24 September 1998

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 436 (1998) 243–250

# Do *hep* neutrinos affect the solar neutrino energy spectrum?

John N. Bahcall [a,1], Plamen I. Krastev [b,2]

[a] *School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540, USA*
[b] *Department of Physics, University of Wisconsin, Madison, WI 53706, USA*

Received 16 July 1998
Editor: W. Haxton

## Abstract

If the low energy cross section for $^3\text{He} + p \rightarrow {}^4\text{He} + e^+ + \nu_e$, the '*hep*' reaction, is $\gtrsim 20$ times larger than the best (but uncertain) theoretical estimates, then this reaction could significantly influence the electron energy spectrum produced by solar neutrino interactions and measured in the SuperKamiokande, SNO, and ICARUS experiments. We compare predicted energy spectra for different assumed *hep* fluxes and different neutrino oscillation scenarios with the observed SuperKamiokande spectrum. The spectra with enhanced *hep* contributions provide better fits to the SuperKamiokande data.

## 1. Introduction

One of the primary science goals of the SuperKamiokande [1,2], SNO [3], and ICARUS [4] solar neutrino experiments is to determine the shape of the solar neutrino spectrum between $\sim 5$ MeV and 14 MeV. In this energy range, neutrinos from the $\beta$-decay of $^8$B are expected, according to solar model calculations carried out using the best available nuclear physics data, to dominate the solar neutrino spectrum [5]. The shape of the neutrino energy spectrum from a single $\beta$-decaying source is independent of all solar physics to an accuracy of 1 part in $10^5$ [6]. Hence, a measurement of the shape is a direct test of whether something happens to the solar neutrinos after they are created, i.e., of the minimal standard electroweak model.

The SuperKamiokande Collaboration has provided [1] preliminary data for the energy distribution of recoil electrons created by solar neutrinos scattering off electrons in their detector. The data are presented in 15 bins between 6.5 MeV and 14 MeV and one higher-energy bin, 14 to 20 MeV, for a total of 16 bins. The three highest energy bins show a relatively large number of events, more than would have been expected from the most popular neutrino oscillation parameters discussed prior to the first detailed report of the energy spectrum by the SuperKamiokande Collaboration [1].

---

[1] E-mail address: jnb@ias.edu.

[2] E-mail address: krastev@nucth.physics.wisc.edu.

PII: S0370-2693(98)00920-4

Could this excess of high energy events be caused by *hep* neutrinos, which have an endpoint well beyond the ~ 14 MeV endpoint of the $^8$B energy spectrum?

The *hep* reaction, first discussed in connection with solar neutrinos by Kuzmin [7],

$$^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e, \tag{1}$$

produces neutrinos with an endpoint energy of 18.8 MeV, the highest energy expected for solar neutrinos. It was pointed out about a decade ago [8] that solar neutrino detectors that measure individual recoil electron energies, like SuperKamiokande [1], SNO [3], and ICARUS [4], might be able to detect the *hep* neutrinos. The total rate is expected to be low, but the background is small in this energy range.

The goal of this paper is to demonstrate the sensitivity of inferences regarding the distortion of the solar neutrino energy spectrum to assumptions regarding the low energy cross section factor, $S_0(hep)$, for the *hep* reaction (Eq. (1)), and to emphasize the importance of experimental and theoretical studies of the possible contribution of *hep* neutrinos.

## 2. Solar model calculations

For a given solar model, the flux of *hep* neutrinos can be calculated accurately once the low-energy cross section factor for reaction (1) is specified. The rate of the *hep* reaction is so slow that it does not affect solar model calculations. Using the uncertainties given in Ref. [9] for the solar age, chemical composition, luminosity, radiative opacity, diffusion rate, and for all nuclear quantities except $S_0(hep)$, we calculate a total uncertainty in the *hep* flux of only 3% if the $S$-factor is known exactly. The best-estimate *hep* flux is very small [9]:

$$\phi(hep) = 2.1(1.0 \pm 0.03)\left[\frac{S_0(hep)}{2.3 \times 10^{-20}\ \mathrm{keV\,b}}\right] \times 10^3\ \mathrm{cm^{-2}s^{-1}}. \tag{2}$$

The bracketed-factor in Eq. (2) is equal to unity for the currently-recommended value for $S_0(hep)$ (see discussion in the following section).

