

## A SEARCH FOR NEUTRINOS FROM THE SOLAR *hep* REACTION AND THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND WITH THE SUDBURY NEUTRINO OBSERVATORY

B. AHARMIM,<sup>1</sup> S. N. AHMED,<sup>2</sup> A. E. ANTHONY,<sup>3</sup> E. W. BEIER,<sup>4</sup> A. BELLERIVE,<sup>5</sup> M. BERGEVIN,<sup>6,7</sup> S. D. BILLER,<sup>8</sup> M. G. BOULAY,<sup>2,9</sup> Y. D. CHAN,<sup>6</sup> M. CHEN,<sup>2</sup> X. CHEN,<sup>6,10</sup> B. T. CLEVELAND,<sup>8</sup> G. A. COX,<sup>11</sup> C. A. CURRAT,<sup>6</sup> X. DAI,<sup>2,8</sup> F. DALNOKI-VERESS,<sup>5,12</sup> H. DENG,<sup>4</sup> J. DETWILER,<sup>11</sup> M. DiMARCO,<sup>2</sup> P. J. DOE,<sup>11</sup> G. DOUCAS,<sup>8</sup> P.-L. DROUIN,<sup>5</sup> F. A. DUNCAN,<sup>2,13</sup> M. DUNFORD,<sup>4</sup> J. A. DUNMORE,<sup>8,14</sup> E. D. EARLE,<sup>2</sup> H. C. EVANS,<sup>2</sup> G. T. EWAN,<sup>2</sup> J. FARINE,<sup>1</sup> H. FERGANI,<sup>8</sup> F. FLEUROT,<sup>1</sup> R. J. FORD,<sup>2,13</sup> J. A. FORMAGGIO,<sup>11,15</sup> N. GAGNON,<sup>6,8,9,11</sup> J. TM. GOON,<sup>16</sup> K. GRAHAM,<sup>2</sup> E. GUILLIAN,<sup>2</sup> R. L. HAHN,<sup>17</sup> A. L. HALLIN,<sup>2</sup> E. D. HALLMAN,<sup>1</sup> P. J. HARVEY,<sup>2</sup> R. HAZAMA,<sup>11,18</sup> K. M. HEEGER,<sup>6,11</sup> W. J. HEINTZELMAN,<sup>4</sup> J. HEISE,<sup>13</sup> R. L. HELMER,<sup>19,20</sup> R. J. HEMINGWAY,<sup>5</sup> R. HENNING,<sup>6</sup> A. HIME,<sup>9</sup> C. HOWARD,<sup>2</sup> M. A. HOWE,<sup>11</sup> M. HUANG,<sup>3</sup> P. JAGAM,<sup>7</sup> N. A. JELLEY,<sup>8</sup> J. R. KLEIN,<sup>3,4</sup> L. L. KORMOS,<sup>2</sup> M. KOS,<sup>2</sup> A. KRÜGER,<sup>1</sup> C. KRAUS,<sup>2</sup> C. B. KRAUSS,<sup>2</sup> T. KUTTER,<sup>16</sup> C. C. M. KYBA,<sup>4</sup> H. LABRANCHE,<sup>7</sup> R. LANGE,<sup>17</sup> J. LAW,<sup>7</sup> I. T. LAWSON,<sup>7,13</sup> K. T. LESKO,<sup>6</sup> J. R. LESLIE,<sup>2</sup> J. C. LOACH,<sup>8</sup> S. LUOMA,<sup>1</sup> R. MACLELLAN,<sup>2</sup> S. MAJERUS,<sup>8</sup> H. B. MAK,<sup>2</sup> J. MANEIRA,<sup>21</sup> A. D. MARINO,<sup>6,22</sup> R. MARTIN,<sup>2</sup> N. MCCAULEY,<sup>4,23</sup> A. B. McDONALD,<sup>2</sup> S. MCGEE,<sup>11</sup> C. MIFFLIN,<sup>5</sup> K. K. S. MIKNAITIS,<sup>11,24</sup> M. L. MILLER,<sup>15</sup> B. MONREAL,<sup>15</sup> B. G. NICKEL,<sup>7</sup> A. J. NOBLE,<sup>2</sup> E. B. NORMAN,<sup>6,25</sup> N. S. OBLATH,<sup>11</sup> C. E. OKADA,<sup>6,26</sup> H. M. O'KEEFFE,<sup>8</sup> G. D. OREBI GANN,<sup>8</sup> S. M. OSER,<sup>20</sup> R. OTT,<sup>15</sup> S. J. M. PEETERS,<sup>8</sup> A. W. P. POON,<sup>6</sup> G. PRIOR,<sup>6</sup> K. RIELAGE,<sup>9,11</sup> B. C. ROBERTSON,<sup>2</sup> R. G. H. ROBERTSON,<sup>11</sup> E. ROLLIN,<sup>5</sup> M. H. SCHWENEDNER,<sup>1</sup> J. A. SECREST,<sup>4</sup> S. R. SEIBERT,<sup>3</sup> O. SIMARD,<sup>5</sup> C. J. SIMS,<sup>8</sup> D. SINCLAIR,<sup>5,19</sup> P. SKENSVED,<sup>2</sup> R. G. STOKSTAD,<sup>6</sup> L. C. STONEHILL,<sup>9,11</sup> G. TEŠIĆ,<sup>5</sup> N. TOLICH,<sup>6</sup> T. TSUI,<sup>20</sup> R. VAN BERG,<sup>4</sup> R. G. VAN DE WATER,<sup>9</sup> B. A. VANDEVENDER,<sup>11</sup> C. J. VIRTUE,<sup>1</sup> T. J. WALKER,<sup>15</sup> B. L. WALL,<sup>11</sup> D. WALLER,<sup>5</sup> H. WAN CHAN TSEUNG,<sup>8</sup> D. L. WARK,<sup>27,28</sup> J. WENDLAND,<sup>20</sup> N. WEST,<sup>8</sup> J. F. WILKERSON,<sup>11</sup> J. R. WILSON,<sup>8,29</sup> J. M. WOUTERS,<sup>9</sup> A. WRIGHT,<sup>2</sup> M. YEH,<sup>17</sup> F. ZHANG,<sup>5</sup> AND K. ZUBER<sup>8,29</sup>

