of the Sun). In addition, this reaction has sensitivity to all neutrino flavors. For $\nu_e$’s, the elastic scattering reaction has both charged and neutral current components, making the cross section for $\nu_e$’s 6.5 times larger than that for $\nu_\mu$’s or $\nu_\tau$’s.

The deuterium in the heavy water makes the second process possible: an exclusively charged current (CC) reaction which (at solar energies) occurs only for $\nu_e$’s. In addition to providing exclusive sensitivity to $\nu_e$’s, this reaction has the advantage that the recoil electron energy is strongly correlated with the incident neutrino energy, and thus can provide a good measurement of the $^8$B energy spectrum. The CC reaction also has an angular correlation with the Sun which falls as $(1 - 0.340 \cos(\theta_\odot))^{14}$, and has a much larger cross section ($\sim 10$ times larger) than the ES reaction.

The third reaction—also unique to heavy water—is a purely neutral current process. This has the obvious advantage that it is equally sensitive to all neutrino flavors, and thus provides a direct model-independent measurement of the total flux of neutrinos from the Sun.

For both the ES and CC reactions, the recoil electrons are directly detected through their production of Cerenkov light. For the NC reaction, the neutrons are not seen directly, but are detected in a multi-step process. When a neutrino liberates a neutron from a deuteron, the neutron wanders within
the D$_2$O and is eventually captured by another deuteron, releasing a 6.25 MeV γ-ray. The γ Compton scatters an electron and it is this secondary particle which is detected.

Although the data we present here were acquired with the acrylic vessel filled with pure D$_2$O, the detector is now running with NaCl added to the heavy water. The addition of the salt provides chlorine which has a larger capture cross section (and hence a higher detection efficiency) for the neutrons. The capture on chlorine also yields multiple γ's instead of the single γ from the pure D$_2$O phase, which aids in the identification of neutron events. Eventually, discrete He$^3$ proportional counters will be added which will count neutrons exclusively.

To determine whether neutrinos which start out as ν$_e$'s in the solar core convert to another flavor before detection on Earth, we have two choices: comparison of the CC reaction rate to the NC reaction rate, or comparison of the CC rate to the ES rate. The former has the advantage of high sensitivity—we compare the total flux to the ν$_e$ flux and therefore expect to see a large difference if the true neutrino flux agrees with standard solar models (which predict a total flux two to three times larger than previous measurements). In addition, uncertainties in the cross sections for the two processes will largely cancel.

The second comparison has the advantage that both the CC and ES recoil electrons provide neutrino spectral information. The spectral information can ultimately be used to show that any excess in the ES reaction over the CC reaction is not caused by a difference in the energy thresholds used to analyze the two reactions. The CC-ES comparison also has the advantage that the strong angular correlation with the Sun demonstrates that any excess seen is not due to some unexpected non-solar background. Lastly, the CC-ES comparison can be made with fairly high precision despite the small ES reaction cross section, because the Super-Kamiokande collaboration has already made a precision, high statistics measurement of the ES rate.$^5$

For the results presented here, only the CC-ES comparison will be described.

4 Data Analysis

The goal of the data analysis is the determination of the relative sizes of the three signals (CC, ES, and neutrons) and ultimately the comparison of the rates. In the pure D$_2$O detector configuration—the configuration with which these data were taken—we cannot separate the signals on an event-by-event basis. Instead, we 'extract' the signals statistically by using the fact that they are distributed distinctly in the following three derived quantities: the kinetic energy of the recoil electron or capture γ ray (T), the reconstructed radial position of the interaction ($R^3$), and the reconstructed direction of the event relative to the Sun ($\cos \theta_\odot$).

Figure 2 shows these distributions for each of the signals. The top row of Figure 2 plots the different energy distributions for the three signals. We see in the figure that the strong correlation between the electron energy and the incident neutrino energy for the CC interaction produces a spectrum which resembles the initial $^8$B neutrino spectrum, while the recoil spectrum for the ES reaction is much softer. The NC reaction is—within the resolution smearing of the detector—essentially a δ-function, because the γ produced by the neutron capture on deuterium always has the same 6.25 MeV.

