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A search for *hep* solar neutrinos and the diffuse supernova neutrino background using all three phases of the Sudbury Neutrino Observatory

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(Dated: July 17, 2020)

A search has been performed for neutrinos from two sources, the *hep* reaction in the solar *pp* fusion chain and the ν_e component of the diffuse supernova neutrino background (DSNB), using the full dataset of the Sudbury Neutrino Observatory. The *hep* search is performed using both a single-bin counting analysis and a likelihood fit. We find a best-fit flux that is compatible with solar model predictions while remaining consistent with zero flux, and set a one-sided upper limit of $\Phi_{hep} < 30 \times 10^3$ cm^{-2} s^{-1} (90% credible interval). No events are observed in the DSNB search region, and we also set an improved upper bound on the ν_e component of the DSNB flux.

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I. INTRODUCTION

Solar neutrinos produced in the *pp* fusion cycle have been studied extensively by several experiments [1–6]. However, the highest energy branch in this cycle, the *hep* reaction (^{3}He($p, e^+\nu_e$)^{4}He), has yet to be directly detected. With a predicted branching ratio of $\sim 2 \times 10^{-7}$, the flux expected on Earth in the BSB05(GS98) solar model is $(7.93 \pm 1.23) \times 10^{-3}$ cm^{-2} s^{-1} [7]. As the *hep* reaction has the highest endpoint energy of all solar neutrinos, and occurs at a relatively high radius in the Sun, an observation may provide sensitivity to non-standard solar models in addition to completing our picture of the *pp* chain neutrino fluxes.

Also expected in the energy range above the endpoint of the ^{8}B solar neutrino spectrum is the diffuse supernova neutrino background (DSNB), the isotropic neutrino flux from past core-collapse supernovae [8]. The DSNB provides information about the average neutrino luminosity and temperature at the flavor-dependent surface of last scattering, which would constrain models of supernova dynamics and provide context for nearby core collapse supernova events detectable on an individual basis, such as SN1987A [9]. This signal remains undetected, and the Sudbury Neutrino Observatory (SNO) experiment provides unique sensitivity to the ν_e component of the flux.

A previous search for the *hep* and DSNB neutrinos with the SNO detector used data from the first operating phase, 306.4 live days with a heavy water (D_2O) target [10]. The present work extends that counting analysis to the full SNO dataset across all operating phases, and additionally a spectral fit is performed. Section II briefly introduces the SNO detector. Next, Section III describes the data set, event selection, and the counting and fit-based analysis methods. Finally, results are presented in Section IV.

II. THE SNO DETECTOR

The SNO detector [11] consisted of a target volume enclosed within a transparent acrylic sphere 6 m in radius, viewed by 9456 inward-looking 8-inch photomultiplier tubes (PMTs) at a radius of 8.4 m, as illustrated in Figure 1. The acrylic vessel and the structure supporting the PMTs (PSUP) were suspended in a water-filled cavity, which was additionally instrumented with outward-looking PMTs to provide an active veto system. In order to shield from cosmic ray muons and from the neutrons and radioisotopes resulting from muon interactions, the detector was located deep underground with a 5890 ± 94 meter water equivalent rock overburden at the Inco (now Vale) Creighton mine near Sudbury, Ontario, Canada.

The detector operated in three distinct phases, differing in the primary mechanism for neutron detection. In the first phase, the detector was loaded with a very low background heavy water (D_2O) target. With the D_2O target, SNO was sensitive to charged current (CC),

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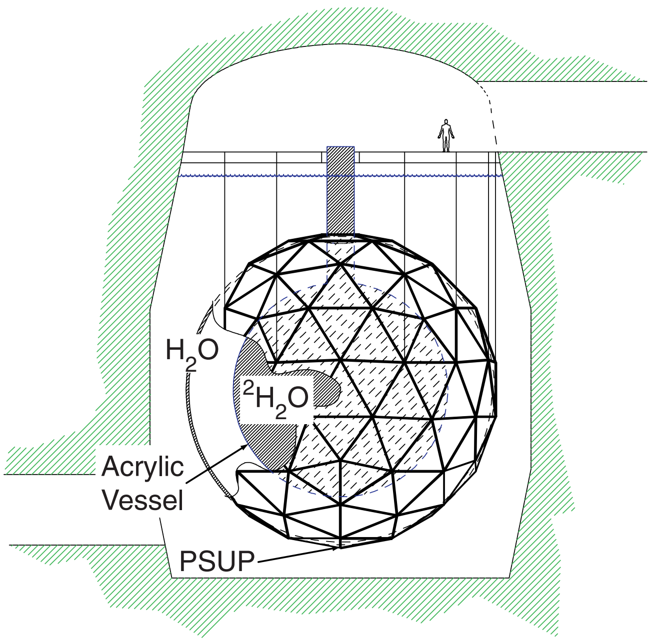


FIG. 1. The SNO detector [5].

neutral current (NC), and elastic scattering (ES) channels:

$$\nu_e + d \to p + p + e^- - 1.44 \text{ MeV (CC)},$$
$$\nu + d \to p + n + \nu - 2.22 \text{ MeV (NC)},$$
$$\nu + e^- \to \nu + e^- \text{ (ES)}.$$

The *hep* and DSNB searches benefit in particular from the enhancement by a factor of about 100 of the CC cross section with respect to that for ES, and from the fact that in the CC interaction, the outgoing electron energy is strongly correlated with the incoming neutrino energy. Additionally, the NC channel allows rejection of atmospheric neutrino interactions by tagging of coincident neutrons.

