Measurement of the $^8$B Solar Neutrino Flux in SNO+ with Very Low Backgrounds


(The SNO+ Collaboration)

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A measurement of the $^8$B solar neutrino flux has been made using a 69.2 kt-day dataset acquired with the SNO+ detector during its water commissioning phase. At energies above 6 MeV the dataset is an extremely pure sample of solar neutrino elastic scattering events, owing primarily to the detector’s deep location, allowing an accurate measurement with relatively little exposure. In that energy region the best fit background rate is $0.25_{-0.07}^{+0.09}$ events/kt-day, significantly lower than the measured solar neutrino event rate in that energy range, which is $1.03_{-0.12}^{+0.14}$ events/kt-day. Also using data
Neutrinos are produced in the core of the Sun through a variety of nuclear reactions. The $^8\text{B}$ $\beta^+$ decay ($Q \approx 18\text{ MeV}$), dominates the high-energy portion of the solar neutrino spectrum [1]. Pioneering measurements of the solar neutrino fluxes, including $^8\text{B}$, were made by the chlorine and gallium radiochemical experiments [2-5], and the first real-time measurement of solar neutrinos was made by the Kamiokande-II experiment [6]. The measurement of $^8\text{B}$ solar neutrinos by the Sudbury Neutrino Observatory (SNO), along with measurements of atmospheric and solar neutrinos from Super Kamiokande (Super-K), led to the resolution of the solar neutrino problem and the initial determination of solar neutrino mixing parameters [7-11]. After the first measurements from SNO and Super-K, further $^8\text{B}$ solar neutrino measurements have been made by the liquid scintillator detectors Borexino [12] and KamLAND [13]. These two experiments have also measured solar neutrinos from reactions other than $^8\text{B}$ [14-16].

Due to the depth and flat overburden at SNOLAB, SNO+ has an extremely low rate of cosmic-ray muons: roughly three per hour. At this rate it is practical to veto all events for a period of time after each muon (see Sec. VI) to reduce spallation backgrounds. As a result, the rate of backgrounds due to cosmogenic activation and spallation is extremely low.

This article presents the first solar neutrino results from the SNO+ experiment. The low level of backgrounds permits a measurement of the $^8\text{B}$ solar neutrino flux down to 5 MeV with the first 8 months of data. The analysis exercises many tools distinct from those used by the SNO Collaboration, including new precision modeling of the detector, energy and vertex reconstruction, instrumental background rejection, and a well understood level of intrinsic radioactive contamination in all detector components. These will be critical to the future sensitivity of SNO+ in searches for neutrinoless double beta decay and measurements of low-energy solar neutrinos [17].

Elastic scattering of electrons by neutrinos, $\nu_x + e^- \rightarrow \nu_x + e^-$ ($x = e, \mu, \tau$), can occur through either a neutral current interaction for neutrinos of all flavors, or a charged current interaction, for electron neutrinos only. The scattered electron’s direction is correlated with the direction of the incident neutrino, so recoil electrons from solar neutrino interactions will typically produce Cherenkov radiation that is directed away from the Sun. The analysis presented here exploits this correlation to measure the solar neutrino flux and spectrum.
IV. RECONSTRUCTION

For each detected or simulated event, the position, time, direction, and energy were reconstructed under the assumption that all light produced is Cherenkov radiation from an electron. The direction, time, and position were determined simultaneously through a likelihood fit based on the pattern and timing of the PMT signals in the event. The likelihood was determined using expected distributions of photon timing and angular spread, which are calculated using MC simulation. Only signals originating from well-calibrated channels were used in the fit.

Energy was determined separately using the position, time, direction, and the number of PMT signals in a prompt 18 ns window as inputs; the prompt time window mitigates the effect of PMT noise and of light that follows a difficult to model path between creation and detection. Using the inputs, the reconstruction algorithm then uses a combination of MC simulation and analytic calculation to estimate the event energy that is most likely to produce the observed number of PMT signals. The same reconstruction algorithms were used for both simulated and detected events.

V. CALIBRATION

Calibration data were taken with a deployed $^{16}$N source [23], which primarily produces a tagged 6.1 MeV $\gamma$-ray. These data are used for calibrating detector components and evaluating systematic uncertainties of reconstructed quantities.