The best-estimate $^8$B neutrino flux is more than 2000 times larger than the flux of *hep* neutrinos given by Eq. (2) if the bracketed factor is set equal to unity. This is the reason why all previous discussions of the measurement of the energy spectrum in the SuperKamiokande, SNO, and ICARUS experiments have concentrated on the recoil electrons produced by $^8$B neutrinos. Even with the high event rate of SuperKamiokande( ~ 6800 solar neutrino events observed in 504 days), only a few *hep* interactions are expected for the standard estimate of $S_0(hep)$.

## 3. Calculated hep Production Cross Sections

Table 1 lists all the published values of the low-energy cross section factor, $S_0(hep)$, with which we are familiar. Since reaction (1) occurs via the weak interaction, the cross section for *hep* neutrinos is too small (see Eq. (3) below) to be measured in the laboratory at low enough energies to be relevant to solar fusion and must therefore be calculated theoretically. We have also given in Table 1, in the column next to each cross section estimate, one or more characteristic features of the physics that was used to estimate the cross section. A review of the history of calculations of $S_0(hep)$ provides insight into the difficulty of obtaining an accurate value.

The first estimate of the cross section factor by Salpeter [10] considered only the overlap of an incoming continuum wave function with that of a bound nucleon in $^4$He, obtaining a large value for $S_0(hep)$, ~ 300 times the current best-estimate. However, Werntz and Brennan [11] pointed out that if one approximates the final $^4$He state by $(1s)^4$ and the initial state by $(1s)^3(s_c)$ (where $s_c$ is a continuum initial state), and antisymmetrizes in

Table 1
Calculated values of $S_0$(hep). The table lists all the published values with which we are familiar of the low energy cross section factor for the hep reaction shown in Eq. (1)

| $S_0$(hep) ($10^{-20}$ keV b) | Physics | Year | Reference |
|---|---|---|---|
| 630 | single particle | 1952 | [10] |
| 3.7 | forbidden; $M_\beta \propto M_\gamma$ | 1967 | [11] |
| 8.1 | better wave function | 1973 | [12] |
| 4–25 | D-states + meson exchange | 1983 | [13] |
| $15.3 \pm 4.7$ | measured $^3$He$(n,\gamma)^4$He | 1989 | [14] |
| 57 | measured $^3$He$(n,\gamma)^4$He shell model | 1991 | [15] |
| 1.3 | destructive interference, detailed wavefunctions | 1991 | [16] |
| 1.4–3.1 | $\Delta$-isobar current | 1992 | [17] |

space, spin, and isospin, then the matrix element of the usual allowed $\beta$-decay operator vanishes between the initial and final states. They obtained a cross section factor more than two orders of magnitude smaller than the single-particle Salpeter estimate.

Werntz and Brennan [11,12] derived and used in an exploratory way a suggested proportionality between the $\beta$-decay matrix element, $M_\beta$ (which cannot be measured), for the reaction $^3$He$(p,e^+\nu_e)^4$He, and the neutron-capture matrix element (which can be measured), $M_\gamma$, for the reaction $^3$He$(n,\gamma)^4$He. Their derivation, which was intended only to give a crude estimate of the cross section factor, neglected initial state interactions and the small $D$-state contributions of the $^3$He and $^4$He ground states and also assumed the dominance of meson exchange currents.

Tegnér and Bargholtz [13] stressed the importance of the $D$-state components of the $^3$He and $^4$He wave functions and argued that the matrix elements for nucleon capture on $^3$He are dominated by one-body operators rather than the two particle meson exchange terms. They derived a new proportionality relation between $M_\beta$ and $M_\gamma$, which they used to estimate a rather large range of possible values for $S_0(hep)$. Wolfs et al. [14] and Wervelman et al. [15] measured accurately the thermal neutron capture rate for $^3$He$(n,\gamma)^4$He and used the proportionality relation of Tegnér and Bargholtz to estimate values of $S_0(hep)$.