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### ABSTRACT

A search has been made for neutrinos from the *hep* reaction in the Sun and from the diffuse supernova neutrino background (DSNB) using data collected during the first operational phase of the Sudbury Neutrino Observatory, with an exposure of 0.65 ktons yr. For the *hep* neutrino search, two events are observed in the effective electron energy range of  $14.3 \text{ MeV} < T_{\text{eff}} < 20 \text{ MeV}$ , where 3.1 background events are expected. After accounting for neutrino oscillations, an upper limit of  $2.3 \times 10^4 \text{ cm}^{-2} \text{ s}^{-1}$  at the 90% confidence level is inferred on the integral total flux of *hep* neutrinos. For DSNB neutrinos, no events are observed in the effective electron energy range of  $21 \text{ MeV} < T_{\text{eff}} < 35 \text{ MeV}$ , and, consequently, an upper limit on the  $\nu_e$  component of the DSNB flux in the neutrino energy range

<sup>1</sup> Department of Physics and Astronomy, Laurentian University, Ramsey Lake Road, Sudbury, ON P3E 2C6, Canada.  
<sup>2</sup> Department of Physics, Queen's University, Kingston, ON K7L 3N6, Canada.  
<sup>3</sup> Department of Physics, University of Texas at Austin, Austin, TX 78712-0264.  
<sup>4</sup> Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104-6396.  
<sup>5</sup> Ottawa-Carleton Institute for Physics, Department of Physics, Carleton University, Ottawa, ON K1S 5B6, Canada.  
<sup>6</sup> Institute for Nuclear and Particle Astrophysics and Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720.  
<sup>7</sup> Physics Department, University of Guelph, Guelph, ON N1G 2W1, Canada.  
<sup>8</sup> Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK.  
<sup>9</sup> Los Alamos National Laboratory, Los Alamos, NM 87545.  
<sup>10</sup> Current address: Goldman Sachs, 85 Broad Street, New York, NY 10004.  
<sup>11</sup> Center for Experimental Nuclear Physics and Astrophysics and Department of Physics, University of Washington, Seattle, WA 98195.  
<sup>12</sup> Current address: Physics Department, Princeton University, Princeton, NJ 08544-0708.  
<sup>13</sup> Sudbury Neutrino Observatory Laboratory, P.O. Box 146, Lively, ON P3Y 1M3, Canada.  
<sup>14</sup> Current address: Department of Physics, University of California, Irvine, CA 92697.  
<sup>15</sup> Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139.  
<sup>16</sup> Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803.  
<sup>17</sup> Chemistry Department, Brookhaven National Laboratory, Upton, NY 11973-5000.  
<sup>18</sup> Current address: Graduate School of Engineering, Hiroshima University, Hiroshima 739-8526, Japan.  
<sup>19</sup> Tri-University Meson Facility, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada.  
<sup>20</sup> Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1, Canada.  
<sup>21</sup> Laboratório de Instrumentação e Física Experimental de Partículas, 1000-149 Lisboa, Portugal.  
<sup>22</sup> Current address: Fermi National Accelerator Laboratory, Batavia, IL 60510.  
<sup>23</sup> Current address: Department of Physics, University of Liverpool, Liverpool L69 7ZE, UK.  
<sup>24</sup> Current address: Department of Physics, University of Chicago, Chicago, IL 60637.  
<sup>25</sup> Current address: Lawrence Livermore National Laboratory, Livermore, CA 94551.  
<sup>26</sup> Current address: Remote Sensing Laboratory, P.O. Box 98521, Las Vegas, NV 89193.  
<sup>27</sup> Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, UK.  
<sup>28</sup> Also at: Imperial College, London SW7 2AZ, UK.  
<sup>29</sup> Current address: Department of Physics and Astronomy, University of Sussex, Brighton BN1 9QH, UK.

of  $22.9 \text{ MeV} < E_\nu < 36.9 \text{ MeV}$  of  $70 \text{ cm}^{-2} \text{ s}^{-1}$  is inferred at the 90% confidence level. This is an improvement by a factor of 6.5 on the previous best upper limit on the *hep* neutrino flux and by 2 orders of magnitude on the previous upper limit on the  $\nu_e$  component of the DSNB flux.

*Subject headings:* neutrinos — Sun: general — supernovae: general

## 1. INTRODUCTION

The Sudbury Neutrino Observatory (SNO) is a real-time, heavy water Cerenkov detector located in the Inco, Ltd. Creighton nickel mine near Sudbury, Ontario, Canada at a depth of 6010 m water equivalent (Boger et al. 2000). SNO detects electrons and neutrons from, respectively, charged-current (CC) and neutral-current (NC) interactions of neutrinos on deuterons, as well as neutrino-electron elastic scattering (ES) interactions, in 1 kton of  $\text{D}_2\text{O}$  contained in a 12 m diameter acrylic vessel (AV). These interactions are observed via Cerenkov light detected by 9456 photomultiplier tubes (PMTs) mounted on a 17.8 m diameter support structure. By comparing the observed rates of these interactions, SNO has demonstrated that a substantial fraction of the  $^8\text{B}$  electron neutrinos produced in the Sun transform into other active neutrino flavors (Ahmad et al. 2001, 2002a, 2002b, 2004; Aharmim et al. 2005). These results are consistent with the predictions of neutrino oscillations (Maki et al. 1962; Gribov & Pontecorvo 1969; Wolfenstein 1978; Mikheyev & Smirnov 1985).