In SNO's second operational phase, the D_2O was doped with 0.2% NaCl by mass, to take advantage of the improved neutron capture cross section on Cl and the higher energy and more isotropic de-excitation γ cascade. In the third phase, the NaCl was removed and an array of ^{3}He proportional counters (NCDs) was deployed to further improve neutron detection.

III. ANALYSIS

We performed a single-bin counting analysis in two different energy ranges, for the *hep* and DSNB neutrino signals. Additionally, a maximum likelihood fit was used to extend the sensitivity of the *hep* search. The following sections describe the data set, event selection criteria, and systematic uncertainties common to the counting and likelihood analyses, and then introduce those techniques.

TABLE I. Duration and live time for each operational phase.

Phase	Target	Dates	Live Time
I	D_2O	11/1999 – 5/2001	306.4 d
II	D_2O + 0.2% NaCl	7/2001 – 8/2003	478.6 d
III	D_2O + NCDs	11/2004 – 11/2006	387.2 d

A. Data Selection

This analysis makes use of the entire SNO dataset, across all three operational phases, with data collected between November 1999 and November 2006. Table I indicates the live time for each phase, corresponding to a total exposure of 2.47 kilotonne-years after fiducialization. We adopted a pseudo-blind approach in which the analysis was tuned on Monte Carlo simulations, then validated on one third of the data randomly sampled in short blocks of time uniformly distributed throughout the phases. Finally, with cuts and parameters having been fixed, the full dataset was re-opened for this analysis.

The set of signal candidate events follows from three stages of event selection. First, entire runs (approximately 8 hour blocks of live time) are accepted or rejected based on detector conditions. The same selection is applied as in Reference [12] for Phase I and Reference [5] for Phase III. For Phase II, the selection from Reference [13] is extended to include periods with higher than average levels of Rn or activated Na, which presented important backgrounds for the low energy threshold ^{8}B oscillation analyses but are insignificant for the higher-threshold *hep* and DSNB searches.

Next, a set of low-level cuts are applied, which address instrumental background events as well as coincidences with bursts of events or tagged muons. The instrumental backgrounds are caused by detector effects, for example high-voltage discharge of a PMT, or electronic pickup. Such events tend to have distinct signatures, such as correlations in the physical locations of electronics channels, which are very different from signal events. For each phase, the same set of low-level cuts are used as in previous work [5], as these have been extensively validated and tuned to optimize signal efficiency. For this analysis, signal-like events are further required to be isolated in time: any candidate event occurring within 250 ms of another candidate event is rejected. This includes coincidences with any event with a reconstructed vertex within a 6 m fiducial volume and a kinetic energy above 4 MeV, a trigger of the external veto, or (in Phase III only) a detected signal in the NCD array. This reduces background classes that produce coincident electrons, neutrons, or photons, and in particular targets Michel electrons following low-energy muons and atmospheric neutrino CC electrons with neutron followers.

Finally, a series of high level criteria have been developed based on reconstructed observables, which discriminate the signals of interest from other physics backgrounds. The signature of a signal *hep* or DSNB neutrino interaction is a single electron-like Cherenkov ring originating within 550 cm of the detector center. This fiducial volume is chosen to reduce backgrounds associated with γ rays and other backgrounds due to the materials surrounding the target volume. Signal Cherenkov rings are highly anisotropic, at a level quantified by the variable β_{14} previously described in Reference [14]. The fraction of PMTs hit within a narrow prompt time window is calculated as the in-time ratio (ITR). This variable can discriminate between well-reconstructed single-ring events or multi-ring events due to a pile up of interactions or particles. To further discriminate single electron-like events, three Kolmogorov-Smirnov (KS) tests are used. The first simply tests the compatibility of the azimuthal distribution of hits around the reconstructed direction relative to a flat distribution. The second test is a two-dimensional extension that includes the polar angle and compares to a probability distribution derived from calibration data, accounting for energy dependence in the polar angle and solid angle effects in the azimuthal angle. A final test compares the time-of-flight corrected PMT hit times for hits inside the Cherenkov ring to a template distribution also extracted from calibration data. Cuts on these parameters have been adjusted relative to previous SNO analyses as described in Section III D, as both the energy regime (> 15 MeV) and the objectives (rejection of atmospheric neutrino backgrounds) differ. The distributions in these high-level observables are validated by comparing simulations to data in the low-energy sideband below the *hep* region of interest and to calibration data using a signal-like ^{8}Li source [15].

B. Monte Carlo Simulation

The detailed microphysical detector model used in previous SNO measurements, SNOMAN [5, 11], was again employed for this analysis. SNOMAN was used to generate solar neutrino events, propagate final state particles through the detector geometry, and simulate the optical, triggering, and electronics response of the detector. The SNOMAN Monte Carlo contains run-by-run detector state information, tracking changes over time. All Monte Carlo was produced with at least 500 times the statistics expected in data.

For atmospheric neutrinos above 100 MeV, we use GENIE v2.12.2 [16, 17] using the default model set, and the Bartol04 flux predictions [18], interpolated between the solar minimum and maximum according to the dates of each operational phase. The final state particles from GENIE are then input into SNOMAN for propagation through the full detector simulation. Atmospheric neutrino oscillations are applied using best-fit parameters in a model which samples an ensemble of baselines from the neutrino production height distributions of Gaisser and Stanev [19].

One potential background which is not simulated in GENIE is a 15.1-MeV γ produced in de-excitation of $^{12}\mathrm{C}^*$ following neutrino interactions on ^{16}O. Here, we take a sample of such untagged γ events following neutral current quasi-elastic (NCQE) interactions from a NUANCE (version 3r009) simulation, which uses the calculation of Ejiri [20], and scale according to the relative NCQE cross section in GENIE.