Carlson [16] revealed another layer of complexity by performing a detailed calculation with sophisticated wave functions, showing the presence in their model of strong destructive interference between the mesonic exchange currents and the one-body matrix elements connecting the small components of the wave functions. In the most comprehensive calculation to date, Schiavilla et al. [17] included a more consistent treatment of the $\Delta$-isobar current and investigated the sensitivity of $S_0(hep)$ to the assumed details of the nuclear physics. They found a range of values

$$S_0(hep) = (2.3 \pm 0.9) \times 10^{-20}\ \mathrm{keV\,b}, \tag{3}$$

which corresponds to a fusion cross section of $\sim 10^{-50}$ cm$^2$ at solar thermal energies. The central value of this range, $S_{0,\,\mathrm{cent.}}(hep)$, was adopted by Adelberger et al. [18] and Bahcall and Pinsonneault [9] as the best available estimate. A value of $S_0(hep)$ in the range 20–30 times $S_{0,\,\mathrm{cent.}}(hep)$ would be consistent (see discussion in the following section) with all the available evidence from solar neutrino experiments.

Is it possible to show from first-principle physics that $S_0(hep)$ cannot exceed, e.g., 10 times $S_{0,\,\mathrm{cent.}}(hep)$? We have been unable to find any such argument. Therefore, for the last decade we have not quoted a total uncertainty in the calculated standard model predictions for the *hep* neutrino fluxes, although well-defined total uncertainties are given for all of the other fluxes [8,9].

The reason it is difficult to place a firm upper limit is, as emphasized by Carlson et al. [16] and Schiavilla et al. [17], that the calculated value of $S_0(hep)$ is sensitive to the model used to describe both the ground sate and the continuum wave functions and to the detailed form of the two-body electroweak interactions. The matrix element $M_\beta$ contains separate contributions from both the traditional single particle Gamow-Teller operator and the axial exchange-current operator. In the most detailed calculations [16,17], there is a delicate cancellation between comparable contributions from the one-body and the two-body operators. For example, if one artificially changes the sign of the principal exchange current contribution relative to the sign of the one-body axial current in the calculation described in Table III of Ref. [16], the size of the calculated $S_0(hep)$ is increased by a factor of 32.

For non-experts, it is instructive to compare the calculations of the *pp* and *hep* reactions. The *pp* fusion reaction [19] occurs via the allowed Gamow-Teller $\beta$-decay matrix element whereas the *hep* transition is forbidden. For the *pp* reaction, the difficult-to-evaluate mesonic exchange corrections and matrix elements connecting small components of the wave functions are only small corrections ($\sim$ a few percent) to the total cross section. For the *hep* reaction, the exchange corrections and matrix elements involving small components of the wave function are the whole story. For the *pp* reaction, the effective range approximation allows one to use measured data to calculate to good accuracy the low energy fusion cross section. The somewhat analogous scaling laws relating *hep* fusion to the measured cross section for ${}^3\mathrm{He}(n,\gamma){}^4\mathrm{He}$ reaction are not valid because low energy nucleon capture by ${}^3$He occurs via competing and cancelling small effects and because of different initial state interactions. Hence, the estimated uncertainty in the low energy *pp* fusion cross section is small($\sim 2\%$ [18]), whereas the uncertainty in the *hep* cross section is much larger and is difficult to quantify.

## 4. Global fits to solar neutrino data

We have investigated the predicted effects on solar neutrino experiments of an arbitrary size *hep* flux, which we will parameterize by multiplying $S_{0,\,\mathrm{cent.}}(hep)$ by a constant $\alpha$ that is much greater than unity (cf. Eq. (3)),

$$\alpha \equiv \frac{S_0(hep)}{(2.3 \times 10^{-20}\ \mathrm{keV\,b})}\ . \tag{4}$$

We have carried out global fits to all of the solar neutrino data, the measured total event rates in the chlorine [20], GALLEX [21], SAGE [22], and SuperKamiokande [1] experiments, the SuperKamiokande energy spectrum [1], and the SuperKamiokande zenith-angle dependence of the event rate [1]. We use the methods and the data described fully in Ref. [23], hereafter BKS98. For MSW fits, the degrees of freedom (d.o.f.) are: 4 (total rates in 4 experiments) $+15$ (normalized spectrum for 16 bins) $+9$ (normalized angular distribution for 10 bins) $-2$ (oscillation parameters) $-1$ (hep flux) or 25 d.o.f. For vacuum oscillations, the Day-Night asymmetry (1 d.o.f.) is a more powerful discriminant than the zenith-angle distribution [23]. Hence, for vacuum oscillations we have 17 d.o.f. The only substantial difference from BKS98 is that in the present paper we find the best-fit to the measured SuperKamiokande energy spectrum by including an arbitrary amount of *hep* neutrinos in addition to the conventional ${}^8$B flux. The contribution of the *hep* flux to the total event rates is negligible for all of the best-fit solutions.