The Sun generates energy by nuclear fusion; protons combine to form helium in reactions that release neutrinos. The primary solar fusion process is a series of reactions known as the *pp* chain. Five reactions in the *pp* chain produce neutrinos; the highest energy neutrinos are those from the *hep* reaction:  $^3\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu_e$ . The endpoint of the *hep* neutrino spectrum is 18.77 MeV and lies above that of the  $^8\text{B}$  spectrum, which is approximately 15 MeV. The flux of *hep* neutrinos (e.g., Bahcall & Krastev 1998; Bahcall & Pinsonneault 2004) is currently predicted to be  $(7.97 \pm 1.24) \times 10^3 \text{ cm}^{-2} \text{ s}^{-1}$  (Bahcall et al. 2006),<sup>30</sup> which is small compared to the fluxes from the other neutrino-producing reactions in the *pp* chain, including the  $^8\text{B}$  flux, which has been measured to be  $(4.95 \pm 0.42) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$  (Aharmim et al. 2005). The dominant contribution to the uncertainty in the *hep* neutrino flux prediction is 15.1% from the calculation of the nuclear matrix elements (Park et al. 2003). The previous best upper limit on the *hep* neutrino flux is  $7.3 \times 10^4 \text{ cm}^{-2} \text{ s}^{-1}$  at the 90% confidence level (CL), based on measurements with the Super-Kamiokande detector (Hosaka et al. 2006). After accounting for neutrino oscillations, this limit can be interpreted as an upper bound on the total flux of *hep* neutrinos of  $1.5 \times 10^5 \text{ cm}^{-2} \text{ s}^{-1}$ . Currently, only one reaction ( $^8\text{B}$ ) from the *pp* chain has been uniquely observed and measured experimentally. An observation of *hep* neutrinos would give further confirmation of the *pp* chain as the primary solar energy generation mechanism and would allow further tests of the solar model.

Neutrinos produced in core-collapse supernovae also contribute to the energy region above the  $^8\text{B}$  endpoint. The current generation of neutrino detectors can detect the transient signal from a supernova in the Milky Way, but the expected signal from a supernova in a more distant galaxy is fewer than one event. Neutrinos from all extragalactic supernovae since the beginning of the formation of stars in the universe constitute the diffuse supernova neutrino background (DSNB), which may be detectable. Model predictions range from 0.19 to  $1.49 \text{ cm}^{-2} \text{ s}^{-1}$  for the  $\nu_e$

component of the DSNB flux in the neutrino energy range  $22.9 \text{ MeV} < E_\nu < 36.9 \text{ MeV}$  (Beacom & Strigari 2006; Ando & Sato 2003<sup>31</sup>). The best upper limit on the  $\bar{\nu}_e$  component of the DSNB flux is  $1.2 \text{ cm}^{-2} \text{ s}^{-1}$  at the 90% CL for  $E_\nu > 19.3 \text{ MeV}$ , based on measurements with the Super-Kamiokande detector (Malek et al. 2003). While an indirect limit on the  $\nu_e$  component of the DSNB flux can be inferred from this (Lunardini 2006), the previous best direct upper limit is  $6.8 \times 10^3 \text{ cm}^{-2} \text{ s}^{-1}$  for neutrino energies  $25 \text{ MeV} < E_\nu < 50 \text{ MeV}$ , based on measurements with the Mont Blanc liquid scintillator detector (Aglietta et al. 1992).

A search for *hep* and DSNB neutrinos has been performed by counting the numbers of events in predefined energy intervals (signal boxes) above the  $^8\text{B}$  endpoint. The most sensitive signal boxes for this analysis were selected by evaluating the predicted signal and background levels before examining the data. Given the predicted signal and background levels in the signal boxes, limits on the flux of *hep* and DSNB neutrinos are set using a modified Feldman-Cousins technique. The following sections describe the data set, detector response, determination of the backgrounds, analysis procedures, and limits obtained for the *hep* and DSNB neutrino fluxes.

## 2. THE DATA SET

The data included in these analyses were collected during the initial phase of SNO operation, during which the detector contained pure  $\text{D}_2\text{O}$ . The data were collected from 1999 November 2 until 2001 May 28 and comprise 306.4 live days corresponding to an exposure of 0.65 ktons yr (Ahmad et al. 2002a).

