Solar neutrinos from CNO electron capture

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(Received 23 September 2003; published 27 January 2004)

The neutrino flux from the sun is predicted to have a CNO-cycle contribution as well as the known pp-chain component. Previously, only the fluxes from \( \beta^+ \) decays of \(^{13}\text{N},^{15}\text{O},\) and \(^{17}\text{F}\) have been calculated in detail. Another neutrino component that has not been widely considered is electron capture on these nuclei. We calculate the number of interactions in several solar neutrino detectors due to neutrinos from electron capture on \(^{13}\text{N},^{15}\text{O},\) and \(^{17}\text{F},\) within the context of the standard solar model. We also discuss possible nonstandard models where the CNO flux is increased.

DOI: 10.1103/PhysRevC.69.015801

PACS number(s): 23.40.—s, 26.65.+t, 14.60.Lm

I. INTRODUCTION

Experimental data gathered from both radiochemical [1–4] and real-time solar neutrino experiments [5,6] not only have revealed the phenomena of neutrino oscillations, but also have established the predominant mechanism for solar fuel burning [7]. The driving component for nuclear burning in the sun is the pp fusion chain. However, it is predicted that a portion of the solar neutrino flux also comes from the CNO cycle [8]. The CNO reaction products that have been shown to produce significant neutrino fluxes include \( \beta^+ \) decays of \(^{13}\text{N},^{15}\text{O},\) and \(^{17}\text{F}\). However, an additional source of neutrinos is electron capture on \(^{13}\text{N},^{15}\text{O},\) and \(^{17}\text{F}\), within the context of the standard solar model. We also discuss possible nonstandard models where the CNO flux is increased.

II. ELECTRON-CAPTURE FLUXES

The electron-capture processes that occur in the CNO cycle involve the following reactions:

\[
^{13}\text{N} + e^- \rightarrow ^{13}\text{C} + \nu_e, \quad (1)
\]

\[
^{15}\text{O} + e^- \rightarrow ^{15}\text{N} + \nu_e, \quad (2)
\]

\[
^{17}\text{F} + e^- \rightarrow ^{17}\text{O} + \nu_e. \quad (3)
\]

If the electron-capture process is dominated by bound electrons, then it is possible to relate the electron-capture flux directly to the \( \beta^+ \) decay flux [10]. At solar temperatures and densities, however, one must take into account the contribution from both bound and continuum electrons. The ratio between electron-capture rates in the sun and laboratory measurements is given by [11]

\[
R = \frac{\lambda_{\text{sun}}}{\lambda_{\text{lab}}} = \frac{1}{2} \left| \frac{\psi(0)_{\text{sun}}}{\psi(0)_{\text{lab}}} \right|^2, \quad (4)
\]

where \( n_e \) is the electron density in the sun, and the atomic wave functions \( \psi \) are given by

\[
|\psi(0)_{\text{lab}}|^2 = \frac{1}{\pi} Z^3 \kappa(Z), \quad (5)
\]

\[
|\psi(0)_{\text{sun}}|^2 = \exp \left( -\frac{Z \beta}{R_D} \right) (\omega_\alpha + \omega_\beta). \quad (6)
\]

Here \( Z \) is the charge, \( \kappa(Z) \) is the correction term applied to the pure Coulomb field of \( 4Z^3 a_0^3 \), as tabulated in Ref. [12], \( \beta = 1/kT \) is expressed in units of \( \hbar = e = m_\gamma = 1 \) [13], and \( T \) is the solar temperature. The factors \( \omega_\alpha \) and \( \omega_\beta \) are continuum and bound state electron density ratios at the nucleus for Coulomb-distorted waves relative to plane waves. Also included is a weak solar plasma screening correction which

| Element | \( \omega_\alpha/(\omega_\alpha + \omega_\beta) \) | \( |\psi(0)_{\text{sun}}|^2 \) | \( R_0 \) | \( R_c \) |
|---------|-----------------|-----------------|---------|---------|
| \(^{\text{7}}\text{Be}\) | 0.302 | 3.76 | 0.858 | 0.804 |
| \(^{\text{13}}\text{N}\) | 0.662 | 11.08 | 0.419 | 0.403 |
| \(^{\text{15}}\text{O}\) | 0.749 | 16.14 | 0.400 | 0.398 |
| \(^{\text{17}}\text{F}\) | 0.818 | 23.75 | 0.406 | 0.405 |