Fig. 1 and Table 2 summarize our principal results. We see from Fig. 1 that one can obtain good fits to the reported SuperKamiokande [1] energy spectrum for all three neutrino scenarios: no oscillations, MSW, and vacuum oscillations.

Table 2 shows the best global fits to all the data that are possible by allowing large enhancements of the current best-estimate *hep* flux. The improvements are significant.

The best-fit MSW solution improves from a confidence level (1 - P) of 7% to 20% (for $\alpha = 26$) even after accounting for the extra d.o.f. A large range of values of $\alpha$ ($\lesssim 30$) give good fits.

Fig. 2 shows the allowed ranges of MSW parameters for a global solution with arbitrary *hep* flux. All three of the conventional MSW solutions [23], small mixing angle(SMA), large mixing angle(LMA), and low

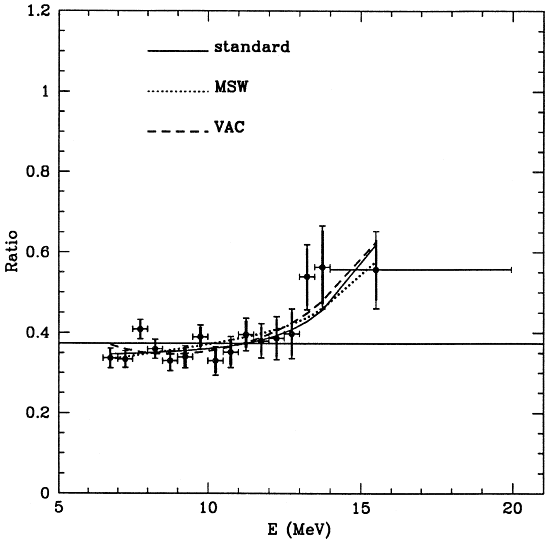

Fig. 1. Combined $^8$B plus *hep* energy spectrum. The total flux of *hep* neutrinos was varied to obtain the best-fit for each scenario. The figure shows the Ratio of the measured [1] to the calculated number of events with electron recoil energy, $E$. The measured points were reported by the SuperKamiokande Collaboration at Neutrino 98 [1]. The calculated curves are global fits to all of the data, the chlorine [20], GALLEX [21], SAGE [22], and SuperKamiokande [1] total event rates, the Superkamiokande [1] energy spectrum, and the SuperKamiokande [1] Day-Night asymmetry. The calculations follow the precepts of BKS98 [23] for the best-fit global solutions for a standard 'no-oscillation' energy spectrum, as well as MSW and vacuum neutrino oscillation solutions. The horizontal line at Ratio = 0.37 represents the ratio of the total event rate measured by SuperKamiokande to the predicted event rate [9] with no oscillations and only $^8$B neutrinos.

mass(LOW) neutrino oscillations are allowed. In the global MSW solution with the standard *hep* flux, the LMA and LOW solutions are marginally ruled out at 99% C.L.

For vacuum oscillations, the value of $\alpha$ corresponding to the global $\chi^2_{\min}$ does not depend strongly on $\Delta m^2$ and $\sin^2 2\theta$ within the acceptable region. The improvement in the C.L. for acceptance increases from 6% to 15% when an arbitrary *hep* flux is considered.