Since results from this phase were last published, numerous improvements have been made to the analysis tools, many of which were used in the analysis of data from phase two (Aharmim et al. 2005), for which 2 tons of salt were dissolved in the heavy water. Further improvements were applied in this analysis, the most significant of which was improved estimation of the effective electron kinetic energies ( $T_{\text{eff}}$ ) of the events, based on the optical paths to each operational PMT. Other enhancements include improved handling of false hits due to cross talk between electronics channels and an improved accounting of working PMTs using both neutrino and calibration data to track bad channels. However, the vertex reconstruction algorithm was the same as that used in previous phase one analyses, in which events were reconstructed under the assumption that they are due to single electrons. This is more suited for the reconstruction of *hep* and DSNB events than the algorithm used in phase two. After the application of the new analysis tools, events inside the kinetic energy window of  $12 \text{ MeV} < T_{\text{eff}} < 35 \text{ MeV}$  were not examined until the *hep* and DSNB signal boxes had been selected.

In addition to the event selection discussed in Aharmim et al. (2005), which includes a selection that removes Michel electrons with visible precursors, selection criteria were applied to remove backgrounds from atmospheric neutrino interactions. As the *hep* and DSNB signals are expected to be single electron events, these backgrounds can be reduced significantly by removing events that

<sup>30</sup> The GS98 elemental abundances are selected for the reference model of solar neutrino fluxes.

<sup>31</sup> Flux predictions from this paper have been increased by a factor of 3, as recommended by the authors, to account for updated star formation rate data. Estimates for the  $\nu_e$  DSNB fluxes were provided by the authors on request.

correlate in time with neutrons, electrons, or  $\gamma$ -rays. Consequently, any candidate event that appeared within 250 ms of another with  $T_{\text{eff}} > 4$  MeV and a reconstructed vertex inside the AV was removed. In addition, two Kolmogorov-Smirnov (K-S) tests were applied: one to test the azimuthal symmetry of the PMT hits about the reconstructed event direction and the other to test the compatibility of the angular distribution of PMT hits with that expected from a single electron. In the signal boxes, the selections on PMT hit isotropy and the prompt light fraction were further tightened with respect to previous SNO analyses (Aharmim et al. 2005), which was possible in this analysis due to the higher energies of the candidate events. The combined event selection reduced the expected number of atmospheric neutrino events in the *hep* signal box by a factor of 29 and in the DSNB signal box by a factor of 77. The signal acceptance of the combined event selection is  $96.6\% \pm 0.7\%$  for *hep* and  $94.0\% \pm 1.5\%$  for DSNB events, measured using calibration source data and simulation.

### 3. DETECTOR RESPONSE

To understand the signals and backgrounds in this analysis, it is important to measure the energy response and uncertainties in the signal boxes. The energy response can be parameterized by a Gaussian of resolution  $\sigma_T = -0.154 + 0.390T_e^{1/2} + 0.0336T_e$ , where  $T_e$  is the true kinetic energy of the electron. In SNO analyses, Monte Carlo simulation is used to estimate the response of the detector to different particles. The propagation of electrons, positrons, and  $\gamma$ -rays is carried out using EGS4 (Nelson et al. 1985). The uncertainties in the energy scale and resolution of the SNO detector have typically been measured using 6.13 MeV  $\gamma$ -rays from a  $^{16}\text{N}$  source (Dragowsky et al. 2002). At the higher energies more characteristic of this analysis, Michel electrons from muon decays and a  $pT$  [ $^3\text{H}(p, \gamma)^4\text{He}$ ] source (Poon et al. 2000), which produces 19.8 MeV  $\gamma$ -rays, were used to complement the  $^{16}\text{N}$  measurements. Using simple event selection criteria, including one based on the time between events, 135 Michel electrons were identified in the data. Potential deviations in energy scale and energy resolution between data and simulations were assumed to be linear functions of energy. These functions were fit with a maximum likelihood technique using data from  $^{16}\text{N}$  and  $pT$  sources as further constraints. The results were used to refine the energy scale and resolution estimates and to measure their uncertainties at the analysis thresholds. An energy scale uncertainty of 0.96% and a resolution uncertainty of 3.8% were estimated at the *hep* threshold of 14.3 MeV. At the DSNB threshold of 21 MeV, an energy scale uncertainty of 1.06% and a resolution uncertainty of 6.0% were estimated. Correlations between these quantities were included in the final analysis. Additional non-Gaussian tails to the resolution function were also considered but were found to be insignificant. Data and Monte Carlo distributions of  $T_{\text{eff}}$  for  $^{16}\text{N}$  and  $pT$  calibration events and for Michel electrons are shown in Figure 1.