The bottom row of Figure 2 shows the reconstructed direction distribution of the events. In the middle of that row we see the familiar peaking for the ES reaction, pointing toward the Sun. The $\sim 1 - 1/3 \cos \theta_\odot$ distribution of the CC reaction is also clear in the left hand side of the bottom row. Not surprisingly, the NC reaction shows no correlation with the solar direction—the γ ray from
the captured neutron knows nothing about the incident neutrino.

The distributions of reconstructed event positions is shown in the middle row of Figure 2. These distributions are plotted as a function of $R^3$, with $R^3 = 1$ occurring at the radius of the acrylic vessel (the edge of heavy water volume). We see here that the CC reactions—which occur only on deuterons—produce events distributed uniformly within the heavy water, while the ES reaction (which occurs on any electron) produces events distributed uniformly well beyond the heavy water volume. The small leakage of events just outside the heavy water volume for the CC reaction is due to the resolution tail of the reconstruction algorithm.

The NC reaction, however, does not have a uniform distribution inside the heavy water like the CC reaction, but instead monotonically decreases from the central region to the edge of the acrylic vessel. The reason for this is that the capture cross section for neutrons on deuterium is very small—the neutron wanders around long enough inside the D$_2$O that it may leak outside and be captured by hydrogen in either the acrylic vessel or the light water. Such hydrogen captures produce a much lower energy $\gamma$ ray ($\sim 2.2$ MeV), below the analysis threshold. Therefore the acceptance for events which are produced near the edge of the volume is reduced, because the probability of leakage there is correspondingly higher than for events produced near the center.

One last point needs to be made regarding the distributions labelled ‘NC’ in Figure 2: they represent equally well the detector response to all neutrons, not just those produced by neutral current interactions, as long as the neutrons are produced uniformly in the detector. For example, neutrons produced through photodisintegration by $\gamma$ rays emitted by U or Th chain daughters inside the D$_2$O will have the same distributions of energy, radial position, and solar direction as those produced by solar neutrinos. In the analysis described here, no separation is done between these neutrons and those from the NC reaction.

To determine the size of the three signals, then, we use these nine distributions to create probability density functions (pdfs) and perform a generalized maximum likelihood fit to the same distributions in the data. There are, however, two principal prerequisites that must be satisfied before we can even begin this ‘signal extraction’ process. First, we need to process the data so that it is in a form we can use to do the fits. For example, we need to reconstruct the events to give us positions and directions that can be used to produce distributions, and we need to calibrate the energy of each event. Even more importantly, we must be sure that the only signals present in the data are the three for which we are doing the fits—we have implicitly assumed that the backgrounds are neg-
ligible. To accomplish this, we apply cuts to the data to eliminate backgrounds and we must ultimately demonstrate that any residual backgrounds are negligible.

The second signal extraction prerequisite is that the distributions used in the fitting process must be good representations of the detector’s true response. In other words, we must build a model of the detector’s response to the three signals which can be used to generate the pdfs used in the fit. The model needs to reproduce the response at all places in the detector, for all neutrino directions, for all neutrino energies, and for all times. The last requirement is necessary because the detector’s response changes over time due to things like failed PMT’s or electronics channels.

The analysis we describe here therefore has three major components before the final fitting stage: the processing of data to remove backgrounds, the building of a model to fit the data, and the demonstration that the residual backgrounds are small enough to use the signal-only model in the fits.

4.1 Data Processing

We recorded the data set used in this analysis between November 2, 1999, and January 15, 2000. Roughly 40% of the time during this period was taken up either by calibration source runs or downtime caused by mine power outages. Of the remaining good data, we selected runs to analyze based on criteria which were ‘blind’ to the data itself—whether enough channels were live, whether calibration sources were present, whether water assays were being run, etc. After passing this run selection stage, no further run removal was allowed from the data set, and the final total livetime amounted to 241 days. Approximately 30% of the data was put aside to serve as a blind test of statistical bias. As no significant differences were found between this sample and the other 70%, all subsequent discussion here refers to the full data set.

During this time, the primary trigger threshold was set to fire on a \(~100\) ns coincidence of 18 PMT’s each exceeding a channel threshold of \(\sim 1/4\) photoelectron. This trigger threshold corresponds to an energy of roughly 2 MeV. The trigger reaches 100% efficiency at 23 hit PMTs. In addition to the 100 ns coincidence, we ran simultaneously with other triggers, such as a pre-scaled (1:1000) lower threshold (11 PMTs) trigger, a trigger on PMT pulse height sums, and a pulsed (random) trigger.