TABLE I. The fraction of bound state electrons in the solar core, the atomic wave function at the nucleus in the sun, and the total correction to the electron-capture rate. Both fixed point \( (R_0) \) and volume-integrated \( (R_c) \) ratios are shown. \(^{\text{7}}\text{Be}\) is shown for comparison.
depends on the Debye radius \( R_D \) [14]. The continuum and bound state electron density ratios are given by [15]

\[
\omega_c = \left( \frac{2 \pi \eta}{1 - e^{-2 \pi \eta}} \right)
\]

\[
\omega_b = \pi^{1/2}(2Z^2\beta)^{3/2} \sum^{1/2} \frac{1}{n!} \exp \left( \frac{Z^2 \beta}{2n^2} \right)
\]

where \( \eta = Z/V \) is the inverse velocity averaged over the electron Maxwell-Boltzmann distribution.

The electron density ratios are evaluated at both a fixed point in the solar core \( (R_0) \) and integrated over the entire solar volume \( (R_s) \). The fixed point used is 0.057 of the solar radius, where the \( 1^3N \), \( 1^5O \), and \( 1^7F \) fluxes peak. At this location, the temperature is 1.48 × 10^7 K, the Debye radius is 0.45, and the density is 5.32 × 10^25 atoms/cm^3 [7]. The effect of the full integration on the fluxes is small for the nuclei of interest (~3% for \( 1^3N \) and less than 1% for \( 1^5O \) and \( 1^7F \)). The total correction due to continuum electron capture is shown in Table I. The relative \( K \)-shell/\( L \)-shell occupancies for \( 1^3N \), \( 1^5O \), and \( 1^7F \) are all greater than 90% [12]. Capture of both \( K \) and \( L \)-shell electrons has been included here. For evaluation of the electron-capture rate with accuracy of a few percent the radiative corrections should be included (see, for example, Ref. [16]).

Table II shows the expected total rate of neutrinos from \( K \) shell and continuum electron-capture processes, assuming the solar burning cycle is dominated by \( pp \) fusion. The major contribution to the uncertainties on the electron-capture fluxes comes from the uncertainties on the standard solar model (SSM) \( \beta^+ \) decay fluxes [7]. The neutrino flux from these sources is of the same order as the \( 8B \) flux, though at lower neutrino energies. The solar neutrino spectrum, including the CNO electron-capture neutrino lines, is shown in Fig. 1. There is in addition an electron-capture branch for \( 8B \) decay [18], but its total flux is 1.3 cm^-2 s^{-1}, too small to appear on the graph.

To determine the observed rate at a given experiment, we consider charged current (CC), neutral current (NC), and elastic scattering (ES) interactions on a variety of targets. The cross sections used for \( ^3H \), \( ^7Li \), \( ^37Cl \), and \( ^71Ga \) are taken from Refs. [19–22]. A precise accounting of radiative corrections has not yet been applied to all of these processes. In the case of deuterium targets, the value of \( L_{1A} \) [19] was set to 4.0 and radiative corrections are included [16]. For the elastic scattering cross section, the following relation was used:

\[
\frac{d\sigma(\nu,e^-)}{dT_e} = \frac{G_F^2 s}{\pi} \left( \frac{\left( 1 - T_e \right)^2}{E_{\nu}} \right) - s_L s_R \frac{m_n T_e}{E_{\nu}^2}
\]

where \( G_F \) is the Fermi constant, \( s \) is the center-of-mass energy, \( s_L(R) \) are the left (right) handed couplings for the weak current, \( T_e \) is the electron kinetic energy, and \( E_{\nu} \) is the neutrino energy. Uncertainties on electron, \( ^3H \), and \( ^7Li \) targets are well understood at the level of 1% [23]. Uncertainties in the CC cross sections for \( ^37Cl \) are dominated by transitions to forbidden states, which at these energies are 1–2%. For CC interactions on \( ^7Ga \), allowed transitions to excited states play a significant role, and the uncertainties are expected to be larger at these energies. The expected neutrino rates for various targets are presented in Table III.