Event vertex and direction reconstruction were unchanged from the analysis in Ahmad et al. (2002a). The position resolution at 15 MeV is  $12.0 \pm 2.5$  cm, and the angular resolution is  $20.6^\circ \pm 0.4^\circ$ . These were measured using a combination of  $^{16}\text{N}$  source data and simulation. The same fiducial volume, defined by events reconstructed within a distance of 550 cm from the center of the detector, was selected. The uncertainty on the expected number of events within the fiducial volume due to vertex accuracy was 2.9%.

### 4. BACKGROUNDS

Three distinct classes of background are considered:  $^8\text{B}$  neutrino interactions, atmospheric neutrino interactions, and instru-

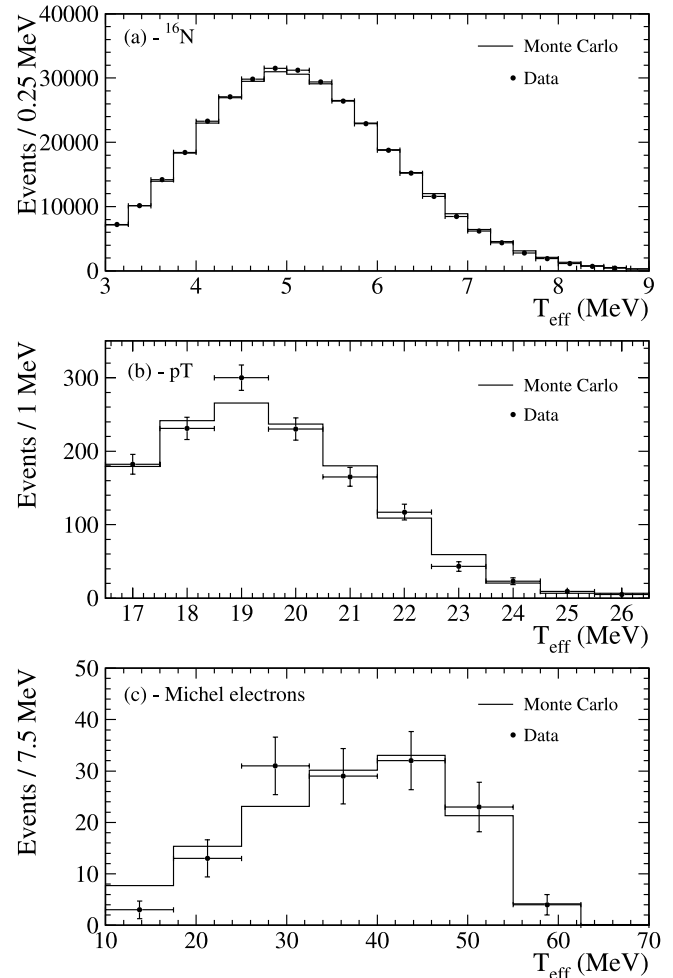


FIG. 1.—Effective electron kinetic energy spectra from data and Monte Carlo for (a) events from the  $^{16}\text{N}$  source, (b) events from the  $pT$  source, and (c) Michel electrons. The data are shown in the energy regions free of source-related backgrounds.

mental backgrounds. Figure 2 shows the simulated energy spectra of the signals and backgrounds, normalized to their expected rates.

Electrons from  $^8\text{B}$  neutrino interactions are the dominant (97%) background for the *hep* analysis but are a negligible background for DSNB. These events can reconstruct into the *hep* signal box due to the finite energy resolution of the detector. The magnitude of the  $^8\text{B}$  background depends on the details of the detector response and is very sensitive to the energy scale and resolution at threshold. In the CC interaction, by which SNO predominantly detects the  $^8\text{B}$  and *hep* neutrinos, there is a strong correlation between neutrino and electron energy. This, in addition to a cross section that rises with the square of the energy rather than linearly, provides a clearer distinction between the two neutrino spectra in the region of the  $^8\text{B}$  endpoint than is possible with the ES interaction.