The raw data set is far from the clean distributions shown in Figure 2. In particular, the data is contaminated by instrumental backgrounds arising primarily from PMT light emission (‘flasher PMTs’), static discharges in the neck of the acrylic vessel, or electronic pickup. Although these instrumental backgrounds are very distinct from the neutrino signal, they occur at far higher rates: flasher events, for example, occur roughly once each minute compared to the five to ten neutrino events we expect each day. We therefore developed a suite of low level cuts designed to remove instrumental backgrounds while losing a minimum of neutrino events. These cuts were applied before any reconstruction of the data was done, and used only primitive information such as the PMT charge distributions, the raw and calibrated time distributions, hits in veto tubes, and event-to-event time correlations. Figure 3 shows the effects of the progressive application of these instrumental background cuts to the raw data set, illustrating the multiple orders of magnitude reduction in the overall number of events.

In any case in which such a large reduction is obtained, the obvious question is what is the consequent reduction in good events—how much acceptance loss have we incurred by applying cuts which remove more than three orders of magnitude of the instrumental backgrounds? To measure this loss, we
Figure 3. Effects of progressive application of instrumental background cuts.

Figure 4. Acceptance loss from low level instrumental background cuts, measured with calibration sources.

used triggered calibration sources which provided both samples of Cerenkov events and isotropic light events, and applied the same cuts to the source data as to the neutrino data. Figure 6 shows the acceptance loss as a function of the number of hit PMTs, for $^{16}\text{N}$, $^{8}\text{Li}$, and laser data. Although there is evidence of a bias at high energies (high number of hit PMTs), the overall scale of the loss is very small, $\sim 0.5\%$.

For events passing this first stage, we reconstructed the vertex position and direction of the particle using the calibrated times and positions of the hit PMTs. The reconstruction algorithm begins with maximum likelihood fits using only PMT times, seeded by positions fixed to a grid throughout the detector volume. The best fit vertex from this grid-seeded procedure is then used as a seed for a second level of fitting which uses both the PMT times and their angular distribution to simultaneously fit both the position and the direction of the event. The fitting process includes cuts on angular figures-of-merit which test both the quality of the fit and the hypothesis that the event is a single Cerenkov electron. Figure 5 shows the vertex resolution for electrons produced by the $^{8}\text{Li}$ source, which provides a localized ($\sim 5$ cm) set of electrons with a broad spectrum of energies. At $^{16}\text{N}$ energies, the vertex resolution is 16 cm and the angular resolution is $26.7^\circ$.

For each event surviving the reconstruction stage, we assigned an energy based on the hypothesis that the event was a single Cerenkov electron. While the number of hit PMTs by itself is directly related to the event energy, it must be corrected for the number of live channels online when the event was recorded, any change in the overall detector gain with time, and the optical effects of the intervening media between the Cerenkov production point (the event position) and the photon detection points (the hit PMTs). The optical corrections were calculated using in-situ measurements of the detector’s optical properties (attenuation lengths, PMT angular responses, etc.) and account for both the vertex position and the event direction. To minimize uncertainties associated with late
hits (reflections, scattering, noise), the optical corrections use only prompt (in-time) photons by requiring the fitted time residuals of the PMT hits to be within a narrow window around $\Delta t = 0$ ns.

Figure 6 shows the calibrated response of the detector to $^{16}$N data. In Figure 6a we see the energy distributions for data taken with the source at the center and at $R = 465$ cm. The only corrections made here are for the number of live channels online, and therefore the shift in the mean of the two distributions is due to the different optical response at the two positions. Figure 6b demonstrates how the two distributions coincide once the optical corrections are applied.

With the event positions and directions fit and the energy calibrated, we passed the data through a final stage of cuts aimed at ensuring that the remaining events were consistent with Cerenkov light. We defined Cerenkov light with two orthogonal cuts: one which tests the narrowness of the timing distribution, and one which tests the angular distribution of PMT hits. The former is done by cutting on the ratio of prompt (in-time) hits to the total number of hits in the event, and the latter by using the average angular distance between hit PMTs.