The best-fit global MSW solution with an arbitrary *hep* flux has neutrino parameters given by $\Delta m^2 = 5.4 \times 10^{-6}$ eV$^2$ and $\sin^2 2\theta = 5.0 \times 10^{-3}$, which are very close to the best-fit MSW parameters [23] with the standard (much smaller) *hep* flux. For vacuum oscillations, the best-fit global solution has $\Delta m^2 = 7.8 \times 10^{-11}$ eV$^2$, and

Table 2
Global fits with arbitrary *hep* neutrino flux. The table lists the best-fit enhancement parameters, $\alpha$, defined by Eq. (4), for three different neutrino scenarios: no oscillations, MSW, and vacuum oscillations. We also list the value of $\chi^2_{\min}$ for the global fit (25 d.o.f. for MSW fits and 17 d.o.f. for vacuum oscillations fits) and the confidence level $P$ at which the solution is rejected, as well as the expected number of neutrino events in the 14–16 MeV bin and the 16–20 MeV bin for the 504 day data set of SuperKamiokande(normalized to the total number of observed events [1] 14–20 MeV). The best-fit values for $\Delta m^2$ and $\sin^2 2\theta$ are given in the text. For comparison, we also list the results for the best-fit global solutions obtained in Ref. [23] for the standard *hep* flux, i. e., $\alpha = 1.0$ (with one less d.o.f.)

| Neutrino | $\alpha_{\text{best}}$ | $\chi^2_{\min}$ | $P$ | 14–16 MeV events | 16–20 MeV events |
|---|---|---|---|---|---|
| no oscillations | 26 | 25.3 | 0.954 | 62 | 14 |
| no oscillations | 1.0 | 36.6 | 0.998 | 70 | 6 |
| MSW | 25 | 30.7 | 0.80 | 64 | 12 |
| MSW | 1.0 | 37.2 | 0.93 | 70 | 6 |
| vacuum | 30 | 23.0 | 0.85 | 66 | 10 |
| vacuum | 1.0 | 28.4 | 0.94 | 69 | 7 |

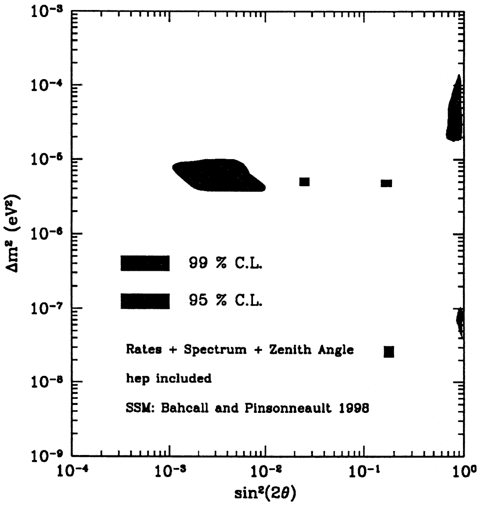

Fig. 2. Global fits: MSW solutions. The figure shows the regions in MSW parameter space that are consistent with the total rates observed in the four solar neutrino experiments (chlorine, SuperKamiokande, GALLEX, and SAGE) and with the electron recoil energy spectrum and zenith angle distribution that are measured by SuperKamiokande [1]. Contours are drawn at both 95% C.L. and 99% C.L.

$\sin^2 2\theta = 0.71$, again similar to the neutrino parameters for the best-fit vacuum solution [23] with the standard *hep* flux.

## 5. Discussion

We have calculated global fits to all the available solar neutrino data allowing for an arbitrarily large *hep* flux. We find good fits to all the data, including the electron recoil energy spectrum (see Fig. 1) reported by SuperKamiokande [1]. The best fits are obtained for *hep* fluxes that are $\gtrsim 20$ times the flux predicted if the best-available estimate (Eq. (3)) for the low-energy cross section factor for the *hep* reaction is used in the standard solar model calculations. We have been unable to find an argument from first-principle physics that rules out values of the cross section factor $S_0(hep)$ that are as large as required by our best-fit solutions that are described in Table 2.

At first glance, these results seem discouraging. If one allows a large *hep* flux to account for the enhancement at higher energies of the measured electron recoil energy spectrum [1], then it would seem to be very difficult to infer anything fundamental about neutrino physics from the measured recoil electron energy spectrum. After all, to a good approximation the distortion of the spectrum can be represented for small distortions by a single parameter [24] and we are suggesting that an additional (unknown) parameter be added to the fit, namely, the magnitude of the *hep* flux.

