Signal Extraction of the Solar Neutrino Fluxes with the Sudbury Neutrino Observatory's Neutral Current Detectors

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Introduction

The Sudbury Neutrino Observatory (SNO) is a real-time water Cherenkov detector using heavy water (D_2O) as its target medium [1]. It detects solar neutrinos via the following interactions:

$\nu_e + d \rightarrow p + p + e^-$	Charged current interactions (CC)
$\nu_x + d \rightarrow \nu_x + p + n$	Neutral current interactions (NC)
$\nu_x + e^- \rightarrow \nu_x + e^-$	Elastic scattering interactions (ES)

The electrons produced by the CC and ES interactions are observed by an array of ~9500 photomultiplier tubes (PMTs) that surround the heavy water. The neutrons produced by the NC interactions are detected via different reactions in the different phases of SNO's operation. In the final phase the Neutral-Current Detection (NCD) Array, an array of ultra-clean proportional counters filled with ^{3}He, was deployed in the heavy water [2]. The ^{3}He counters detect neutrons via the reaction:

$$n + {}^3He \rightarrow p + t + 764\ keV$$

Some neutrons are captured by deuterium producing a 6.25 MeV gamma detected in the PMT array. Signal extraction involves determining the CC, ES, and NC fluxes from the observable data. For this analysis we have improved the handling of the systematic errors and had to handle signals from both the PMT and NCD arrays. Three independent codes were developed and the results were compared in order to verify these new methods worked as expected.

Observables, Signals, and PDFs

The NCD events consist primarily of neutrons produced either by solar NC interactions or background radioactivity, and alpha particles from radioactive decays in the proportional counters themselves. Neutron/alpha separation is achieved by fitting the energy spectrum of the events in the range $0.4 < E_{NCD} < 1.4$ MeV. The probability distribution function (PDF) for neutrons is taken from neutron calibration data, while the PDF for alphas is determined from Monte Carlo simulation. In addition to neutrons and alpha events, two NCD counters showed evidence for instrumental background events not consistent with either alphas or neutrons. These strings were excluded from the analysis. Although we have no evidence for such events occurring on "good" strings, we conservatively included PDFs for them in the fit based upon their observed energy spectra in the excluded counters. We find that these events are highly covariant with the alpha event distributions, and allowing for their presence results in an ~2% systematic on the extracted number of neutrons.

The proportional counters cannot distinguish "NC" neutrons produced by solar neutrino interactions from neutrons produced by radioactive backgrounds such as photo-disintegration of deuterium. We therefore constrained the numbers of neutrons from radioactive backgrounds by including additional terms in the likelihood function to reflect external determinations of their rates. The rates of neutron backgrounds were allowed to vary in the signal extraction fits in accordance with these constraints.

There are two independent data streams:

PMT array observables:	NCD array observables:
Energy (E_{PMT})	Energy (E_{NCD})
Radial position (R)	
angle w.r.t. to the sun (θ_{sun})	

The PMT events consist almost entirely of events from CC and ES interactions, plus Cherenkov events from neutron captures on deuterium due to either NC or background neutrons. The fitted neutron rates in the PMT data were constrained to match the rates of NC and background neutrons in the NCD data stream, after scaling for the different detection efficiencies of the NCD and PMT array for each source of neutrons. The CC and ES fluxes are only observed in the PMT array, and to avoid assumptions on the neutrino production and propagation they are extracted separately as a function of reconstructed energy E_{PMT} in 13 energy bins above 6 MeV kinetic energy. Each bin except the highest was 0.5 MeV wide. For the PMT array events the signal PDFs were fully three dimensional PDFs in (E_{PMT},R,θ_{sun}) and were obtained from Monte Carlo simulation.

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A publication based on these results will be forthcoming in the next couple of weeks.

