

Does the Sun Shine by pp or CNO Fusion Reactions?

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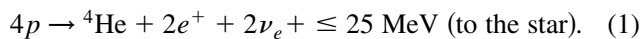
(Received 23 December 2002; published 2 April 2003)

We show that solar neutrino experiments set an upper limit of 7.8% (7.3% including the recent KamLAND measurements) to the fraction of energy that the Sun produces via the CNO fusion cycle, which is an order of magnitude improvement upon the previous limit. New experiments are required to detect CNO neutrinos corresponding to the 1.5% of the solar luminosity that the standard solar model predicts is generated by the CNO cycle.

DOI: 10.1103/PhysRevLett.90.131301

PACS numbers: 26.65.+t, 14.60.Pq

In 1939, Hans Bethe described in an epochal paper [1] two nuclear fusion mechanisms by which main sequence stars like the Sun could produce the energy corresponding to their observed luminosities. The two mechanisms have become known as the p - p chain and the CNO cycle [2]. For both the p - p chain and the CNO cycle the basic energy source is the burning of four protons to form an alpha particle, two positrons, and two neutrinos. Thus



In the p - p chain, fusion reactions among elements lighter than $A = 8$ produce a characteristic set of neutrino fluxes, whose spectral energy shapes are known but whose fluxes must be calculated with a detailed solar model. In the CNO chain, with ${}^{12}\text{C}$ as a catalyst, ${}^{13}\text{N}$ and ${}^{15}\text{O}$ beta decays are the primary source of neutrinos.

The first sentence in Bethe's paper reads as follows: "It is shown that the most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons." Bethe's conclusion about the dominant role of the CNO cycle relied upon a crude model of the Sun. Over the next two and a half decades, the results of increasingly more accurate laboratory measurements of nuclear fusion reactions and more detailed solar model calculations led to the theoretical inference that the Sun shines primarily by the p - p chain rather than the CNO cycle. Currently, solar model calculations imply [3] that 98.5% of the solar luminosity is provided by the p - p chain and only 1.5% is provided by CNO reactions.

In recent years, there have been many analyses of solar neutrino oscillations, essentially all of which assumed that the CNO neutrino fluxes were equal to their predicted standard solar model values (see Refs. [4–6] and

references cited therein). However, from the earliest days of solar neutrino research, a primary goal of the field was to test the solar model prediction that the Sun shines by the p - p chain and not by the CNO cycle [7]. This goal has largely been ignored in the last decade or so as solar neutrino experiments concentrated on the more accessible, higher-energy ${}^8\text{B}$ neutrinos. In this paper, we return to the question of how well we can measure, or set an upper limit to, the CNO neutrino fluxes.

Unfortunately, the standard solar model prediction for the CNO fluxes is difficult to test. Radiochemical experiments with chlorine [8] and gallium [9–11] do not measure the energy of the neutrinos detected; they measure the rate of neutrino induced events above a fixed energy threshold. The neutrino-electron scattering experiments, Kamiokande [12] and Super-Kamiokande [13], provide information about neutrinos but only those that have energies well above the maximum energies of the ${}^{13}\text{N}$ ($E_{\text{max}} = 1.2 \text{ MeV}$) and ${}^{15}\text{O}$ ($E_{\text{max}} = 1.7 \text{ MeV}$) neutrinos. The radiochemical experiments are sensitive to only electron-type neutrinos, and the neutrino-electron scattering experiments are primarily sensitive to electron-type neutrinos. The heavy water experiment, SNO [5,14], measures higher energy neutrinos. The goal of uniquely identifying CNO neutrinos is made even more difficult by the fact that neutrino oscillations can change in an energy dependent way the probability that electron-type neutrinos created in the Sun reach the Earth as electron-type neutrinos [15,16].

Because of these complications, it was possible to find neutrino oscillation solutions in which 99.95% of the Sun's luminosity is supplied by the CNO cycle [17]. These "large CNO" oscillation solutions describe well all of the measurements from the chlorine [8], SAGE [9],

GALLEX [10], and Kamiokande [12] solar neutrino experiments. Modern solar models do not predict a large CNO contribution to the solar luminosity, but the goal is to test experimentally — not just assume — this prediction.

In this paper, we use data from the chlorine, SAGE, GALLEX, GNO, Super-Kamiokande, and SNO solar neutrino experiments, and from the recent KamLAND [18] reactor measurements, to set an experimental limit on the CNO contribution to the solar luminosity that is an order of magnitude more stringent than the previous best limit [17]. Although individual experiments do not constrain well the CNO fluxes, a global solution to all the available neutrino data provides a powerful upper limit. We also discuss how well future experiments can do in detecting the CNO neutrinos.