To model low-energy ($E_\nu < 100$ MeV) atmospheric neutrino interactions, we use the flux given by Battistoni et al. [21]; for this subdominant background only ν_e and $\bar{\nu}_e$ are simulated, and the fluxes at the solar minimum (when the background is largest) are used. This simulation is performed directly in SNOMAN. We note that the low- and high-energy atmospheric neutrino fluxes are the same as those used in the 2006 SNO *hep* and DSNB search analysis [10].

C. Signals and Backgrounds

For the *hep* solar neutrino signal, we use the spectrum computed by Bahcall [22] and use the BSB05(GS98) flux of $7.93(1 \pm 0.155) \times 10^3$ cm^{-2} s^{-1} [7] as a benchmark. The primary background for the *hep* search is due to electrons from ^{8}B solar neutrino interactions, at a level that depends on the shape of the spectrum near the endpoint. The spectral shape from Winter et al. [23] is used, and oscillations are applied according to a three-neutrino oscillation model using best-fit parameters [24]. The ^{8}B solar neutrino flux is based on a three-phase analysis of SNO ^{8}B solar neutrino data, identical to that presented in Reference [5] except that an upper energy threshold at 10 MeV was applied to eliminate any contamination from a possible *hep* signal. The extracted ^{8}B flux is $\Phi_{^8\mathrm{B}} = (5.26 \pm 0.16\ (\mathrm{stat.})^{+0.11}_{-0.13}\ (\mathrm{syst.})) \times 10^6$ cm^{-2} s^{-1}, consistent with the published value.

The DSNB signal is modeled as an isotropic ν_e source using a benchmark energy spectrum and total flux. We use the model of Beacom and Strigari [25] with $T = 6$ MeV, which predicts a total flux of $\Phi^{\mathrm{DSNB}}_{\nu_e} = 0.66$ cm^{-2} s^{-1} in the energy range $22.9 < E_\nu < 36.9$ MeV.

Backgrounds due to isotropic light emission from the acrylic vessel [13] have also been studied using a dedicated event selection and Monte Carlo. The background contamination depends on the choice of fiducial volume, and is constrained to the negligible level of < 0.01 events within our energy regions of interest for the chosen cut of 550 cm. Atmospheric neutrinos and associated $^{12}\mathrm{C}^*$ backgrounds are modeled as described in III B.

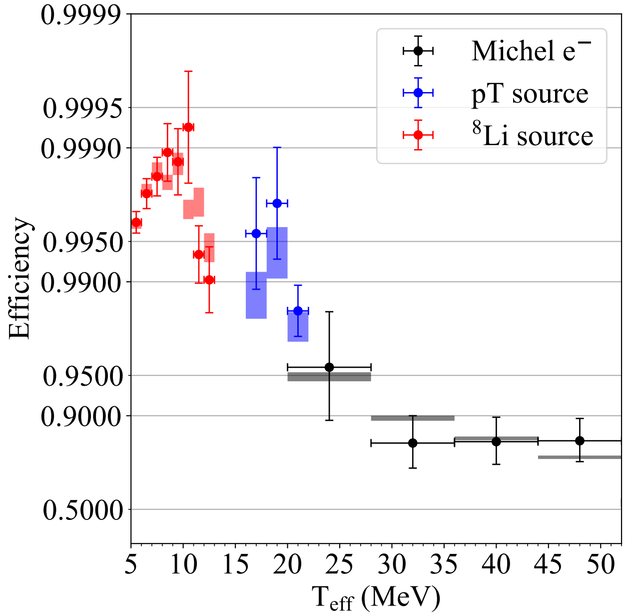


FIG. 2. Efficiency of the high-level event selection cuts for Phase I, compared between calibration sample data (points) and Monte Carlo (shaded boxes). The calibration samples include deployed ^{8}Li [15] and pT [26] sources and Michel electrons from muons that stop and decay inside the detector.

D. Counting Analysis

Within each energy region of interest (ROI) for the single-bin counting analysis, 1D cuts on high level features are simultaneously tuned to optimize the search sensitivity in Monte Carlo, with further adjustments to minimize the impact of the systematic uncertainties on the shapes of the observable distributions. The *hep* energy ROI of $14.3 < T_{\text{eff}} < 20$ MeV and DSNB ROI of $20 < T_{\text{eff}} < 40$ MeV are chosen to optimize signal-to-background ratio while maximizing signal acceptance, following the procedure described in Reference [10]. The signal efficiency of the high-level cuts is validated using calibration data sets as shown in Figure 2. Within the *hep* ROI, the high level and burst cuts together reduce the atmospheric neutrino backgrounds by 97%, with a signal efficiency of $\sim 99\%$.

For the purposes of this cut-based analysis, confidence intervals are constructed using a Bayesian framework in which we construct intervals from a Poisson likelihood function marginalized over the expected background distribution. This function is defined as

$$\begin{aligned} -\log \mathcal{L}(\mu, b|n, \hat{b}, \sigma_b) = \mu + b \\ + \log \Gamma(n+1) \\ - n \times \log(\mu + b) \\ + \frac{1}{2}\frac{(b-\hat{b})^2}{\sigma_b^2}\ , \end{aligned} \tag{1}$$

where μ is the true signal mean, b the true background rate, n the observed number of events, $\hat{b}$ the mean background expectation, and σ_b the Gaussian uncertainty on b. Integrating over the background parameter b yields $-\log \mathcal{L}(\mu|n)$, which is treated as a posterior PDF for μ and used to construct intervals. For a confidence level α, a two-sided interval $\mathcal{C}$ is defined by the highest posterior density region, i.e. adding points μ in order of their posterior probability density until $\sum_{\mathcal{C}} \mathcal{L}(\mu|n) \geq \alpha$. One-sided intervals are constructed by direct integration of $\mathcal{L}$ to determine the smallest μ' such that $\sum_0^{\mu'} \mathcal{L}(\mu|n) \geq \alpha$. We note that in this construction we implicitly assume a uniform step function prior, constant for $\mu > 0$.