Figure 7 shows three data sets distributed in these two variables: data tagged by the low level instrumental background cuts (triangles), Cerenkov data from the $^{16}$N source (open circles), and neutrino data (closed circles). The box used to define Cerenkov light is also shown, illustrating how both the source data and the neutrino data lie inside, while the instrumental backgrounds stay well outside. We required all data in the final signal sample to lie within the box shown in Figure 7.

The reconstruction quality cuts and the ‘Cerenkov box’ cuts contribute to the overall acceptance loss, and we measured the scale of this loss along with the losses by the low level instrumental background cuts by using Cerenkov and laser calibration sources. The systematic uncertainties on these losses are associated with the calibration sources themselves (source reflectivity and shadowing), the low level electronic calibrations (for example, ADC pedestals), and changes in the detector over time. Using the calibration source data, we find that the total loss for all cuts is $1.4^{+0.7}_{-0.6}$%.

For the final signal sample, we further restricted events to be within a fiducial volume of 550 cm and have a kinetic energy $T > 6.75$ MeV. The fiducial volume restriction minimizes backgrounds associated with the acrylic vessel, light water, and PMTs, while the energy threshold reduces radioactive backgrounds and neutron events in the final signal sample. Table 1 summarizes the data processing, from the total number of

| Analysis step                  | No. of events |
|-------------------------------|---------------|
| Total event triggers          | 355 320 964   |
| Neutrino data triggers        | 143 756 178   |
| $N_{\text{hit}} \geq 30$      | 6 372 899     |
| Inst. bkgnd cuts              | 1 842 491     |
| Muon followers                | 1 809 979     |
| Cerenkov box cuts             | 923 717       |
| Fiducial volume cut           | 17 884        |
| Threshold cut                 | 1 169         |
| Total events                  | 1 169         |
events in the raw data set to the final sample of 1169 events. The table also includes the effects of cuts which remove the spallation products of cosmic ray muons. These cuts remove all events within 20 s of a parent muon. At this stage of the analysis, we have a data set which has been reconstructed and calibrated, and has had the majority of backgrounds removed. However, before fitting the resulting distributions, we still need to build a model of the detector’s response, and demonstrate that the background removal has been successful enough that we can perform the fits using a signal-only model.

4.2 Model Building

The model of detector response we have used in this analysis takes as its inputs the physics of electron and $\gamma$ interactions in matter, the geometry of the detector, the behavior of the front-end data acquisition electronics and trigger, and—most importantly—the same measured optical parameters used in the energy calibration described in the previous section. The model is a Monte Carlo simulation, which combines these inputs as well as the state of the detector as a function of time (the number of channels online, the overall energy scale determined by the $^{16}$N source, etc.) to produce a predicted response function for all event positions, directions, and energies. This response function is what we use to create the pdfs which are ultimately used to fit the data.

To ensure that the model is correct, we tested it against Cerenkov data representative of the neutrinos we are trying to detect, for as many positions, directions, and energies as possible. The degree to which the model does not correctly reproduce the various measurements sets the scale for the systematic uncertainties on the predicted response function.

Figure 8 depicts the positions inside the D$_2$O and H$_2$O for some of the $^{16}$N scans. For the dependence on energy of the energy response, we compared $^{16}$N data to pT data (6.13 MeV $\gamma$’s to 19.8 MeV $\gamma$’s). For the dependence on position and direction we compared different source positions and different sources—the Cf neutron source, for example, provides a very different event position distri-
Figure 9. Differences between predicted energy response and measured response for different sources as a function of time. In addition to the $^{16}$N source, are a 19.8 MeV $\gamma$ from the pT source and a 6.25 MeV $\gamma$ from the neutrons produced by the Cf source.
bution than the $^{16}$N source does, and samples many more positions within the volume. We also tested the dependence on data rate by varying the rates for some of the calibration sources. Figure 9 summarizes the differences between the predicted energy response and the measured response for various sources as a function of time. The overall systematic uncertainty on the energy scale determined through these measurements is 1.4%.

We performed the same kinds of tests for the prediction of the reconstruction accuracy, and Figure 10 compares the vertex resolution measured with the $^{16}$N source at various positions to the model prediction. There is a small systematic shift ($\sim 1$ cm) between the two, but otherwise the model tracks the data well. The model prediction of the angular resolution agrees very well with the measurements made with the $^{16}$N source, and has a negligible contribution to the overall systematic uncertainty on the measured fluxes.