The  $^8\text{B}$  background also depends on the details of the shape of the detected electron spectrum. The  $^8\text{B}$  neutrino spectrum from Winter et al. (2003, 2006) was assumed along with its quoted uncertainties. Neutrino oscillations were taken into account by correcting and combining the electron spectra from CC and ES interactions using the energy-dependent  $\nu_e$  survival probability from the joint solar neutrino and KamLAND (Kamioka Liquid Scintillator Anti-Neutrino Detector; Araki et al. 2005) oscillation analysis presented in Aharmim et al. (2005). Additional spectral

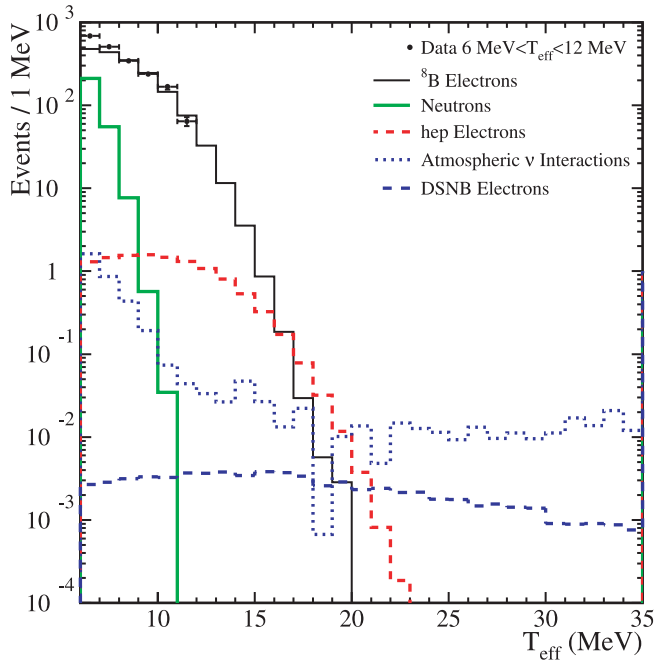


FIG. 2.—Simulated effective electron kinetic energy spectra of the signals and backgrounds of interest in the *hep* and DSNB analyses. Also shown are the data in the range  $6 \text{ MeV} < T_{\text{eff}} < 12 \text{ MeV}$  that are used to normalize the  ${}^8\text{B}$  electron and neutron distributions. The atmospheric neutrino background is made up of a number of different signals: neutrons at low energies,  $\gamma$ -rays from nuclear de-excitations at intermediate energies, and Michel electrons and CC interactions of atmospheric  $\nu_e$  and  $\bar{\nu}_e$  on deuterons at higher energies. The DSNB model in this figure is the  $T = 6 \text{ MeV}$  model from Beacom & Strigari (2006). The third class of background, instrumental backgrounds, is negligible and is not shown in this figure.

adjustments were included to account for CC interactions on  ${}^{18}\text{O}$ , radiative corrections to the CC deuteron cross section (Nakamura et al. 2002; Kurylov et al. 2002), and the acceptance of the event selection. The expectation for the *hep* signal is constructed in the same way using the neutrino spectrum from Bahcall & Ulrich (1988) with corrections from Bahcall (1997).

After the determination of the  ${}^8\text{B}$  signal shape, its normalization was determined using data at lower energies, where the *hep* signal is insignificant. In an energy window of  $6 \text{ MeV} < T_{\text{eff}} < 12 \text{ MeV}$ , 2006 events were observed. To determine normalizations, these data were fit using a maximum likelihood technique with probability density functions (PDFs) for the  ${}^8\text{B}$  electrons (CC and ES signals) and neutrons (NC signal and background). The distributions used in this fit were functions of event energy and direction with respect to the Sun ( $\cos \theta_\odot$ ). The results of this fit were then used to estimate the  ${}^8\text{B}$  contribution inside the signal boxes.