E. Likelihood Analysis

In order to leverage the energy dependence of the signal spectra and lower the threshold for the *hep* search, an unbinned maximum likelihood fit was also performed. The fit considers all three phases simultaneously, with the ^{8}B and *hep* fluxes held constant across time, as well as the overall atmospheric neutrino flux normalization after accounting for differences across the solar minimum and maximum. The dominant systematic uncertainties are varied in the fit using Gaussian pull terms, and include the oscillation parameters θ_{12} and Δm^2_{12} as well as the energy scale and resolution model parameters and angular and β_{14} resolutions, which are treated as uncorrelated. The fit uses three-dimensional probability distribution functions (PDFs), binned in reconstructed energy (T_{eff}, 10 bins, 10 – 20 MeV), the angle relative to the Sun ($\cos\theta_{\text{sun}}$, 10 bins, -1 – 1), and the isotropy parameter (β_{14}, 15 bins, -0.12 – 0.95). PDFs are constructed for ^{8}B CC electrons, ^{8}B ES electrons, *hep* CC electrons, *hep* ES electrons, and atmospheric neutrino interactions for each phase. The relative normalizations of the CC and ES components for each signal are fixed. The cuts described previously are applied to data and Monte Carlo prior to PDF construction and fitting; these include the fiducial volume, ITR, three KS probability figures of merit, and low-level cuts. In contrast to the counting analysis, energy and isotropy are observables in the fit.

The full negative log likelihood function optimized in the fit is of the form [27]:

$$
\begin{aligned}
&-\log\mathcal{L}(\mathbf{r},\Delta) = \\
&\quad \sum_{j=1}^{M} \tilde{N}_j(\mathbf{r},\Delta) \\
&\quad -\sum_{i=1}^{N} \log\left(\sum_{j=1}^{M} \tilde{N}_j(\mathbf{r},\Delta) \times P_j(\mathbf{x}_i,\Delta)\right) \\
&\quad +\frac{1}{2}\sum_{k=1}^{M'} \frac{(r_k-\bar{r}_k)^2}{\sigma^2_{r_k}} \\
&\quad +\frac{1}{2}\sum_{m=1}^{s} \frac{(\Delta_m-\bar{\Delta}_m)^2}{\sigma^2_{\Delta_m}},
\end{aligned}
\tag{2}
$$

where the first term corresponds to the total normalization constraint, the second the unbinned likelihood given the PDFs, and the final two terms represent Gaussian uncertainties on rate and systematic parameters. In Equation 2, P are PDFs for each signal, binned in observables $\mathbf{x}$. These PDFs are constructed from Monte Carlo events, modified according to the set of s systematic parameters Δ, with associated Gaussian uncertainties σ_Δ. Rate parameters $\mathbf{r}$ are related to an expected number of events $\tilde{N}$ by an efficiency matrix ϵ such that $\tilde{N}_i = \epsilon_i^{\,j} r_j$, and have Gaussian uncertainties σ_r. M' is simply the number of rate parameters which are externally constrained. The efficiency matrix ϵ relates the fit parameters to the signal rates, e.g. with a single *hep* flux parameter controlling the *hep* ES and CC components. These matrix elements also include a weighting with a factor of $|\{\mathbf{x}_i | S(\mathbf{x}_i,\Delta) \in V\}|$ to account for the number of events (described by a set of observables $\mathbf{x}$) shifting across the boundary of the analysis window (a volume V in the observable space) after application of a systematic transformation S.

The fit was performed using purpose-built Markov Chain Monte Carlo (MCMC) code. Two specific tasks were accelerated using general-purpose GPUs: the building of PDFs from Monte Carlo performed at each iteration of the fit to account for varying systematic parameters, and the computation of the unbinned likelihood function, where the sum over events is performed in parallel. The use of GPU acceleration reduces the time required per iteration by about a factor of 1000 relative to a single CPU. A number of metrics were used to evaluate fit quality and convergence, including a check of statistical compatibility of parameter distributions within subdivisions of the MCMC random walk, and a toy Monte Carlo to evaluate the goodness of fit through a χ^2 hypothesis test. Additional validation included signal injection tests varying the *hep* flux from 0.01 − 10 times model predictions.

TABLE II. Systematic uncertainties. Values apply to all three phases except as noted for those in lower part of the table.