4.3 Backgrounds

We are not quite ready yet to fit for the signal amplitudes, because we must still demonstrate that the data is free enough from backgrounds to justify the use of a model which contains only signal distributions. There are three classes of background: the instrumental backgrounds discussed in Section 4.1, high energy $\gamma$ rays from the phototube support sphere and cavity walls, and low energy backgrounds from radioactivity both within and without the D$_2$O volume.

To measure the residual instrumental backgrounds, we used the ‘Cerenkov box’ cuts described earlier. The low level cuts aimed at reducing the instrumental backgrounds and the higher level Cerenkov box cuts are independent and orthogonal—and so the fraction of the instrumental backgrounds which lie inside the Cerenkov box is the same whether the instrumental background cuts identify the events or not. We therefore used the fraction of identified instrumental backgrounds which lie inside the box and multiplied it by the number of events in the ‘clean’ data sample which lie outside. From this, we found the fraction of the clean data sample inside the Cerenkov box which may be due to instrumental backgrounds missed by the low level cuts. As a fraction of the final CC data sample, this is $<0.2\%$, small enough to ignore in the fit for signals.

The determination of the high energy backgrounds was similar in principle, but here we had at our disposal calibration sources which provide triggered samples of high energy $\gamma$ rays. The $^{16}$N source is nearly ideal for this measurement, as it acts as a triggered ‘point source’ of events which—with the exception of energy spectrum—look exactly like the background we are trying to measure. To use this source to measure the backgrounds, we deployed it near where the backgrounds originate—out (and beyond) the detector’s active volume. We then measured the ratio of the number of inward-going $\gamma$ events reconstructing just inside the source position (the ‘monitoring’ box) to the number of events reconstructing inside the 550 cm fiducial volume. With the number of events in the final data sample which reconstruct inside the same (but now spherically symmetric) monitoring box, we determined the number of background events which lie inside the 550 cm volume by mul-
tiplying by the source-measured ratio. We explored systematic uncertainties by varying the monitoring box size, the deployment position, and by using Monte Carlo simulation to explore the variation of the leakage with energy. The final limit on this source of background measured in this way is < 0.8%.

Low energy backgrounds originate from several sources: radioactivity in the heavy water, the acrylic, the light water, and the PMTs. Their typical energy is \( \sim 2 \text{ MeV} \), and our energy threshold of 6.75 MeV is high enough that the leakage can only come from the tail of the background energy spectrum. The small fiducial volume of 550 cm also greatly restricts the number of events from the PMTs, light water, and acrylic. To estimate the number of events from low energy backgrounds which leak above the signal energy threshold or inside the fiducial volume, we used a combination of radioassays, encapsulated U and Th calibration sources, and Monte Carlo simulation. Figure 11 shows that the radioactivity in the heavy water—as determined by radioassays—is well below the original target values. At these levels, simulation shows that the tail of the backgrounds above our energy threshold is negligible. In the light water, assays also show that the backgrounds are near or below target levels, but because these levels are still relatively high, we deployed calibration sources to measure the fraction that reconstruc\(\ldots\)struct within the 550 cm fiducial volume. Of the external sources of background, by far the largest is the radioactivity in the PMTs themselves. With calibration sources placed near the PMT sphere, we measured an upper limit on the leakage of the PMT radioactivity of < 0.2% of the final CC rate.

5 Results and Implications

We now have satisfied all the pre-requisites for doing a signal extraction: we have a clean data set in which the backgrounds are low enough to justify a signal-only fit, and a model which correctly predicts the response function of the detector as measured by calibration sources. For the neutrino spectrum input to the model, we use an undistorted \( ^8\text{B} \) shape.

The maximum likelihood fit to the 1169 events in our sample gives us 975.4±39.7 CC events, 106.1±15.2 ES events, and 87.5±24.7 neutron events, where the uncertainties given are statistical only. Figure 12 shows the best fit to the distribution of event directions with respect to the Sun. The elastic scattering peak can clearly be seen, but with the available statistics, only a hint of the slope of the CC electrons.

