PHYSICAL REVIEW LETTERS

VOLUME 73 | 18 JULY 1994 | NUMBER 3

Semiempirical Bound on the ^{37}Cl Solar Neutrino Experiment

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(Received 22 April 1994)

The Kamiokande measurement of energetic ^{8}B neutrinos from the Sun is used to set a lower bound on the contribution of the same neutrinos to the signal in the ^{37}Cl experiment. Implications for ^{7}Be neutrinos are discussed.

PACS numbers: 96.60.Kx, 14.60.Pq

Energetic ^{8}B neutrinos from the Sun have been detected in the Kamiokande experiment [1] at about one-half the rate predicted by the standard solar model of Bahcall and Pinsonneault (SSM) [2]. These same neutrinos must also interact with the ^{37}Cl detector [3] and so it is important to understand their contribution to the measured ^{37}Cl signal. By comparing this contribution to the total signal, we can extract information about other parts of the solar neutrino spectrum, especially ^{7}Be.

We find that, even allowing for neutrino flavor oscillations, the Kamiokande experiment imposes a bound on the ^{37}Cl signal that does not leave much room for a significant contribution from ^{7}Be neutrinos. This finding is not inconsistent with the latest results from the ^{71}Ga experiments [4,5], and so we may refine the statement of the solar neutrino problem to read: Where have all the ^{7}Be neutrinos gone?

Since the basic physical process in the Kamiokande and ^{37}Cl experiments are different, the former being neutrino-electron scattering and the latter neutrino capture on ^{37}Cl, we must follow a semiempirical method to relate them to one another. In Kamiokande, the calculated signal involves a convolution over $\phi(E_\nu)$, the SSM spectrum [2] of ^{8}Be neutrinos with energy E_ν, the differential cross section for scattered electrons with kinetic energy T, and the electron resolution function $\theta(T, T')$ which represents the probability that T will appear as T' in an actual measurement. We call this function $\phi\sigma(\nu_e e; E_\nu)$ and plot in Fig. 1 its normalized shapes as a function of E_ν for two choices of $\theta(T, T')$: The first is a Gaussian shape that closely approximates the actual experimental resolution [6], the second is a δ function representing perfect resolution, and both assume $7.5 \le T' \le 15$ MeV. Notice that because of the experimental resolution, the first case has developed a significant tail below the 7.5 MeV threshold. Only the first case with the experimental resolution will be used for calculations below.

In the ^{37}Cl experiment, the relevant quantity is the product of $\phi(E_\nu)$ with the total capture cross section [7]

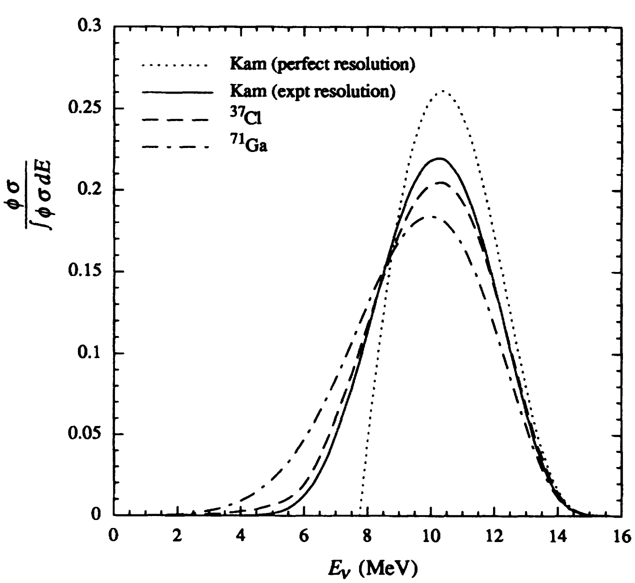

FIG. 1. Normalized shapes of $\phi\sigma$ for various experiments.

for neutrinos of energy E_ν on ^{37}Cl. We call this function $\phi\sigma(^{37}\mathrm{Cl};E_\nu)$ and plot its normalized shape also in Fig. 1. The integral of $\phi\sigma(^{37}\mathrm{Cl};E_\nu)$ gives the ^{8}B contribution to the SSM signal in ^{37}Cl, $R_{\mathrm{SSM}}(^7\mathrm{Be};^{37}\mathrm{Cl})$.

Comparing the normalized functions for the two experiments, we see that they are remarkably similar to one another, especially at the high energy end. We therefore write

$$\frac{\phi\sigma(^{37}\mathrm{Cl};E_\nu)}{\int\phi\sigma(^{37}\mathrm{Cl};E_\nu)\,dE_\nu}=\alpha\,\frac{\phi\sigma(\nu_e e;E_\nu)}{\int\phi\sigma(\nu_e e;E_\nu)\,dE_\nu}+r(E_\nu), \tag{1}$$

where α is a constant whose value is maximized subject to the condition that the remainder function $r(E_\nu)$ be everywhere positive. It turns out that the largest value of α is 0.93, and so we obtain an inequality

$$\phi\sigma(^{37}\mathrm{Cl};E_\nu)\geq 0.93\,\frac{R_{\mathrm{SSM}}(^8\mathrm{B};^{37}\mathrm{Cl})}{R_{\mathrm{SSM}}(\mathrm{Kam})}\,\phi\sigma(\nu_e e;E_\nu)\,. \tag{2}$$