**TABLE III.** Neutrino interaction rates with various detector materials, assuming no neutrino oscillations. Rates are given in units of SNU’s (1 SNU = 10^{-36} interactions/atom/s), except for ES, which is given in 10^{-36} interactions/electron/s.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>ES</th>
<th>(^3H) NC</th>
<th>(^3H) CC</th>
<th>(^7Li)</th>
<th>(^37Cl)</th>
<th>(^71Ga)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^1^3N)</td>
<td>2.220</td>
<td>7.98 × 10^{-3}</td>
<td>0</td>
<td>3.63 × 10^{-3}</td>
<td>8.79 × 10^{-2}</td>
<td>2.11 × 10^{-3}</td>
</tr>
<tr>
<td>(^1^5O)</td>
<td>2.754</td>
<td>4.46 × 10^{-3}</td>
<td>2.26 × 10^{-4}</td>
<td>5.79 × 10^{-3}</td>
<td>6.65 × 10^{-2}</td>
<td>1.60 × 10^{-3}</td>
</tr>
<tr>
<td>(^1^7F)</td>
<td>2.761</td>
<td>7.80 × 10^{-5}</td>
<td>4.08 × 10^{-6}</td>
<td>1.02 × 10^{-4}</td>
<td>1.17 × 10^{-3}</td>
<td>2.80 × 10^{-5}</td>
</tr>
</tbody>
</table>
TABLE IV. CNO electron-capture neutrino interaction rates in various detectors. Rates are presented for the SSM CNO fraction, the upper limit to the CNO fraction that comes from solar neutrino data, and a toy model where almost all of the solar luminosity is due to the CNO cycle. Rates are given as a fraction of the observed rate, except for BOREXINO, which is given as a fraction of the expected rate.

<table>
<thead>
<tr>
<th>Detector</th>
<th>SSM</th>
<th>7.3%</th>
<th>99.95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNO NC (salt phase)</td>
<td>0.01%</td>
<td>0.05%</td>
<td>0.6%</td>
</tr>
<tr>
<td>BOREXINO</td>
<td>0.1%</td>
<td>0.3%</td>
<td>4.3%</td>
</tr>
<tr>
<td>$^{37}$Cl</td>
<td>0.2%</td>
<td>0.7%</td>
<td>9.7%</td>
</tr>
<tr>
<td>$^{71}$Ga</td>
<td>0.1%</td>
<td>0.2%</td>
<td>3.3%</td>
</tr>
</tbody>
</table>

III. ALTERNATIVE SOLAR MODELS

The relatively large rates suggest that a $^7$Li-based detector might be a viable next-generation solar neutrino experiment. For example, a water Cherenkov detector with dissolved $^7$Li, such as suggested in Ref. [24], might be a workable design.

Of particular interest is whether the CNO electron-capture flux constitutes a serious background for current neutrino experiments. For SNO, these NC rates correspond to about 0.4 $^{15}$O neutrino NC event per year and about 0.01 $^{17}$F events per year. The latter is negligible, but the $^{15}$O contributes a small model-dependent background to the $^8$B measurement. The CC interactions are below the SNO analysis threshold, so they do not contribute significantly to SNO results. Below the 5.5 MeV analysis threshold in the recent SNO publication [23] there were about 13 events expected from this source. The ES interactions could be detected in a liquid scintillator experiment such as KamLAND [25] or BOREXINO [26]. For example, in BOREXINO the electron-capture neutrino rates would be about 0.1% of the expected SSM signal. The expected rates for $^{71}$Ga and $^{37}$Cl have also been calculated and are shown in Table IV.

IV. CONCLUSION

The neutrino flux from electron capture in the solar CNO cycle has been calculated. The rate of such neutrinos on current detectors is expected to be small, though the process does introduce a model-dependent background to the SNO measurement of the total $^8$B flux, at the level of about one event per year. However, the model-dependence is small, since the fractional contribution of the CNO cycle to the solar luminosity is limited experimentally to 7.3%, only about a factor of 5 above the SSM fraction. Future experiments can take advantage of the electron-capture channels to explicitly set more stringent limits on the fraction of CNO neutrinos.

ACKNOWLEDGMENTS

The authors would like to thank M. K. Bacrania for his assistance in preparing Fig. 1. This work was supported by the U.S. Department of Energy under Grant No. DE-FG06-90ER40537.


[13] With this convention, the unit of energy is the Hartree energy $m_e c^2 a_0^2$ and the unit of length is the Bohr radius $a_0$.