To convert the CC and ES event numbers into fluxes, we need to correct for the acceptance of the cuts, the energy threshold, and the fiducial volume restriction. We then need to normalize by the interaction cross sections and the number of deuterons and electrons inside the fiducial volume. For the CC cross section, we use the calculation of Butler et al.\[16\], and do not include any radiative corrections. The radiative corrections may serve to increase the cross section by up to a few percent\[17\], and therefore decrease the measured value of the flux (and ultimately increase the significance of any difference between the CC and ES fluxes). We also include small correc-
tions due to the isotopic abundances of $^{17}$O and $^{18}$O, upon which CC reactions can also occur. Finally, we normalize by the overall livetime.

Table 2 lists the systematic uncertainties on the flux measurements. The dominant uncertainties arise from our lack of knowledge of the true response function of the detector. As described above, we characterize the scale of the uncertainties on the model by comparing the model predictions to measurements made with calibration sources, for example the 1.4% on the energy scale. To derive the uncertainties on the fluxes shown in Table 2, we varied the model predictions over the range of the uncertainties and repeated the analysis. In some cases this resulted in a larger uncertainty on the flux measurement—the 1.4% uncertainty on the energy scale becomes a $\sim 6\%$ uncertainty on the flux derived from the CC rate, for example.

In addition to the measurement of the systematic uncertainties, we have explored the systematic behavior of our results under

Table 2. Systematic uncertainties on fluxes.

| Error source                  | CC error (percent) | ES error (per cent) |
|-------------------------------|--------------------|---------------------|
| Energy scale                  | -5.2, +6.1         | -3.5, +5.4          |
| Energy resolution             | ±0.5               | ±0.3                |
| En. non-linearity             | ±0.5               | ±0.4                |
| Vertex accuracy               | ±3.1               | ±3.3                |
| Vertex resolution             | ±0.7               | ±0.4                |
| Angular resolution            | ±0.5               | ±2.2                |
| High energy $\gamma$'s       | -0.8, +0.0         | -1.9, +0.0          |
| Low energy bkgrnd             | -0.2, +0.0         | -0.2, +0.0          |
| Inst. bkgrnd                  | -0.2, +0.0         | -0.6, +0.0          |
| Trigger efficiency            | 0.0                | 0.0                 |
| Live time                     | ±0.1               | ±0.1                |
| Cut acceptance                | -0.6, +0.7         | -0.6, +0.7          |
| Earth orbit ecc.              | ±0.1               | ±0.1                |
| $^{17}$O, $^{18}$O            | 0.0                | 0.0                 |
| Exp. uncertainty              | -6.2, +7.0         | -5.7, +6.8          |
| Cross section                 | 3.0                | 0.5                 |
| Solar Model                   | -16, +20           | -16, +20            |
many different analysis approaches: for example, comparing different suites of low level cuts, reconstruction algorithms, Cerenkov box cuts, and choices of fiducial volume. We have also compared the results we get using the total number of hit PMTs as the measure of energy scale (thus changing the sensitivity to the knowledge of the late light distribution) to the results from the energy calibration described above. Lastly, we have performed fits using an analytical (as opposed to Monte Carlo) model of the detector response. In all cases, the results from these alternative approaches agree with the fluxes presented here to well within the systematic uncertainties quantified in Table 2.

Converting the fit numbers to fluxes and including the systematic uncertainties listed in Table 2, we find that the flux of neutrinos inferred from the ES reaction (assuming no flavor transformation) is

\[ \phi^{\text{ES}}_{\text{SNO}}(\nu_e) = 2.39 \pm 0.34 \text{(stat.)} \]

\[ \pm^{+0.16}_{-0.14} \text{(sys.)} \times 10^6 \text{ cm}^{-2}\text{s}^{-1} \]

and the flux of \(^8\text{B}\) \(\nu_e\)'s measured by the CC reaction is

\[ \phi^{\text{CC}}_{\text{SNO}}(\nu_e) = 1.75 \pm 0.07 \text{(stat.)} \pm^{+0.12}_{-0.11} \text{(sys.)} \]

\[ \pm 0.05 \text{(theor.)} \times 10^6 \text{ cm}^{-2}\text{s}^{-1} \]

where the theoretical uncertainty comes from the uncertainty in the CC cross section \[\phi\](\nu_e). The difference between these two numbers is 1.6\(\sigma\), assuming that the systematic errors are distributed normally. The low significance of this result is driven mainly by the large statistical errors on the ES measurement. However, the Super-Kamiokande collaboration has measured the flux with the ES reaction to high precision \[\phi\](\nu_e) and finds

\[ \phi^{\text{ES}}_{\text{SK}}(\nu_e) = 2.32 \pm 0.03 \text{(stat.)} \pm^{+0.08}_{-0.07} \text{(sys.)} \]

\[ \times 10^6 \text{ cm}^{-2}\text{s}^{-1}. \] (2)