Here is our strategy. For each value of the CNO luminosity fraction, L_{CNO}/L_{\odot} , we search the two-component neutrino oscillation parameter space with a dense mesh corresponding to the neutrino mass difference $10^{-12} \text{ eV}^2 < \Delta m^2 < 10^{-3} \text{ eV}^2$ (721 mesh points) and mixing angles $0.0001 < \tan^2\theta < 10$ (401 mesh points), as well as the solar neutrino fluxes (see below). [We verify later that our approximation of only two neutrinos does not limit the validity of the upper bound we derive. See discussion following Eq. (5).] We calculate the global χ^2 by fitting to all the available data,

$$\chi^2 = \chi_{\text{solar}}^2 + \chi_{\text{KamLAND}}^2. \quad (2)$$

We carry out a global analysis [4] of the solar neutrino data letting the neutrino fluxes be free variables and using data from 80 measurements: 44 data points from the Super-Kamiokande zenith-angle energy distribution, 34 data points from the SNO day-night energy spectrum [5,14], and 2 radiochemical rates from Cl [8] and Ga [9–11]. We define the 3σ upper limit for the CNO neutrino fluxes by determining when $\chi^2 = \chi_{\text{min}}^2 + 9$ after marginalizing over the oscillation parameters Δm^2 and $\tan^2\theta$ and over the other neutrino fluxes.

Using the data provided in Ref. [18], we calculate the positron spectrum in the KamLAND detector with the procedures described in Refs. [18–21]. In the absence of neutrino oscillations, we find (in agreement with Ref. [18]) 86.8 expected neutrino events above 2.6 MeV visible energy for the stated experimental conditions. The positron energy spectrum that we calculate is in excellent agreement with the energy spectrum presented by the KamLAND Collaboration. Further details of our analysis of the KamLAND and solar data can be found in Ref. [22].

We impose the “luminosity constraint” on the solar neutrino fluxes; i.e., we require that the sum of the thermal energy generation rates associated with each of the solar neutrino fluxes be equal to the solar luminosity [23]. The fraction of the Sun’s luminosity that arises from CNO reactions can be written as [24]

$$\frac{L_{\text{CNO}}}{L_{\odot}} = \sum_{i=N,O,F} \left(\frac{\alpha_i}{10 \text{ MeV}} \right) a_i \phi_i, \quad (3)$$

where the constant α_i is the energy provided to the star by nuclear fusion reactions associated with the i th neutrino flux, a_i is the ratio of the neutrino flux $\Phi_i(\text{BP00})$ of the standard solar model to the characteristic solar photon flux defined by $L_{\odot}/[4\pi(\text{AU})^2(10 \text{ MeV})]$, and ϕ_i is the ratio of the true solar neutrino flux to the neutrino fluxes predicted by the BP00 standard solar model [3]. Reference [24] presents a detailed derivation of Eq. (3) and the numerical values for the coefficients α_i and a_i .

We treat as free parameters all the solar neutrino fluxes that are normally reported in solar neutrino calculations (cf. the Bayesian approach of Ref. [25] and of Refs. [21,24]). There are then 10 free parameters: the two oscillation parameters, Δm^2 and $\tan^2\theta$, and the 8 neutrino fluxes, p - p , pep , ${}^7\text{Be}$, ${}^8\text{B}$, and hep (from the p - p chain) and ${}^{13}\text{N}$, ${}^{15}\text{O}$, and ${}^{17}\text{F}$ (from the CNO cycle). To speed up the calculations, we made some approximations that we have checked do not affect the accuracy of our search. Two of the solar neutrino fluxes, hep and ${}^{17}\text{F}$, are small as a result of nuclear physics considerations. In the initial search calculations, we set hep equal to its solar model value and ${}^{17}\text{F} = [({}^{17}\text{F}/{}^{13}\text{N})_{\text{solar model}}]{}^{13}\text{N}$. We checked that our results are unchanged if the hep solar model flux is multiplied by eight (present experimental bound from the high energy bins at Super-Kamiokande [26]) or if we set the ${}^{17}\text{F}$ flux equal to the ${}^{17}\text{N}$ flux. Also, the ratio of the pep neutrino flux to the p - p neutrino flux is fixed to high accuracy because they have the same nuclear matrix element. We have set the ratio equal to the standard solar model value and have checked that our results are unchanged if this ratio is varied by 10% (an enormous change). We set the ${}^{13}\text{N}$ flux equal to the ${}^{15}\text{O}$ flux, which is expected in the limit that the CNO contribution to the luminosity is dominant. We also verified that the results of our search are unchanged if we set the ratio of ${}^{13}\text{N}$ to ${}^{15}\text{O}$ neutrino fluxes equal to the standard solar model value, the ratio expected if the p - p contribution is dominant. Finally, we checked several intermediate values of this ratio to see that the upper limit we quote here is robust and valid in all cases.