The source position was controlled using a system of ropes to perform a 3-dimensional scan of the space inside the AV, and a 1-dimensional vertical scan in the region between the AV and the PMTs. For the purpose of evaluating systematics, the distributions of events in position, direction, and energy were fitted with response functions. The parameters from fits performed on data and MC simulation were compared to assign systematic uncertainties on each reconstructed quantity. Figure 1 shows comparisons between simulation and data for the reconstructed energy and direction of $^{16}$N events.

The 6.1 MeV $^{16}$N $\gamma$-ray typically Compton scatters in the detector to produce one or more electrons that reconstruct to energies peaking near 5 MeV. In addition to Compton scattering, energy deposition in the source container also produces a substantial tail at lower energies. This tail fades out below about 1.7 MeV due to the detector trigger thresholds (see Fig. 1a). The energy resolution is composed of several effects including Compton scattering, detector resolution, and photon statistics; the latter being dominant. In the fit of the energy response function, the detector resolution was modeled as Gaussian and convolved with an $^{16}$N energy spectrum determined from MC simulation to account for the other two components. The resulting fractional uncertainty on the resolution within the fiducial volume and at kinetic energy $T_e$ is $0.018 \sqrt{T_e/\text{MeV}}$; the fractional energy scale uncertainty is 2.0%. Similarly, for the position fit, the response function includes a convolution with the angular distribution of photon production to account for the non-negligible mean free path of the $^{16}$N $\gamma$-ray. The photon production distribution was also determined from MC simulation. More information about the $^{16}$N source analysis is available in Ref. [24], in which other water phase physics results from SNO+ are presented.

VI. DATASET

Data for this analysis were gathered from May through December, 2017. Calibrations and detector maintenance
were also performed during this period. Data taking periods were split into runs; the typical run length was between 30 and 60 minutes. Each run was checked against a number of criteria to ensure its quality. This included checks on the spatial uniformity of PMT signals, trigger rate, laboratory activity, and detector stability.

Within each run, muons and interactions from atmospheric neutrinos were tagged using the number of OWL PMT signals in an event and the number of events that follow closely in time. After each muon or atmospheric event, a 20 second deadtime was introduced to reduce backgrounds from cosmogenically produced isotopes, such as $^{16}$N. Additional adjustments to the overall livetime were made to account for removal of time-correlated instrumental backgrounds. The resulting overall livetime were made to account for removal of 16 isotopes, such as $^{16}$N. Additional adjustments to the overall livetime were made to account for removal of time-correlated instrumental backgrounds.

A fiducial volume cut was then introduced requiring a region of well-understood and near-perfect trigger efficiency. The trigger efficiency cut requires the number of PMT signals in a 100 ns coincidence window to be above a certain threshold. During the first 60% of dataset livetime, the threshold for this cut was 23, while the trigger threshold itself was 15 in-time signals. For the remaining section of data, the trigger threshold was lowered to 7 in-time PMT signals and the corresponding trigger efficiency cut was 10.

For events passing the low level cuts, it was further required that the vertex reconstruction fits successfully converged. Unsuccessful fits can occur if an event takes place in an optically complicated region of the detector, e.g., near the cylindrical chimney at the top of the AV. These regions often distort the light distribution from an event such that its vertex cannot be reliably determined.

A fiducial volume cut was then introduced requiring that each event reconstruct within 5.3 m of the detector center, reducing backgrounds from events originating on or outside the AV. A more restrictive cut on position was used for the beginning of data taking to minimize the impact of an increased rate of external backgrounds in the upper half of the detector. For that data, events observed in the upper half of the detector were required to be within 4.2 m of the center. The more restrictive cut was applied for 13% of the dataset livetime.

After vertex reconstruction, additional cuts were placed on the timing and isotropy of PMT signals in each event. These cuts removed residual contamination from instrumental backgrounds (which have neither the prompt timing nor angular distribution of Cherenkov light), as well as events with poorly fit vertices. The timing cut required at least 55% of the PMT signals occur within a time-of-flight corrected prompt time window of width 7.5 ns. Isotropy was parameterized by $\beta_{14}$, a value determined by the first and fourth Legendre polynomials of the angular distribution of PMT signals within an event [25]. Events were required to have $\beta_{14}$ is between $-0.12$ and 0.95.