Parameter	Magnitude
Vertex accuracy	2.9% [5]
Vertex resolution	2.4 cm [5]
Angular resolution	2%
^{8}B flux	See §III C
^{8}B ν_e spectrum	Ref. [23]
ν Mixing parameters	Ref. [24]
Atm. ν flux	
$E_\nu > 100$ MeV	10% [18]
$E_\nu < 100$ MeV	25% [21]
Cross sections	
CC $\nu - D$	1.2%
Atm. ν	See §III F 2
15.1 MeV γ rays	100%

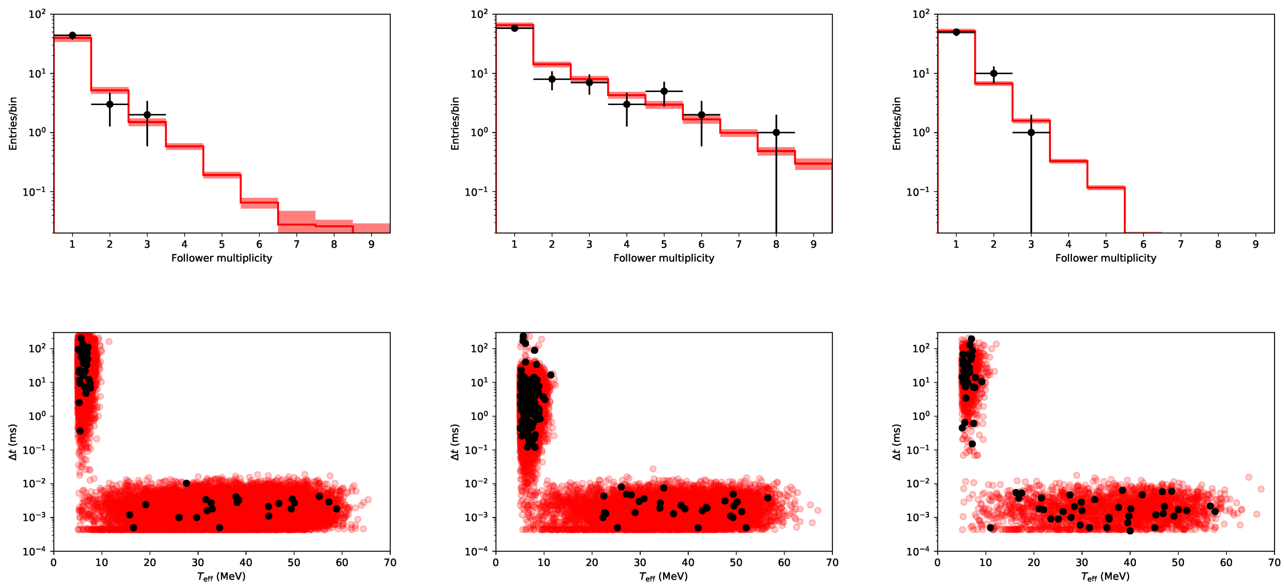
	Phase I	Phase II	Phase III
Live time	0.006%	0.021%	0.36%
Energy scale			
$T_{\rm eff} = 14.3$ MeV	0.61%	0.55%	0.82%
$T_{\rm eff} = 20.0$ MeV	0.71%	0.65%	0.86%
Energy resolution scale	1.60%	1.71%	1.37%

F. Systematic Uncertainties

A number of systematic effects are important within these analyses. The primary background to the *hep* search is electrons from ^{8}B solar neutrino interactions, where the spectrum is affected by the energy response modeling as well as the flux normalization and intrinsic shape. The flux uncertainty is taken from the three-phase fit to low-energy SNO data described in Section III C, and the shape is varied within the uncertainties provided by Winter et al. [23]. For solar neutrinos, the uncertainties in the oscillation parameters and the $\nu - d$ CC cross section are also included. To address the energy response modeling, which affects all signals and backgrounds, uncertainties are derived from fits to deployed calibration sources and samples of Michel electrons; this procedure is described in Section III F 1. Uncertainties impacting atmospheric neutrino backgrounds are detailed in Section III F 2. The major systematic uncertainties impacting the analyses are summarized in Table II.

1. Detector Response

In order to calibrate the response in the detector across an energy range up to 40 MeV, several event samples were compared against SNOMAN Monte Carlo predictions. The vertex reconstruction is described in References [28] (Phases I and II) and [29] (Phase III), and based on this we include a 2.4 cm uncertainty on reconstructed position resolution, and an overall 2.9% fiducial volume uncertainty. Additionally, a 2% uncertainty on the angular resolution for ES events is modeled as a scal-



(a)Phase I (b)Phase II (c)Phase III

FIG. 3. Data/Monte Carlo comparisons for atmospheric neutrino event samples. Red points/lines are Monte Carlo, and black points are data.

ing via a parameter Δ_θ [5]:

$$(\cos\theta)' = 1 + (\cos\theta - 1)(1 + \Delta_\theta), \quad (3)$$

where $(\cos\theta)'$ outside the interval $[-1, 1]$ are assigned a random value within that interval.

In each of the three phases, a large sample of 6.13-MeV γ rays from a deployed ^{16}N source provided the primary calibration. Additionally, a pT source in Phase I provided a sample of 19.8-MeV γ rays [26]. To extend the model to higher energies, samples of Michel electrons from decays of stopping cosmic ray muons were selected and fit to a response model allowing an energy-dependent fractional energy scaling ($\Delta_S^{(i)}$) and shift in resolution (ΔR):

$$T'_{\text{eff}} = T_{\text{eff}} + (\Delta_S^{(0)} + \Delta_S^{(1)} \cdot T_{\text{eff}}) \cdot T_{\text{eff}} + \Delta_R \cdot (T_{\text{eff}} - T_{\text{true}}). \quad (4)$$

The parameters were extracted using a maximum likelihood fit to the Michel electron samples for each phase, subject to prior constraints based on the deployed source measurements. The extracted parameters are given in Table III. We find that the parameters are consistent with zero, confirming that the initial ^{16}N-based energy calibration provides a reasonable estimate of energy across the regions of interest, and the correlated errors in each phase indicate the magnitude of systematic shifts that remain compatible with the higher-energy calibration samples. This provides a data-driven constraint on the smearing of the spectrum of electrons produced by ^{8}B solar neutrino interactions, which forms a dominant background for the *hep* search.