Fortunately, the SuperKamiokande [1,2], SNO [3], and ICARUS [4] experiments can all test for the possible existence of a large *hep* flux by measuring the energy spectrum beyond the energy corresponding to the endpoint of the $^8$B neutrino spectrum. Table 2 shows that solutions with a large admixture of *hep* neutrinos are expected to produce appreciable numbers of events more energetic than 14 MeV in the 504 days of observations studied so far in the SuperKamiokande detector. The region beyond the endpoint energy of the $^8$B spectrum is an excellent region in which to search for rare events since the background is expected to be very small between 16 to 20 MeV .

The SNO detector should be even more sensitive than SuperKamiokande at the highest electron energies because the neutrino absorption cross section on deuterium rises more rapidly with energy than does the electron scattering cross section and because higher energy neutrinos absorbed by deuterium produce higher energy electrons, whereas for $\nu - e$ scattering the energy is divided almost equally between recoiling electrons and final state neutrinos [25]. Quantitatively, we estimate that SNO would have, depending on which neutrino oscillation parameters are chosen, two to three times the rate of production of electrons in the 14–16 MeV bin if the energy resolution were the same in the two detectors. Moreover, the energy discrimination for SNO may actually be better than for SuperKamiokande, further helping in determining the possible contribution of *hep* neutrinos.

The ratio, $r$, of the number of detected events in the 14–16 MeV bin to the number of detected events in the 16–20 MeV bin should be large if – as predicted by the standard solar model – the only important neutrino sources contributing to events in this energy region are $^8$B and *hep*. For the best global fits (large $\alpha$), we see from Table 2, that $r$ satisfies for SuperKamiokande operating characteristics

$$r(\text{global}) \equiv \frac{(\text{events: 14–16 MeV})}{(\text{events: 16–20 MeV})} \gtrsim 4\,, \tag{5}$$

and for the standard $S_0(hep)$,

$$r(\alpha = 1) \equiv \frac{(\text{events: 14–16 MeV})}{(\text{events: 16–20 MeV})} \gtrsim 10\,. \tag{6}$$

Eq. (5) is a prediction, valid with or without neutrino oscillations, of the standard solar model and can be tested with the available SuperKamiokande [1] data. Basically, Eq. (5) is a statement that there are no other important sources of high energy solar neutrino neutrinos except $^8$B and *hep*. Eq. (6) is valid if the current best-estimate for $S_0(hep)$ is correct.

For 504 days of SuperKamiokande operation, the best global fits predict (see Table 2) about $12 \pm 2$ events in the 16–20 MeV energy bin, whereas the standard standard fluxes with $\alpha = 1$ predict $\sim 6$ or 7 high energy events. Many more events may be required before SuperKamiokande can distinguish empirically between the small and large $\alpha$ descriptions of the energy spectrum.

Measurements at energies below the current 6.5 MeV lower limit are also very important. Fig. 1 shows that the best-fit vacuum solution has a small upturn in the spectrum at the lowest available energies. The upturn is intrinsic to this vacuum solution; *hep* neutrinos are unimportant at the lower energies.

Solar neutrino experiments may be able to determine, after several years of operation, both the contamination (at higher energies) by *hep* neutrinos of the energy spectrum and also a strong constraint (from measurements at lower energies) on the allowed range of distortion parameters due to neutrino oscillations. We hope that the discussion in this paper will stimulate further experimental and theoretical considerations of the possible effects of *hep* neutrinos.

## Acknowledgements

We are grateful to the SuperKamiokande Collaboration for making available at Neutrino 98 their crucially important data on the electron recoil energy spectrum. We are also indebted to many members of the SuperKamiokande Collaboration for informative and stimulating conversations on the possible relevance of *hep* neutrinos for their measurements. This work is an extension of our earlier collaboration with A. Smirnov, to whom we are grateful for many insightful remarks, on BKS98. We are indebted to K. Babu, G. Beier, S. Bilenky, J. Carlson, D. Eisenstein, A. Gruzinov, W. Haxton, C. Kolda, H. Robertson, R. Shiavilla, and R. Wiring for valuable comments that improved an initial version of this paper. JNB and PIK acknowledge support from NSF grant #PHY95-13835. PIK also acknowledges support from #PHY96-05140.