A final cut was placed on the reconstructed kinetic energy of each event, selecting only events within the energy region 5.0 to 15.0 MeV, removing most of the backgrounds from radioactivity and atmospheric neutrino interactions; the only solar neutrinos with a significant flux in this energy region are $^8$B neutrinos. The fiducial volume and energy cuts select 21.4% of simulated solar $\nu_e$ events that interact within the AV; events were simulated according to the $^8$B energy spectrum. The efficiency of the other cuts on events that are within the energy region and fiducial volume are given in Table I Table II shows the effect of each cut on the dataset.

Since the direction of the recoil electron in a solar neutrino scattering event is correlated with the position of the Sun, the rate of solar neutrino events in the dataset was extracted by fitting the distribution of events in $\cos\theta_{\text{sun}}$, where $\theta_{\text{sun}}$ is the angle between an event’s reconstructed direction and the vector pointing directly away from the Sun at the time of the event. The rate of radioactive backgrounds present in the dataset can be determined as one of the parameters in the fit, so no $a \text{ priori}$ knowledge of the background rate was required.

Events with reconstructed kinetic energy, $T_e$, between 5.0 and 10.0 MeV were distributed among five uniformly wide bins, and a single bin from 10.0 to 15.0 MeV. In each

### Table I. Efficiency for each cut on MC simulated solar $\nu_e$ events that are within the fiducial volume and the energy region.

<table>
<thead>
<tr>
<th>Selection</th>
<th>Passing MC Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (after energy &amp; position cuts)</td>
<td>1.0</td>
</tr>
<tr>
<td>Low-level cuts</td>
<td>0.988</td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td>0.988</td>
</tr>
<tr>
<td>Hit Timing</td>
<td>0.988</td>
</tr>
<tr>
<td>Isotropy</td>
<td>0.986</td>
</tr>
</tbody>
</table>

### Table II. Dataset reduction for each applied cut. The second column is the number of triggered events from the detector that pass each cut.

<table>
<thead>
<tr>
<th>Selection</th>
<th>Passing Triggers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>12 447 734 554</td>
</tr>
<tr>
<td>Low-level cuts</td>
<td>4 547 357 090</td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td>126 207 227</td>
</tr>
<tr>
<td>Fit Valid</td>
<td>31 491 305</td>
</tr>
<tr>
<td>Fiducial Volume</td>
<td>6 958 079</td>
</tr>
<tr>
<td>Hit Timing</td>
<td>2 752 332</td>
</tr>
<tr>
<td>Isotropy</td>
<td>2 496 747</td>
</tr>
<tr>
<td>Energy</td>
<td>820</td>
</tr>
</tbody>
</table>
energy bin, a maximum likelihood fit was performed on
the distribution of events in $\cos \theta_{\text{sun}}$ to determine the rate
of solar neutrino events and the rate of background events
as a function of energy. The expected distribution for
solar neutrino events in $\cos \theta_{\text{sun}}$ was calculated from MC
simulation. The PDF for background events was taken to
be uniform in $\cos \theta_{\text{sun}}$. The best fit flux over all energies
was found by maximizing the product of the likelihoods
from the fit in each energy bin. The resulting likelihood
function is given by

$$\mathcal{L}(S, B, \delta \theta | n, \mu \theta, \sigma \theta) =$$

$$\mathcal{N}(\delta \theta, \mu \theta, \sigma \theta) \prod_{j=0}^{N} \prod_{i=0}^{N} \text{Pois}(n_{ij}, B_j + S p_{ij}(\delta \theta)). \quad (1)$$

The number of energy bins and angular bins are repre-
sented by $N_E$ and $N_\theta$ respectively. $S$ is the solar neutrino
interaction rate and is the parameter of interest for this
analysis. $B_j$ is the background rate in each energy bin.
$\mathcal{N}$ represents a normalized Gaussian distribution. The $\delta \theta$
parameter represents an adjustment to the angular res-
olution; $\mu \theta$ and $\sigma \theta$ are respectively the best fit and
the constraint on $\delta \theta$ from the $^{16}$N source analysis. The num-
er of observed counts in the $i^{th}$ angular bin and $j^{th}$
energy bin is given by $n_{ij}$, and $p_{ij}(\delta \theta)$ is the corre-
sponding predicted solar probability density for a given angular
resolution parameter. Pois $(k, \lambda)$ is the value of the Pois-
son distribution at the value $k$ for a rate parameter $\lambda$.