Atmospheric neutrino interactions produce a second class of background events. They are the dominant background in the DSNB signal box and come from several sources:

1. Electrons from low-energy ( $E_\nu < 100 \text{ MeV}$ ) charged-current  $\nu_e$  and  $\bar{\nu}_e$  interactions;
2. Michel electron events, in which the precursor muons (and pions) are below the Cerenkov threshold and do not trigger the detector;
3. 15.1 MeV  $\gamma$ -rays from de-excitation of an excited state of  ${}^{12}\text{C}$  created via a nuclear cascade from neutrino interactions on  ${}^{16}\text{O}$ ;
4. Misidentified nonelectron events.

For low-energy atmospheric  $\nu_e$  and  $\bar{\nu}_e$ , the flux prediction from Battistoni et al. (2005) is used, which has an uncertainty of 25%.

Only charged current interactions on deuterons, with cross sections from Nakamura et al. (2002) and Kurylov et al. (2002), are considered; the contributions from other interaction types are not significant. The interactions of these neutrinos constitute 14% of the DSNB background but are insignificant in the *hep* signal box.

Events from sources 2–4 are associated with atmospheric neutrinos of higher energy ( $E_\nu > 100 \text{ MeV}$ ). Monte Carlo simulations were used to generate atmospheric neutrino interactions in the SNO detector with statistics equivalent to 500 times the expected number of events. For this purpose, the package NUANCE (Casper 2002) was used,<sup>32</sup> with the Barto04 flux prediction for Sudbury (Barr et al. 2004). The flux uncertainty in the neutrino energy range that contributes to the background is 10%. The events generated by NUANCE were then propagated and fully simulated in the SNO Monte Carlo, from which background predictions were obtained after application of the event selection.

To assess uncertainties these events were divided into three categories. The first category,  $\nu_\mu$  quasi-elastic (QE) CC events, is the primary source of untagged Michel electrons and originates from neutrinos in the energy range 150–250 MeV. The uncertainty on the cross section in this energy region is 25% (Barish et al. 1977). These Michel electrons comprise 80% of the DSNB background. For the second category, 15.1 MeV  $\gamma$ -ray events, there are no data in the literature on production rates, and thus a 100% uncertainty was assigned to the production rate predicted by NUANCE, which uses the calculation of Ejiri (1993). These  $\gamma$ -rays constitute half of the atmospheric background in the *hep* analysis, but due to the magnitude of the  ${}^8\text{B}$  background they constitute only 1.5% of the total *hep* background. The final category comprises QE NC events and interactions that produce pions, to which a cross section uncertainty of 30% is assigned (Ahrens et al. 1987).

There is an additional uncertainty applicable to the latter two categories of atmospheric neutrino interactions. A comparison of events from data and the simulation has shown that the simulation underestimates the production of correlated neutrons. It is unclear whether this is due to errors in the prediction of primary neutron production or in the transport of hadrons in the simulation. However, there is good agreement between data and Monte Carlo for correlated electron events. Events in the simulation are reweighted in such a way that the average neutron multiplicity is changed to better match the data. This results in a change to the background rejection rate in the simulation due to time-correlated neutrons. This correction results in an additional uncertainty of 7% in the rate of atmospheric background events inside the signal box that are not due to QE CC interactions. After application of the event selection to remove events with correlated neutrons, electrons, and  $\gamma$ -rays, the atmospheric background in these analyses is reduced by a factor of 2.

To verify the predictions for the atmospheric neutrino background, data outside the signal box in the energy range  $35 \text{ MeV} < T_{\text{eff}} < 55 \text{ MeV}$  were examined. This energy range was selected to be most sensitive to the main component of the atmospheric neutrino background: the Michel electrons. In this energy range, 0.28 Michel electrons and 0.05 electrons from low-energy charged-current atmospheric neutrino interactions are expected. One event was observed, consistent with the predictions of the simulation. Inside this energy range, the effect of the event selection on events correlated with neutrons, electrons, or  $\gamma$ -rays was also examined. Two such events were observed, each consistent with being an otherwise untagged Michel electron preceded by a  $\gamma$ -ray from the de-excitation of the nucleus participating in the primary neutrino

<sup>32</sup> NUANCE ver. 3r009 was used in this analysis.