We find the minimum value of χ^2 for each assumed value of the CNO luminosity fraction by marginalizing over the neutrino oscillation parameters and over the non-CNO neutrino fluxes. We performed the calculations in two stages: first using only the solar neutrino data and second using both the solar neutrino and the KamLAND data. We carried out calculations for oscillations to purely active neutrinos, to purely sterile neutrinos, and to active-sterile admixtures as described in Ref. [27] (see also last reference in Ref. [19]). We considered sterile admixtures that range from the maximum allowed by the recent KamLAND data, $\sin^2\eta = 13\%$ [22], to 25%, 50%, 75%, as well as the extremes of 0% and 100%. For all

values of the CNO luminosity fraction, the minimum χ^2 was, as expected, achieved for purely active oscillations.

Figure 1 summarizes our main results. The figure shows $\Delta\chi^2$ as a function of the CNO luminosity fraction when only solar neutrino data are used (denoted by dotted curves) and when solar and KamLAND data are used (denoted by solid curves). The minimum value of χ^2 , relative to which $\Delta\chi^2$ is measured, is reached in both cases for a zero value of the CNO flux. However, as is apparent from Fig. 1, the global χ^2 is essentially flat for all values of $L_{\text{CNO}}/L_{\odot} < 5\%$. Current experiments are not sensitive to CNO neutrino fluxes that correspond to less than 5% of the solar luminosity. For example, the $\Delta\chi^2$ is only 0.5 between the best fit at $L_{\text{CNO}}/L_{\odot} = 0.0$ and the standard solar model value of 1.5%.

In all cases, the best fit is a LMA (large mixing angle) Mikheyev-Smirnov-Wolfenstein (MSW) solution [16]. In principle, new solutions might have been found by allowing L_{CNO}/L_{\odot} to be a free parameter. In practice, no preferred new solutions are found for any value of L_{CNO}/L_{\odot} .

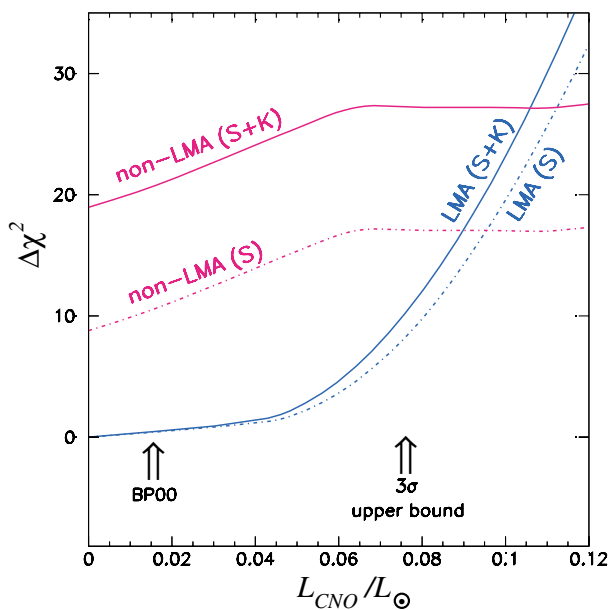


FIG. 1 (color online). Experimental bound on L_{CNO}/L_{\odot} . The figure shows how the χ^2 fit worsens as one increases the assumed fraction of the Sun’s luminosity that arises from CNO reactions. The dotted lines were computed using just solar neutrino data; the solid lines use both solar neutrino experiments and the KamLAND results. The curves labeled LMA were calculated for the favored large mixing angle MSW solution; the curves labeled non-LMA were calculated for the best fit of the LOW, SMA, vacuum, and sterile oscillation solutions. The arrows indicate the predicted 1.5% CNO luminosity from the standard solar model [3] and the $\sim 8\%$ [see Eq. (4)] 3σ upper bound (1 dof) allowed by the chlorine, gallium, Super-Kamiokande, and SNO solar neutrino data [5,8–10,13,14] and the KamLAND reactor data [18].

