HOWTO use the SNO NCD Flux Results

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1 Introduction

This document provides technical details about the data presented in SNO's NCD flux publication **An Independent Measurement of the Total Active ^{8}B Solar Neutrino Flux Using an Array of ^{3}He Proportional Counters at the Sudbury Neutrino Observatory** [1]. It describes how SNO uses the data in this publication to produce its own MSW contour plots; as well as how someone can combine the SNO data with other experiments.

2 Differences with the previous SNO analyses

In the D_2O phase, the SNO oscillation analysis [2] compared the expected summed energy spectrum (CC + NC + ES + bkgd events) at each point in the MSW parameter space with the summed energy spectrum from the SNO data. Details of the D_2O phase analysis can be found in [3]. For the salt phase data analysis [4], SNO used the different event isotropy, radial and angular distributions for neutron capture events to separate the NC events from CC and ES events without any assumptions about the shapes of the CC or ES energy spectra. SNO thus extracted the CC energy spectrum and used the extracted spectrum to fit oscillation models and determine oscillation parameters. Details of the salt phase analysis can be found in [4].

In the first publication of results from the NCD phase *only* the integral CC, ES and NC fluxes were used to make oscillation contour plots. See Figure 2(a) of Reference [1]. For now, not using the shape of the energy spectrum ignores some information. For the first SNO NCD analysis, the extracted fluxes have no energy constraint and benefits from the uncorrelated nature of the measurement of the NC flux with the PMTs and the array of ^{3}He proportional counters (NCDs). Both PMT and NCD data were used to extract fluxes that were used in the oscillation analysis. More advanced MSW analyses are being developed that will jointly fit multiple phases of SNO data, using all available information - isotropy, extracted energy spectra, day-night measurements, as well as position and direction - in a joint maximum likelihood fit.

2.1 Input to the MSW fit - NCD Phase

We used the latest BS05(OP) [5] Standard Solar Model (SSM) that agrees best with helioseismology. For the combined solar analysis, the yield tables for the D_2O and salt papers, as well as the newest SK-I [6] and Borexino [7], were also generated with the newest BP05(OP) solar model. The shape of the ^{8}B energy spectrum is taken from Winter *et al* [8]. The solar model fluxes and their correlations were applied to the interpretation of all three SNO phases, the newest SK-I and Borexino data, and data from the Ga and Cl radiochemical experiments [9, 10].

The mean fluxes used and their statistical errors for the NCD phase are (in unit of $10^6\text{cm}^{-2}\text{s}^{-1}$):

$$\begin{aligned}
\phi_{CC}^{\text{NCD}} &= 1.669 \pm 0.047 \\
\phi_{ES}^{\text{NCD}} &= 1.768 \pm 0.227 \\
\phi_{NC}^{\text{NCD}} &= 5.543 \pm 0.317
\end{aligned}$$

The statistical correlation matrix is given in Table 1. The mean values for the fluxes together with their statistical errors and correlations can be used to build the statistical covariance matrix for the NCD phase.

2.2 Correlation between Fluxes for the NCD Publication

The breakdown of the experimental systematic errors for the NCD phase is tabulated in Table 2. For the NCD data samples, the correlation between fluxes for each systematic uncertainty are summarized in Table 3.

NCD	CC	ES	NC
CC	1.0000	0.2376	-0.1923
ES	0.2376	1.0000	0.0171
NC	-0.1923	0.0171	1.0000

Table 1: Statistical correlation matrix for the first SNO NCD flux publication [1].

Source of systematic	NC	CC	ES
PMT energy scale	± 0.6	± 2.7	± 3.6
PMT energy resolution	± 0.1	± 0.1	± 0.3
PMT radial scaling	± 0.1	± 2.7	± 2.7
PMT angular resolution	± 0.1	± 0.2	± 2.2
PMT radial energy dep.	± 0.0	± 0.9	± 0.9
Background neutron	± 2.3	± 0.6	± 0.7
Neutron capture	± 3.3	± 0.4	± 0.5
Čerenkov/AV background	± 0.0	± 0.3	± 0.3
NCD instrumental	± 1.6	± 0.2	± 0.2
NCD energy scale	± 0.5	± 0.1	± 0.1
NCD energy resolution	± 2.7	± 0.3	± 0.3
NCD alpha syst	± 2.7	± 0.3	± 0.4
PMT data cleaning	± 0.0	± 0.3	± 0.3

Table 2: Relative systematic errors on the fluxes in percent (%) for the NCD phase from Table II of Reference [1]. Note that we use a detailed description of the SNO detector response to constrained the oscillation parameters when we need to evaluate the systematic errors associated with the energy scale and energy resolution. For simplicity we advise one to use a fixed uncertainty as quoted here because the difference between this approach and the one with uncertainties evaluated at each point in MSW parameter space is small and has little effect on the resulting contours plotted.