Systematic uncertainties were propagated by varying
the reconstructed quantities for each simulated event. A
fit was then performed with each modified solar PDF to
determine the effect the systematic uncertainty has on
the final result. Because this analysis relies heavily on
direction reconstruction, the angular resolution ($\delta \theta$) was
treated as a nuisance parameter in the fit for the solar
flux. Details about the systematic uncertainties can be
found in Ref. [24].

VIII. RESULTS

Figure 2 shows the distribution of events in $\cos \theta_{\text{sun}}$ for
events over the entire energy range of 5 to 15 MeV and
the fit to that distribution. The fit gives a solar event
rate of $1.30 \pm 0.18$ events/kt-day and background rate
of $10.23 \pm 0.38$ events/kt-day. Performing a similar fit in
each individual energy bin yielded a best fit solar flux as a
function of energy. The fits were combined, in accordance
with Eq. 1, yielding an overall best fit flux of

$$\Phi_{ES} = 2.53^{+0.31}_{-0.28} \text{(stat.)}^{+0.13}_{-0.10} \text{(syst.)} \times 10^6 \text{cm}^{-2}\text{s}^{-1}. $$

This value assumes the neutrino flux consists purely
of electron flavor neutrinos. The result agrees with the
elastic scattering flux published by Super-K,
$$\Phi_{ES} = (2.345 \pm 0.039) \times 10^6 \text{cm}^{-2}\text{s}^{-1} \quad [20],$$
combining statistical and systematic errors.

Including the effects of solar neutrino oscillations, using
the neutrino mixing parameters given in Ref. [28] and
the solar production and electron density distributions
given in Ref. [1] gave a best fit solar flux of

$$\Phi_{ES} = 5.95^{+0.75}_{-0.71} \text{(stat.)}^{+0.28}_{-0.30} \text{(syst.)} \times 10^6 \text{cm}^{-2}\text{s}^{-1}.$$  

This result is consistent with the $^8$B flux as measured by the SNO experiment,
$$\Phi_{ES} = (5.25 \pm 0.20) \times 10^6 \text{cm}^{-2}\text{s}^{-1} \quad [24],$$
combining statistical and systematic uncertainties. Figure 3 shows the best fit solar neutrino $^8$B event rate in each energy
bin along with the predicted energy spectrum scaled to
the best fit flux, and scaled to the flux measured by
SNO. Each statistical error bar on the measured rate is
affected by both the solar neutrino and background rates
in that energy bin. Table III details how each systematic
uncertainty affects this result.

The upper five energy bins, 6.0–15.0 MeV, were an
extremely low background region for this analysis. There
was very little background contamination from cosm-
ogenically produced isotopes due primarily to depth of the
detector. The comparatively high rate of backgrounds in
the 5.0–6.0 MeV bin comes primarily from decays of ra-
Described here is the first measurement of the $^8$B solar neutrino flux as observed by the SNO+ detector in its water phase using 114.7 days of data. Our results are consistent with measurements from other experiments, and serve to provide continued monitoring of reactions within the core of the Sun.

The low rate of backgrounds above 6 MeV, in conjunction with the measured systematic uncertainties, allows an accurate measurement of the solar neutrino flux despite the limited size of the dataset. The low background rates at high energies come primarily from a low rate of cosmic-ray muons within the detector volume, and allows the measurement of other physical phenomena, including invisible nucleon decay and potentially the local reactor anti-neutrino flux in the SNO+ water phase. The presence of radon backgrounds from the internal water limits this analysis at lower energies. In SNO+’s scintillator and tellurium loaded phases the internal radioactive backgrounds will be significantly reduced, allowing further measurements of solar neutrinos at lower energies.

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