## References

[1] SuperKamiokande Collaboration, Y. Suzuki, in: Y. Suzuki, Y. Totsuka (Eds.), Neutrino 98, Proceedings of the XVIII International Conference on Neutrino Physics and Astrophysics, Takayama, Japan, 4–9 June 1998, to be published in Nucl. Phys. B (Proc. Suppl.).
[2] SuperKamiokande Collaboration, Y. Fukuda et al., Phys. Rev. Lett. (accepted for publication, hep-ex/9805021).
[3] A.B. McDonald, in: A. Astbury et al. (Eds.), Proceedings of the 9th Lake Louise Winter Institute, Singapore, World Scientific, 1994, p. 1.
[4] J.P. Revol, in: Y. Suzuki, K. Nakamura (Eds.), Frontiers of Neutrino Astrophysics, Tokyo, Universal Academy Press Inc., 1993, p. 167.
[5] J.N. Bahcall, Neutrino Astrophysics, Cambridge, Cambridge University Press, 1989.
[6] J.N. Bahcall, Phys. Rev. D 45 (1991) 1644.
[7] V.A. Kuzmin, Phys. Lett. 17 (1965) 27.
[8] J.N. Bahcall, R.K. Ulrich, Rev. Mod. Phys. 60 (1988) 297; see also R. Escribano, J.M. Frere, A. Gevaert, D. Monderen, hep-ph/9805238 (1998), who suggest a possible spectral distortion of the SuperKamiokande spectrum.
[9] J.N. Bahcall, S. Basu, M.H. Pinsonneault, Phys. Lett. B 433 (1998) 1.
[10] E.E. Salpeter, Phys. Rev. 88 (1952) 547.
[11] C. Werntz, J.G. Brennan, Phys. Rev. 157 (1967) 759.
[12] C. Werntz, J.G. Brennan, Phys. Rev. C 8 (1967) 1545.
[13] P.E. Tegnér, Chr. Bargholtz, Astrophys. J. 272 (1983) 311.
[14] F.L.H. Wolfs, S.J. Freedman, J.E. Nelson, M.S. Dewey, G.L. Greene, Phys. Rev. Lett. 63 (1989) 2721.
[15] R. Wervelman, K. Abrahams, H. Postma, J.G.L. Booten, A.G.M. Van Hees, Nucl. Phys. A 526 (1991) 265.
[16] J. Carlson, D.O. Riska, R. Schiavilla, R.B. Wiringa, Phys. Rev. C 44 (1991) 619.
[17] R. Schiavilla, R.B. Wiringa, V.R. Pandharipande, J. Carlson, Phys. Rev. C 45 (1992) 2628.
[18] E. Adelberger et al., Rev. Mod. Phys. (accepted, October 1998) astro-ph/9805121.
[19] M. Kamionkowski, J.N. Bahcall, Astrophys. J. 420 (1994) 884; J.N. Bahcall, R.M. May, Astrophys. J. 155 (1969) 501; E.E. Salpeter, Phys. Rev. 88 (1952) 547.
[20] R. Davis Jr., Prog. Part. Nucl. Phys. 32 (1994) 13; B.T. Cleveland, T. Daily, R. Davis Jr., J.R. Distel, K. Lande, C.K. Lee, P.S. Wildenhain, J. Ullman, Astrophys. J. 495 (1998) 505.
[21] GALLEX Collaboration, P. Anselmann et al., Phys. Lett. B 342 (1995) 440; GALLEX Collaboration, W. Hampel et al., Phys. Lett. B 388 (1996) 364.
[22] SAGE Collaboration, V. Gavrin et al., in: K. Huitu, K. Enqvist, J. Maalampi (Eds.), Neutrino'96, Proceedings of the 17th International Conference on Neutrino Physics and Astrophysics (Helsinki), Singapore, World Scientific, 1997, p. 14.
[23] J.N. Bahcall, P.I. Krastev, A. Smirnov, Phys. Rev. D (submitted, hep-ph/9807216).
[24] W. Kwong, S.P. Rosen, Phys. Rev. Lett. 68 (1992) 748.
[25] J.N. Bahcall, E. Lisi, Phys. Rev. D 54 (1996) 5417; J.N. Bahcall, M. Kamionkowski, A. Sirlin, Phys. Rev. D 51 (1995) 6146.