Using the systematic errors of Table 2 taken from the NCD publication and the information provided in Table 3, one can assemble the covariance matrix for each systematic. Then, to get the *total* covariance matrix for the CC, ES and NC fluxes, one simply adds all of the covariance matrices together:

$$\mathbf{V}_{\text{total}} = \mathbf{V}_{\text{stat}} + \mathbf{V}_{\text{syst},1} + \mathbf{V}_{\text{syst},2} + \mathbf{V}_{\text{syst},3} \dots \tag{1}$$

3 SNO χ^2

For the first NCD publication [1], there is one basic scenario in which neutrino oscillation is tested: two-neutrino (2ν) with two active states ν_e and ν_a, with $a = \mu + \tau$.

Having assembled the total covariance matrix $\mathbf{V_{total}}$ between the fluxes, the calculation of the χ^2 for the NCD fluxes alone is relatively easy. At each point in the MSW plane, the expected CC, ES and NC fluxes from the SSM above the analysis threshold of 6.0 MeV kinetic energy are calculated. As a function of the oscillation parameters Δm^2 and $\tan^2\theta$ the fraction of $\phi_{^8\mathrm{B}}$ is allowed to float.

The χ^2 is then easy to calculate. We define a vector:

$$\vec{v}[\phi(^8\mathrm{B})] = (\phi_{NC}^{\mathrm{NCD}} - \phi_{NC}^{\mathrm{MSW}}, \phi_{CC}^{\mathrm{NCD}} - \phi_{CC}^{\mathrm{MSW}}, \phi_{ES}^{\mathrm{NCD}} - \phi_{ES}^{\mathrm{MSW}}).$$

Then the χ^2 is given by:

$$\chi^2[\phi(^8\mathrm{B})] = \vec{v}^T \cdot (\mathbf{V_{total}})^{-1} \cdot \vec{v}\,. \tag{2}$$

Minimizing the χ^2 with respect to $\phi_{^8\mathrm{B}}$ at each point, we then draw χ^2 contours in the usual way. For the computation of the SNO-only contours of Figure 2(a), one will then need to add all SNO observables from the three phases of the experiment. Please refer to [3] and [4] for further information on the D_2O and salt phase data samples, respectively.

Source of systematic	$CC - ES$	$CC - NC$	$ES - NC$
PMT energy scale	+1	+1	+1
PMT energy resolution	+1	+1	+1
PMT radial scaling	+1	+1	+1
PMT angular resolution	−1	+1	−1
PMT radial energy dep.	+1	+1	+1
Background neutron	+1	+1	+1
Neutron capture	+1	+1	+1
Čerenkov/AV background	+1	+1	+1
NCD instrumental	+1	+1	+1
NCD energy scale	+1	+1	+1
NCD energy resolution	+1	+1	+1
NCD alpha syst	+1	+1	+1
PMT data cleaning	+1	0	0

Table 3: Values of the correlation coefficients between the fluxes for each source of systematic error. An entry of +1 indicates a 100% positive correlation; while -1 a 100% negative correlation. Note that the values of the correlation coefficients are not the ones obtained by the MCMC method, but reproduce well the general behavior of the flux variation with respect to the experimental systematic errors.

4 Correlations With Other Experiments

All SSM model uncertainty (^{8}B shape and cross-sections) are fully correlated between all solar experiments. The χ^2 calculated above from the NC, CC and ES fluxes can then be added into a global solar analysis as new experimental inputs. Correlated systematics with other experiments, such as cross-section uncertainties or uncertainties on the ^{8}B shape (which should be small for the NCD integral flux analysis) can then be accounted for in the usual way by including covariance terms between different experimental results [11].

Please note that in SNO's global analysis, while we use only average fluxes from the NCD phase, we still include day-night energy spectra from our D_2O and salt phases in the global fit. SNO is working at producing a day-night analysis for the NCD phase.

One thing we wish to comment upon are experimental correlations between SNO's results. There are in fact common systematic uncertainties, since it is the same detector. However, these correlations are not as large as one might expect. Proper treatment of experimental correlations requires a very detailed knowledge of the SNO detector, and since these correlations have little impact on the resulting MSW contours, we recommend that experimental correlations between SNO's data sets be ignored for the time being. A complete summary of the correlations through the experimental systematic uncertainties could be provided upon request [11].

5 Contact Persons

For more information about how SNO produces MSW contours from its data, you may contact the following individuals, who will forward your questions to the appropriate parties:

- Alain Bellerive (alainb@physics.carleton.ca)
- Mark Chen (mchen@queensu.ca)

A χ^2 map of the SNO MSW contours depicted in Figure 2(a) of Reference [1] can be found at:

`http://www.sno.phy.queensu.ca/sno/papers/ncd_chi2/`

References

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