The difference between SNO’s measurement using the CC reaction (sensitive only to \(\nu_e\)’s) and Super-Kamiokande’s measurement using the ES reaction (sensitive to \(\nu_\mu\)’s and \(\nu_\tau\)’s as well as \(\nu_\tau\)'s in the ratio of 1./6.5) is 3.3\(\sigma\). This difference is therefore evidence of an active, non-\(\nu_e\) component to the solar \(^8\text{B}\) neutrino flux.

Figure 13 summarizes the situation for all published solar neutrino experiments, including SNO. The points are plotted as ratios of the measured fluxes to the Standard Solar Model predictions of Bahcall, Pinsonneault and Basu (BPB01), for the energy threshold used in each experiment. Here we can see the 3.3\(\sigma\) difference between the SNO and Super-Kamiokande measurements as well as the poor statistical accuracy of the SNO ES. Also plotted in Figure 13 is the total flux of all \(^8\text{B}\) neutrinos using the SNO CC measurement and the Super-Kamiokande ES measurement:

\[ \phi(\nu_e) = 5.44 \pm 0.99 \times 10^6 \text{ cm}^{-2}\text{s}^{-1}. \]

We see in the figure that the agreement between the measurement and the model prediction is very good.

Figure 13 also shows that the differences in the thresholds for the SNO and Super-Kamiokande measurements allows for the possibility that there is some spectral distortion which could be causing the difference. Such a spectral distortion could occur if, for example, the oscillation were into a sterile neutrino. To look for such an effect, we can...
first examine the spectrum of recoil electrons created by the CC interactions relative to the prediction for an undistorted $^8$B spectrum. We derive such a spectrum by re-fitting the data energy bin-by-energy bin, without using the pdf for the CC energy spectrum. Figure 14 shows the ratio of the spectrum derived this way to the standard solar model prediction. The dominant systematic uncertainties are indicated by the horizontal lines on the plot. Figure 14 shows that there is no large distortion in the expected spectrum.

We can also eliminate the possibility of a spectral distortion leading to the difference in the SNO CC and Super-Kamiokande ES measurements by comparing the two measurements for the same neutrino energy. As described by Fogli et al., this can be done by using different recoil energy thresholds for the SNO and Super-Kamiokande measurement. For these ‘matched’ thresholds ($\sim$ 8.5 MeV for the Super-Kamiokande measurement compared to SNO’s 6.75 MeV) we still get a difference of 3.1σ. This measurement is independent of both the standard solar model flux prediction and the predicted shape of the $^8$B spectrum—we need only know that the Sun produces $\nu_e$’s to see that there is a change to other active flavors.

6 Future and Conclusions

SNO’s current and future data sets will provide many more interesting measurements. We are now analyzing the pure $\text{D}_2\text{O}$ data in order to make a the measurement of the NC rate. The NC measurement should give us a confirmation of the CC-ES result, a higher precision measurement of the total $^8$B flux, and a higher significance for the excess of non-$\nu_e$ flavors (because we will be comparing a $\nu_e$ flux of $1.75 \times 10^6\text{cm}^{-2}\text{s}^{-1}$ to $\sim 5 \times 10^6\text{cm}^{-2}\text{s}^{-1}$ rather than to $\sim 2.3 \times 10^6\text{cm}^{-2}\text{s}^{-1}$). We are also analyzing the data in day and night bins, to determine whether any asymmetry is present (which would indicate that matter oscillations are the cause of
the flavor change as well as better restrict the allowed regions in the \((\tan^2 \theta, \Delta m^2)\) plane. In addition, we are working on an analysis which includes the hep neutrinos.