For completeness, we explored the entire oscillation parameter space specified just preceding Eq. (2), including the parameter ranges of all previously recognized oscillation solutions [4–6]. The best-fit results for these searches for other oscillation cases are labeled “non-LMA” in Figure 1. For L_{CNO}/L_{\odot} less than about 5%, the best-fit non-LMA solution is the well-known LOW solution. For the larger values of L_{CNO}/L_{\odot} shown in Figure 1, the best-fit LMA solution is a vacuum solution with $\Delta m^2 = 7.9 \times 10^{-11} \text{ eV}^2$ and $\tan^2\theta = 0.22$. We conclude, using both solar neutrino and KamLAND experimental data (using just solar neutrino data), that

$$\frac{L_{\text{CNO}}}{L_{\odot}} < 7.3\%(7.8\%) \quad \text{at } 3\sigma. \quad (4)$$

The recent KamLAND measurements reduce the upper limit by 0.5%.

The order of magnitude improvement between the previous limit of 99.95% [17] and the present limit, Eq. (4), is due to the Super-Kamiokande and SNO measurements. The earlier large CNO oscillation solution was confined to small mixing angles, SMA, which cannot fit simultaneously the flat recoil energy spectrum measured by Super-Kamiokande [13] and the total event rates measured by Super-Kamiokande and SNO [13,14].

The maximum CNO neutrino flux allowed by the existing experiments is

$$\phi_{\text{CNO,max}} < 3.41 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1} (L_{\text{CNO}}/L_{\odot}), \quad (5)$$

where $\phi_{\text{CNO,max}} = \phi(^{13}\text{N})_{\text{max}} = \phi(^{15}\text{O}\sigma)_{\text{max}}$.

We have verified that the upper limits given in Eqs. (4) and (5) are not affected by the approximation of assuming that there is just one mass scale (i.e., two neutrinos). We repeated the analysis assuming the standard three-neutrino mixing scenario invoked to explain both solar and atmospheric data and assumed values for θ_{13} values below the CHOOZ bound [28], $\tan^2(\theta_{13}) = 0.0, 0.03$ and 0.06 (the CHOOZ bound at 3σ [29]). The minimum χ^2 was, as expected, achieved for $\tan^2(\theta_{13}) = 0.0$.

New solar neutrino experiments are required to measure the CNO contribution to the solar luminosity.

How much can a future ^7Be neutrino-electron scattering experiment, BOREXINO [30] or KamLAND [18], improve the limit given in Eq. (4)? We find an approximate answer to this question by computing a global χ^2 including the existing solar neutrino data, the KamLAND reactor data, and a simulated BOREXINO rate measurement (simulations guided by Ref. [30]). We assume that the BOREXINO rate will be consistent with the predicted best fit point from the solar plus KamLAND global fit with a total error of 10% (5%) for the rate measurement. If these assumptions are valid, one will be able either to measure L_{CNO}/L_{\odot} or conclude that $L_{\text{CNO}}/L_{\odot} < 5.6\%(4.9)\%$.

In order to measure the CNO contribution at the 1.5% level predicted by the standard solar model, one must be able to distinguish the continuum ^{13}N and ^{15}O neutrinos from the ^7Be and pep neutrino lines, as well as from all the sources of background. The appropriate analyses of proposed low energy neutrino-electron scattering detectors have not yet been carried out, so one cannot say for sure whether or not this will be possible. But, it seems very difficult. The energy resolution required to measure the energy of the CNO neutrinos and determine their flux, may, however, be within the reach of low-energy CC experiments [31].

The solar model predictions for CNO neutrino fluxes are not precise because the CNO fusion reactions are not as well studied as the p - p reactions [32] and because the Coulomb barrier is higher for the CNO reactions, implying a greater sensitivity to details of the solar model. For the standard solar model CNO neutrino fluxes, the 1σ errors vary between 17% and 25% [3]. A measurement of the CNO neutrino fluxes would constitute a stringent test of the theory of stellar evolution and provide unique information about the solar interior.

J. N. B. and C. P. G. acknowledge support from NSF Grant No. PHY0070928. M. C. G.-G. is supported by the European Union Grant No. HPMF-CT-2000-00516 and by Spanish Grants No. PB98-0693 and No. CTIDIB/2002/24.

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