Additionally, a similar model including a linear scaling and resolution was applied to the shape of the isotropy

TABLE III. Energy response model parameters extracted from maximum likelihood fits to calibration sample data in each phase.

Parameter	Phase I	Phase II	Phase III
Normalization	135 ± 12.2	213 ± 14.8	172 ± 13.0
$\Delta_S^{(0)}/10^{-3}$	-5.20 ± 7.21	-0.01 ± 6.14	1.25 ± 10.2
$\Delta_S^{(1)}/10^{-3}$	0.44 ± 0.42	-0.16 ± 0.37	-0.16 ± 0.43
$\Delta_R^{(0)}/10^{-2}$	1.83 ± 1.60	2.38 ± 1.71	1.61 ± 1.37

parameter β_{14}, with $\Delta_S^{(0)} = \Delta_R = 4.2 \times 10^{-3}$ for all three phases, based on measurements with the ^{16}N calibration source [5]. Finally, the contribution of any non-Gaussian (flat) tails in the energy response was constrained to the level of $\lesssim 10^{-3}$ events in the energy region of interest based on samples of events from the deployed ^{8}Li source [15], which has a β spectrum similar to that of the ^{8}B solar neutrinos.

2. *Atmospheric Neutrinos*

Two main classes of uncertainty affect the atmospheric neutrinos: the flux uncertainty, which is taken to be 25% [21] and 10% [18] for low (< 0.1 GeV) and high ($0.1 - 10$ GeV) energies, respectively, and the cross sections. The cross section uncertainties are evaluated through event reweighting, by simultaneously varying the parameters in the default GENIE model set (see Ref. [17]) within their respective uncertainties to produce an ensemble of weights corresponding to different model hypotheses.

To validate the modeling of atmospheric neutrino interactions, a sample of events coincident with a fully contained atmospheric neutrino predecessor event was selected. The predecessors are required to have $200-5000$ PMTs hit, no activity in the veto region, and not to follow a through-going μ event. The follower events, which consist of Michel electrons and neutrons, must pass all analysis cuts and have an energy $5 < T_{\text{eff}} < 100$ MeV. For the selected events, we compare the multiplicity and timing of coincidences as well as the energy, position, isotropy, and other high-level observables between the atmospheric Monte Carlo and data. The distributions are shown in Figure 3 for the follower multiplicity distributions for each phase, and the joint distribution of reconstructed energy T_{eff} and the time difference between the predecessor and follower event (Δt). The two populations correspond to neutron captures and stopped muon decays. The distributions show reasonable agreement with the GENIE Monte Carlo processed through SNOMAN, consistent within the uncertainties due to statistics, flux, and cross section modeling.

IV. RESULTS

A. Counting Analysis

Within the sensitivity-optimized energy regions of interest for the *hep* and DSNB signals, we performed a single-bin counting analysis as introduced in Section III D. The energy spectra for selected events are shown in Figure 4. The total signal and background expectations in the $14.3-20$ MeV *hep* energy ROI are 3.09 ± 0.12 and 13.89 ± 1.09, respectively, with 22 events observed; the distribution across phases is given in Table IV.

The uncertainties on the total three-phase signal and background expectations are correlated ($r_{hep} = 0.83$, $r_{\text{DSNB}} = 0.12$), and are obtained using an ensemble of 500 three-phase pseudo-experiments with systematic parameters randomly sampled according to their correlated uncertainties. The dominant source of uncertainty in the *hep* region is the energy response modeling, due to the steeply-falling tail of the ^{8}B solar neutrino backgrounds. This model is constrained using data spanning the energy range as described in Section III F 1.

The majority of candidate events, 13 of 22, occurred during Phase III. These events appear signal-like in all respects, and consistency with background is observed in sidebands with respect to energy and all other high-level observables. According to toy Monte Carlo studies, the probability of observing a statistical fluctuation of at least this magnitude in any one phase is approximately 8%.

Applying the Bayesian procedure described in Section III D yields an 68.3% credible interval (CI) of $\Phi_{hep} = (9.6-33)\times10^3$ cm^{-2} s^{-1}; however, as the probability of a statistical fluctuation of this magnitude is significant, we set a one-sided upper limit of

$$\Phi_{hep} < 40\times10^3 \text{ cm}^{-2}\text{ s}^{-1} \text{ (90\% CI)}.$$

TABLE IV. Summary of expected and observed events for each ROI and phase in the counting analysis.

	Expected Signal	Expected Background	Events Observed
Phase I *hep*	0.84 ± 0.08	3.14 ± 0.63	3
Phase II *hep*	1.28 ± 0.06	5.37 ± 0.65	6
Phase III *hep*	0.98 ± 0.05	5.38 ± 0.52	13
Total *hep*	3.09 ± 0.12	13.89 ± 1.09	22
Phase I DSNB	0.02 ± 0.00	0.62 ± 0.10	0
Phase II DSNB	0.03 ± 0.00	0.91 ± 0.15	0
Phase III DSNB	0.02 ± 0.00	1.06 ± 0.17	0
Total DSNB	0.08 ± 0.00	2.58 ± 0.26	0

For comparison, in the previous Phase I analysis two events were observed with 0.99 ± 0.09 signal and 3.13 ± 0.60 background events expected; this resulted in a 90% CL frequentist upper limit on the *hep* flux of 23×10^3 cm^{-2} s^{-1} [10].