The next step of the argument is to note that the actual quantity measured in these experiments involves the product of $\phi\sigma$ with an electron-neutrino "survival probability" $P(E_\nu)$ which, in general, may be a function of the neutrino energy E_ν. If $P(E_\nu)$ represents some, possibly energy-dependent, reduction of the ^{8}B spectrum, or an oscillation into a sterile neutrino, then we find from Eq. (2) that

$$\int\phi\sigma(^{37}\mathrm{Cl};E_\nu)P(E_\nu)\,dE_\nu \geq 0.93\,\frac{\int\phi\sigma(\nu_e e;E_\nu)P(E_\nu)\,dE_\nu}{R_{\mathrm{SSM}}(\mathrm{Kam})}\,R_{\mathrm{SSM}}(^8\mathrm{B};^{37}\mathrm{Cl})$$

or

$$R(^8\mathrm{B};^{37}\mathrm{Cl})\geq 0.93\times(0.51\pm0.07)\times[6.2\text{ solar neutrino units (SNU)}] = 2.94\pm0.40\text{ SNU}, \tag{3}$$

where we have used the most recent result from the Kamiokande experiment [1]. This falls within the errors of the twenty-year average of the Davis value [3]

$$\langle R_{\mathrm{Davis}}\rangle = 2.32\pm0.23\text{ SNU}, \tag{4}$$

but is somewhat on the high side. Note that the bound in Eq. (3) also holds in the simple case of a reduction of the total ^{8}B flux with no change in the spectral shape.

Next, consider the case of oscillations of solar electron neutrinos into ν_μ or ν_τ, or some combination thereof. The signal observed in Kamiokande is then given by

$$R(\mathrm{Kam}) = \int\{\phi\sigma(\nu_e e;E_\nu)P(E_\nu) + [1-P(E_\nu)]\phi\sigma(\nu_\mu e;E_\nu)\}\,dE_\nu, \tag{5}$$

where we must now distinguish between the cross sections for electron neutrinos and muon or tau neutrinos. As is well known [7] the latter cross section lies somewhere between 1/6 and 1/7 of the former in magnitude and is very similar in shape for energetic neutrinos. For our case it is an extremely good approximation to set

$$\sigma(\nu_\mu e;E_\nu) = 0.148\,\sigma(\nu_e e;E_\nu)\,. \tag{6}$$

We can then rewrite Eq. (5) in the form

$$\int\phi[\sigma(\nu_e e;E_\nu)-\sigma(\nu_\mu e;E_\nu)]P(E_\nu)\,dE_\nu = R(\mathrm{Kam}) - \int\phi\sigma(\nu_\mu e;E_\nu)\,dE_\nu,$$

or

$$0.852\int\phi\sigma(\nu_e e;E_\nu)P(E_\nu)\,dE_\nu = R(\mathrm{Kam}) - 0.148R_{\mathrm{SSM}}(\mathrm{Kam})\,. \tag{7}$$

From Eqs. (2) and (7) and the Kamiokande data [1], we see that the contribution of the ^{8}B neutrinos must be bounded in the case of flavor oscillations by

$$\begin{aligned}R(^8\mathrm{B};^{37}\mathrm{Cl}) &= \int\phi\sigma(^{37}\mathrm{Cl};E_\nu)P(E_\nu)\,dE_\nu\\ &\geq 0.93\,\frac{\int\phi\sigma(\nu_e e;E_\nu)P(E_\nu)\,dE_\nu}{R_{\mathrm{SSM}}(\mathrm{Kam})}\,R_{\mathrm{SSM}}(^8\mathrm{B};^{37}\mathrm{Cl})\\ &= 0.93\,\frac{(0.51\pm0.07)-0.148}{0.852}\,(6.2\text{ SNU})\\ &= 2.45\pm0.47\text{ SNU}.\end{aligned} \tag{8}$$

As an example of this argument, we consider the special case in which, inspired by the nonadiabatic Mikheyev-Smirnov-Wolfenstein (MSW) solution [8], we take the electron-neutrino survival probability to be [9]

$$P(E_\nu) = e^{-C/E_\nu}, \tag{9}$$

where C is a constant to be determined by fitting the Kamiokande data. When there is either no oscillation or oscillation into a sterile neutrino, we find

$$C = 6.7^{+1.6}_{-1.3}\text{ MeV},\qquad R(^8\mathrm{B},^{37}\mathrm{Cl}) = 3.1\pm0.4\text{ SNU}. \tag{10}$$

Allowing for neutrino oscillations, we find instead

$$C = 8.6^{+2.1}_{-1.8}\text{ MeV},\qquad R(^8\mathrm{B},^{37}\mathrm{Cl}) = 2.6\pm0.5\text{ SNU}. \tag{11}$$

Both rates are larger than the corresponding lower bounds in Eqs. (3) and (8), respectively.