References:
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Likelihood Function

Extended likelihood functions are used to fit the PMT and NCD data. For NCD data the log likelihood function has the form:

$$\ln L_{NCD} = -\sum_{i=1}^{M^{NCD}} f_i^{NCD} S_i^{NCD} \phi_i + \sum_{j=1}^{N_{NCD}} \ln \sum_i^{M^{NCD}} f_i^{NCD} S_i^{NCD} \phi_i Q^i(E_{NCD})$$

where there are M^{NCD} NCD event classes (i=NC,alpha,...) and there are N^{NCD} events in the fit region 0.4-1.4 MeV. For the i'th event class, the conversion from flux to events is f^{NCD}, the fit flux is ϕ_i, the cut acceptance factor is S_i and the normalized probability density function is Q_i. The PMT likelihood has an identical form, except that the flux parameters now include 13 CC and 13 ES bin-by-bin fluxes in addition to the NC flux ϕ_{NC}, and the PDFs are now functions of (E_{PMT},R,θ_{sun}) instead of E_{NCD}. The combined log likelihood function is $\ln L_{combined} = \ln L_{NCD} + \ln L_{PMT}$.

Systematic Uncertainties

Systematic uncertainties in the flux extraction include uncertainties in:

detector response parameters	uncertainties in Monte Carlo inputs
PMT and NCD energy scales	Po and Bi distributions in the NCD alpha event simulation
PMT reconstruction	uncertainties in background activities
neutron detection efficiencies	instrumental backgrounds

We associate a nuisance parameter with each systematic uncertainty, and for each systematic we use data independent from the neutrino data we are fitting to assign prior estimates of the values and uncertainties for each nuisance parameter. In the "floating systematics" approach, we write down a joint likelihood function for the neutrino fluxes and the systematic parameters:

$$L = L_{combined}(NC, CC_1, \ldots, CC_{13}, ES_1, \ldots, ES_{13} | \alpha_i) L(\alpha_i)$$

Here the first term in the product is the extended likelihood function for the PMT and NCD data as a function of the 27 neutrino flux parameters (1 NC + 13 CC bins + 13 ES bins), given assumed values for the systematic nuisance parameters α_j. The second term, referred to as the "constraint term", reflects our knowledge of these nuisance parameters from data external to the signal extraction fit.

In the "floating systematics" approach to systematic error propagation, we allow the values of all 27 flux parameters and all nuisance parameters to vary in the fit. This approach has the advantages that it allows the fit to the neutrino data itself to provide additional constraints on nuisance parameters, easily handles non-Gaussian constraints on systematics, and provides a completely self-consistent way to treat flux parameters and systematics. The constraint term prevents the nuisance parameters from fitting very far from their values we assign to them based on external calibrations.

An alternate approach to floating systematics is to fit the data with a given systematic parameter fixed at its nominal value, then to shift the value by $\pm 1\sigma$ and to refit the data, taking the resulting change in the extracted fluxes to be the contribution from that systematic to the flux uncertainties. This approach works well when the systematics are poorly constrained by the data itself, and are uncorrelated, although it does ignore correlations and will often tend to overestimate the uncertainties. This was the approach taken to systematic error propagation in SNO's previous analyses.

The three signal extraction methods used for the NCD analysis, and described in the following panes, differ in which of the systematic parameters are propagated using the floating systematics method.

Maximum Likelihood Fit

Our simplest signal extraction technique was to do a straightforward maximum likelihood fit to the data while floating most important NCD systematic nuisance parameters (backgrounds, neutron capture efficiency, instrumental background PDFs, and systematics on the Monte Carlo prediction of the alpha energy spectrum, parameterized by re-weighting functions corresponding to 8 uncertain inputs of the Monte Carlo.) All other NCD systematics, and all PMT systematics, were propagated by the shift-and-refit method.