With 0.08 signal and 2.58 ± 0.26 background events expected in the DSNB ROI, the median experiment in a Monte Carlo ensemble provides 90% CI sensitivity to signals at least 52 times larger than the benchmark Beacom & Strigari $T = 6$ MeV model. With an apparent downward fluctuation, zero events are observed, and we set an upper limit of 29 times the model prediction, corresponding to DSNB ν_e flux of $\Phi^{\text{DSNB}}_{\nu_e} < 19$ cm^{-2} s^{-1} (90% CI) in the energy range $22.9 < E_\nu < 36.9$ MeV. The dominant source of systematic uncertainty in the DSNB ROI is the 10% normalization uncertainty for the flux of atmospheric neutrinos with $E_\nu > 100$ MeV.

B. Likelihood Analysis

For the *hep* search, we additionally performed a likelihood fit as described in Section III E. One-dimensional projections of the best fit in the observable dimensions T_{eff}, β_{14}, and $\cos\theta_{\text{sun}}$ are shown in Figure 6. The quality of the fit was evaluated using a χ^2 test based on an effective test statistic distribution derived using a toy Monte Carlo, yielding a p-value of 16.0% considering statistical errors only.

A Bayesian credible interval for the *hep* flux is obtained by marginalizing over all other parameters, and constructing the highest posterior density region (HPDR) containing a given probability, as shown in Figure 5. The intervals and best fit value obtained with the Bayesian HPDR approach are consistent with quantities obtained by directly analyzing the likelihood space sampled by the MCMC.

In agreement with the counting analysis up to differences introduced by the statistical treatments, this result

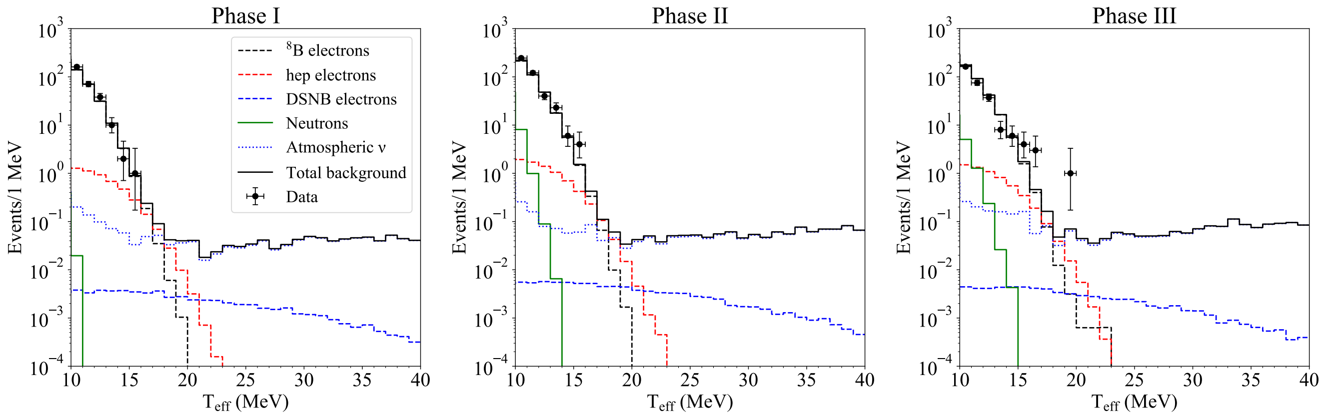


FIG. 4. Reconstructed energy spectra for each phase.

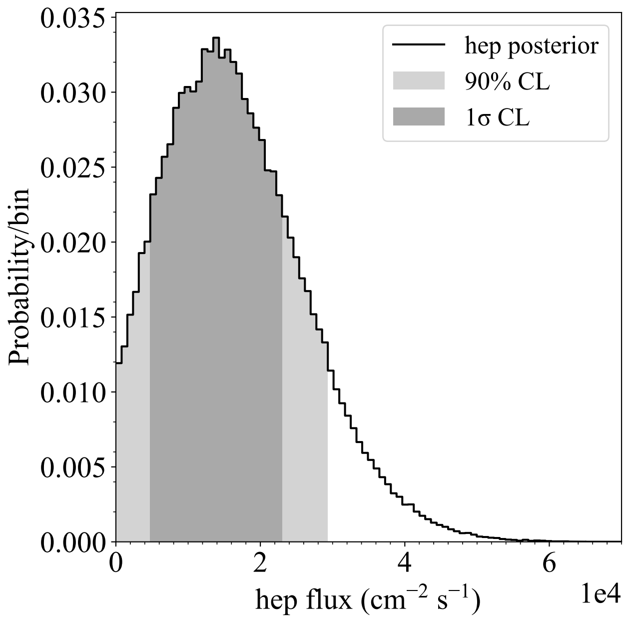


FIG. 5. Posterior distribution for the *hep* flux, marginalized over all other fit parameters..

is compatible with the BSB05(GS98) model prediction and is consistent with zero *hep* flux. The fit yields a 68.3% HPDR credible interval for the *hep* flux parameter corresponding to $\Phi_{hep} = (5.1 - 23) \times 10^3$ cm^{-2} s^{-1}; as in the counting-based analysis, we define a one-sided upper limit:

$$\Phi_{hep} < 30 \times 10^3 \text{ cm}^{-2} \text{ s}^{-1} \text{ (90\% CI)}.$$

V. CONCLUSIONS

Data from the full SNO dataset, representing an exposure of 2.47 kilotonne years with a D_2O target, has been analyzed to search for neutrinos from the *hep* reaction in the Sun's *pp* chain and ν_e from the diffuse supernova neutrino background. In addition to increasing the exposure by a factor of 3.8 relative to the previous SNO search for these signals [10], a new spectral fit has been employed to improve the sensitivity to the *hep* flux.