When compared with the Davis result of Eq. (4), our bounds on the energetic ^{8}B neutrino contribution in

Eqs. (3) and (8) do not leave much room for the 1.8 SNU coming from all other sources, or the 1.1 SNU from ^{7}Be neutrinos alone. Indeed, the contribution from all other sources, call them X, is given in the two cases we have considered by

$$R(X,{}^{37}\mathrm{Cl}) \le \begin{cases} -0.62 \pm 0.46\ \mathrm{SNU}\ \text{(no oscillations)}, \\ -0.13 \pm 0.52\ \mathrm{SNU}\ \text{(with oscillations)}. \end{cases} \tag{12}$$

At the 95% confidence limit, this means

$$R(X,{}^{37}\mathrm{Cl}) \le \begin{cases} 0.13\ \mathrm{SNU}\ \text{(no oscillations)}, \\ 0.72\ \mathrm{SNU}\ \text{(with oscillations)}. \end{cases} \tag{13}$$

Assuming that the ^{7}Be contribution is approximately 1.1/1.8, or 60% of this, we find it to be

$$R({}^7\mathrm{Be},{}^{37}\mathrm{Cl}) < \begin{cases} 0.08\ \mathrm{SNU}\ \text{(no oscillations)}, \\ 0.44\ \mathrm{SNU}\ \text{(with oscillations)}. \end{cases} \tag{14}$$

To pursue this line of argument further, we can set lower bounds on the contribution of the ^{8}B neutrinos to the ^{71}Ga experiments. Replacing the absorption cross section of ^{37}Cl by that of ^{71}Ga everywhere [10], we obtain an inequality similar to Eq. (2) but with $\alpha = 0.81$. The bounds on the ^{8}B contribution to the ^{71}Ga experiments are

$$R({}^8\mathrm{B},{}^{71}\mathrm{Ga}) \ge \begin{cases} 5.7 \pm 0.8\ \mathrm{SNU}\ \text{(no oscillations)}, \\ 4.7 \pm 0.9\ \mathrm{SNU}\ \text{(with oscillations)}. \end{cases} \tag{15}$$

The corresponding values in the $e^{-C/E}$ model,

$$R({}^8\mathrm{B},{}^{71}\mathrm{Ga}) = \begin{cases} 6.6 \pm 1.0\ \mathrm{SNU}\ \text{(no oscillations)}, \\ 5.5 \pm 1.1\ \mathrm{SNU}\ \text{(with oscillations)}, \end{cases} \tag{16}$$

are again larger than their counterparts in Eq. (15).

Combining the bounds of Eq. (15) with the latest ^{71}Ga results [4,5,11]

$$R({}^{71}\mathrm{Ga}) = \begin{cases} 79 \pm 12\ \mathrm{SNU},\ \text{GALLEX}, \\ 73 \pm 19\ \mathrm{SNU},\ \text{SAGE}, \\ 77 \pm 10\ \mathrm{SNU}\ \text{(combined)} \end{cases} \tag{17}$$

we find an interesting situation, namely, that the sum of the signals from pp neutrinos, ^{7}Be neutrinos, and other non-^{8}B sources is very close to the SSM prediction of 71 SNU for pp neutrinos alone:

$$R({}^{71}\mathrm{Ga}) - R({}^8\mathrm{B},{}^{71}\mathrm{Ga}) \le \begin{cases} 72 \pm 10\ \mathrm{SNU}\ \text{(no oscillations)}, \\ 73 \pm 10\ \mathrm{SNU}\ \text{(with oscillations)}. \end{cases} \tag{18}$$

Scaling up the ^{7}Be neutrino bounds in Eq. (14) by the ratio of the capture cross sections on ^{71}Ga and ^{37}Cl, we find that the bounds on the ^{7}Be neutrino contribution to the ^{71}Ga signals are

$$R({}^7\mathrm{Be},{}^{71}\mathrm{Ga}) < \begin{cases} 2.4\ \mathrm{SNU}\ \text{(no oscillations)}, \\ 13.1\ \mathrm{SNU}\ \text{(with oscillations)}, \end{cases} \tag{19}$$

at the 95% confidence level; this should be compared with the SSM prediction of 35.8 SNU [2]. It will be interesting to test these bounds by direct observation of the ^{7}Be, or pp neutrinos themselves [12].

Although we have worked with the Bahcall-Pinsonneault SSM [2], the bound in Eq. (3) for sterile or no oscillations is actually independent of the solar model. By contrast, the bound in Eq. (8) for flavor oscillations does depend on the solar model by virtue of the second term on the right-hand side of Eq. (7); models yielding a flux of ^{8}B neutrinos smaller than that of Ref. [2], for example, Ref. [13], will give a bound slightly larger than that of Eq. (8).

This work was supported in part by the U.S. Department of Energy Grant No. DE-FG05-92ER40691. The authors are grateful to Serguey Petcov and Gene Beier for helpful conversations. One of the authors (S. P. R.) would like to thank Professor W. C. Haxton for the hospitality of the Institute for Nuclear Theory at the University of Washington, where part of this work was carried out.

Note added.—After this work was completed, the authors learned from Professor David Schramm that he had obtained a bound in the nonoscillation case similar to that in Eq. (3).

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