Beyond the pure \(D_2O\) data, we will also have the salt data set, which should provide us with an even better NC measurement, as well as new measurements of the other fluxes as well. Non-solar neutrino physics analyses are underway as well—looking at atmospheric neutrinos, anti-neutrinos (for which SNO has an exclusive coincidence tag), and supernova searches.

SNO's first results, in combination with the Super-Kamiokande collaboration’s measurements, provide direct evidence that solar neutrinos undergo flavor change on their way from the Sun to the Earth. They also show that the Standard Solar Model prediction of the \(^8\)B flux is correct within the uncertainties of both the prediction and the measurement. We expect many more interesting measurements to come out of SNO for a long time to come.

Acknowledgments

This research was supported by the Natural Sciences and Engineering Research Council of Canada, Industry Canada, National Research Council of Canada, Northern Ontario Heritage Fund Corporation and the Province of Ontario, the United States Department of Energy, and in the United Kingdom by the Science and Engineering Research Council and the Particle Physics and Astronomy Research Council. Further support was provided by INCO, Ltd., Atomic Energy of Canada Limited (AECL), Agra-Monenco, Canatom, Canadian Microelectronics Corporation, AT&T Microelectronics, Northern Telecom and British Nuclear Fuels, Ltd. The heavy water was loaned by AECL with the cooperation of Ontario Power Generation.

References

1. B.T. Cleveland et al., Astrophys. J. 496, 505 (1998).
2. K.S. Hirata et al., Phys. Rev. Lett. 65, 1297 (1990); K.S. Hirata et al., Phys. Rev. D 44, 2241 (1991), 45 2170E (1992); Y. Fukuda et al., Phys. Rev. Lett. 77, 1683 (1996).
3. J.N. Abdurashitov et al., Phys. Rev. C 60, 055801, (1999).
4. W. Hampel et al., Phys. Lett. B 447, 127 (1999).
5. S. Fukuda et al., Phys. Rev. Lett. 86, 5651 (2001).
6. M. Altmann et al., Phys. Lett. B 490, 16 (2000).
7. J.N. Bahcall, M. H. Pinsonneault, and S. Basu, astro-ph/0010346 v2. The reference \(^8\)B neutrino flux is \(5.05 \times 10^6 \text{cm}^{-2}\text{s}^{-1}\).
8. A.S. Brun, S. Turck-Chièze, and J.P. Zahn, Astrophys. J. 525, 1032 (1999); S. Turck-Chièze et al., Ap. J. Lett., v. 555 July 1, 2001.
9. N.Hata, S. Bludman, and P. Langacker, Phys. Rev. D 49, 3622 (1994)
10. K.M. Heeger and R.G.H. Robertson, Phys. Rev. Lett. 77, 3720 (1996)
11. Q.R. Ahmad et al., Phys. Rev. Lett. 87, 071301 (2001)
12. The SNO Collaboration, Nucl. Instr. and Meth. A449, 172 (2000).
13. A.W.P. Poon et al., Nucl. Instr. and Meth. A452, 115, (2000).
14. J.F. Beacom and P. Vogel, hep-ph/9903554, Phys. Rev. Lett. 83, 5222 (1999).
15. C.E. Ortiz et al., Phys. Rev. Lett. 85, 2909 (2000).
16. S. Nakamura, T. Sato, V. Gudkov, and K. Kubodera, Phys. Rev. C 63, 034617 (2001); M. Butler, J.-W. Chen, and X. Kong, Phys. Rev. C 63, 035501 (2001); G. ’t Hooft, Phys. Lett. 37B 195 (1971). The Butler et al. cross section with
$L_{I,A} = 5.6 \text{ fm}^3$ is used.

17. I. S. Towner, J. Beacom, and S. Parke, private communication; I. S. Towner, Phys. Rev. C 58 1288 (1998), J. Beacom and S. Parke hep-ph/0106128; J.N. Bahcall, M. Kamionkowski, and A. Sirlin, Phys. Rev. D 51 6146 (1995).

18. Given the limit set for the hep flux by Ref. 5, the effects of the hep contribution may increase this difference by a few percent.

19. G. L. Fogli, E. Lisi, A. Palazzo, and F.L. Villante Phys. Rev. D 63, 113016 (2001); F.L. Villante, G. Fiorentini and E. Lisi Phys. Rev. D 59 013006 (1999).