Maximum Likelihood Fit with Random Sampling of Systematics

A second approach was to perform this maximum likelihood fit many times to the data, choosing different random values for the nuisance parameters for each fit. Most important NCD systematics were allowed to vary as free parameters in the fit as above. Other systematics were fixed in the fit, but were assigned random values drawn from their external constraint distributions. For example, with a PMT energy scale uncertainty of 1.1%, each fit was done with a different assumed value for the energy scale drawn from a Gaussian with RMS width of 1.1%. Each individual fit yields a different value for each neutrino flux. Each set of fitted flux values was then re-weighted in proportion to the best-fit likelihood from its fit. This method approximates the effects of floating all systematics by effectively doing a Monte Carlo integration over the nuisance parameters and using the best-fit likelihood to re-weight each trial in accordance with the overall joint likelihood for the neutrino data and the external constraints. This "statistical sampling" method achieves most of the benefits of floating systematics, although it neglects correlations between statistical and systematic uncertainties.

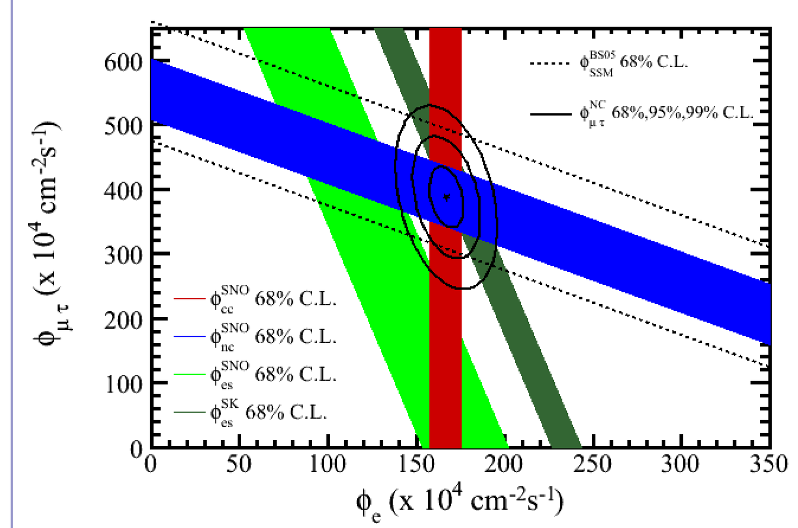
Markov Chain Monte Carlo

The primary signal extraction method for SNO's NCD-phase analysis is a Markov Chain Monte Carlo fitter. In this approach, all systematics are fully floated in the fitting procedure. Rather than attempting to maximize the likelihood, the Metropolis-Hastings algorithm [3,4] is instead used to randomly sample points from the joint likelihood of the 27 flux and 35 nuisance parameters. The PDFs for all signals are rebuilt at each step of the Markov Chain in order to account for variations in the PDF shape as nuisance parameters change. The end result of the Markov Chain procedure is a multidimensional posterior distribution for all flux and nuisance parameters, and the procedure itself can be usefully understood as a Bayesian determination in which the flux parameters are assigned uniform priors while the systematic nuisance parameters are assigned priors based upon calibrations determined independently of the neutrino data set itself. For each flux we report the peak of its 1D posterior distribution, marginalizing over all other parameters, as well as upper and lower uncertainties from a two-sided Gaussian fit to the posterior distribution.

Preliminary Results

All three signal extraction procedures gave consistent results for the CC, NC, and ES fluxes. The fitted values from the Markov Chain Monte Carlo method, in units of 10^6 neutrinos/cm^2/s, are:

The CC and NC fluxes are consistent with previous SNO measurements. The ES result is ~2.2σ lower than Super-Kamiokande's previous measurement. There is no indication that this is anything but a statistical fluctuation. The following distributions compare the NCD energy spectrum and the PMT energy, radial, and angular distributions of the data to the fitted PDFs.



PRELIMINARY

$$\phi_{NC} = 5.54^{+0.33}_{-0.31}(stat.)^{+0.36}_{-0.34}(sys.)$$
$$\phi_{CC} = 1.67^{+0.05}_{-0.04}(stat.)^{+0.07}_{-0.08}(sys.)$$
$$\phi_{ES} = 1.77^{+0.24}_{-0.21}(stat.)^{+0.09}_{-0.10}(sys.)$$

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