We have performed the most sensitive search to date for the *hep* solar neutrino flux, the final unobserved branch of the *pp* fusion chain. This measurement is compatible with the BSB05(GS98) model prediction, while remaining consistent with zero *hep* flux, and we extract a one-sided upper limit of $\Phi_{hep} < 30 \times 10^3$ cm^{-2} s^{-1} 90% CI. In a search at energies above the solar neutrino endpoints, we observe no evidence for the DSNB ν_e flux, and set an upper limit on this flux; our results suggest that a ν_e flux larger than about thirty times the current predictions is disfavored. Future experiments sensitive to DSNB $\bar{\nu}_e$ through inverse beta decay, in particular SuperK-Gd [30], are expected to achieve sensitivity to the model predictions in the near future. There also exists great potential to further explore both the *hep* and DSNB ν_e in upcoming experiments such as DUNE [31, 32], where the CC $\nu_e-{}^{40}$Ar cross section provides similar advantages to $\nu_e - d$ in SNO, together with low threshold and large exposure.

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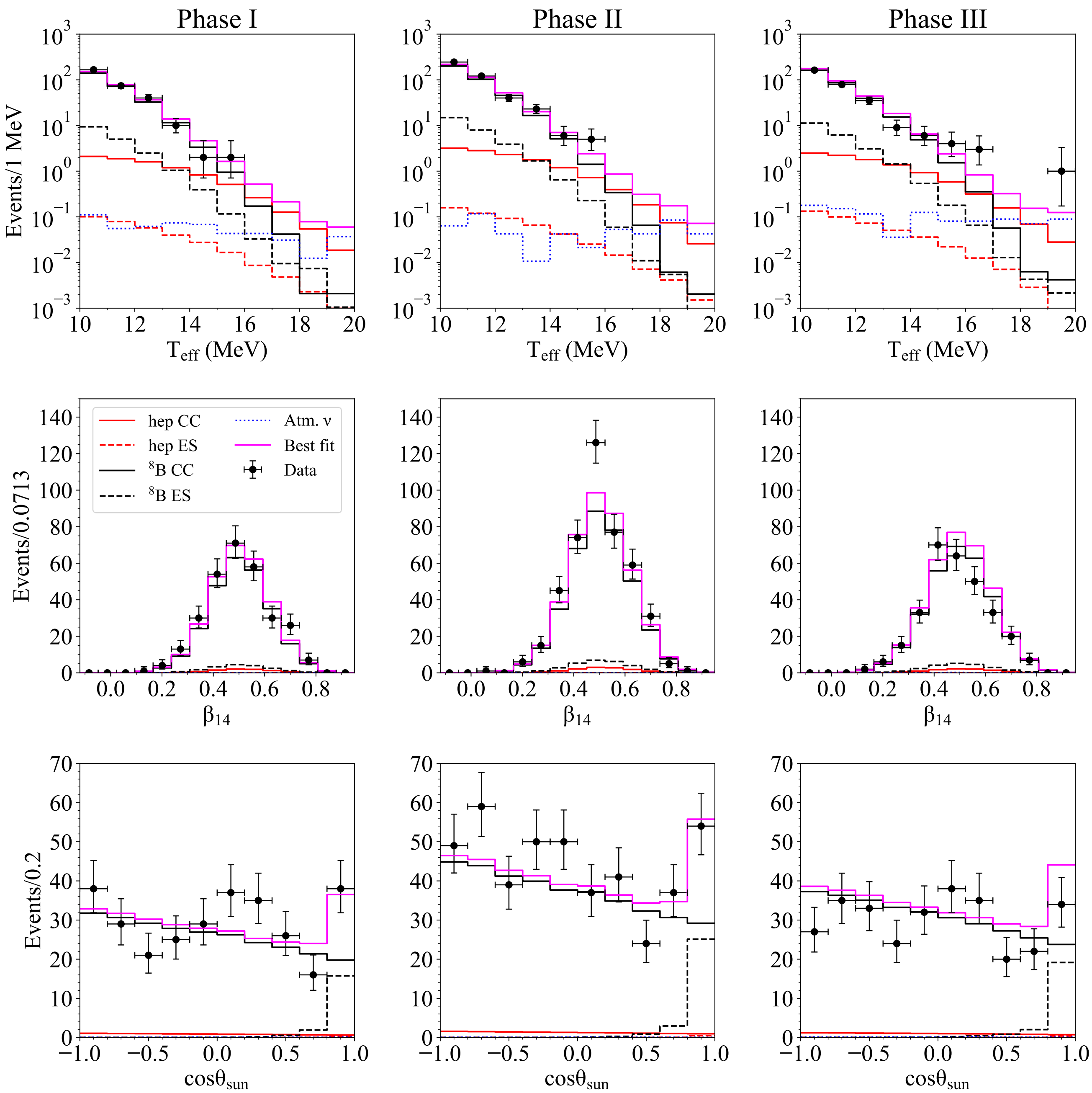

FIG. 6. Distributions of events in the full dataset compared to the best fit in the joint three-phase likelihood analysis, with projections shown for each phase and fit observable. The model and systematic uncertainties are discussed in Sections III E and III F, respectively, with the extraction of the *hep* flux described in Section IV B.

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