Homestake result, sterile neutrinos, and low energy solar neutrino experiments

P. C. de Holanda
Instituto de Física Gleb Wataghin - UNICAMP, 13083-970 Campinas SP, Brazil

A. Yu. Smirnov
The Abdus Salam International Centre for Theoretical Physics, I-34100 Trieste, Italy
and Institute for Nuclear Research of Russian Academy of Sciences, Moscow 117312, Russia

(Received 11 August 2003; published 2 June 2004)

The Homestake result is about $\sim 2\sigma$ lower than the Ar-production rate, Q_{Ar}, predicted by the large mixing angle (LMA) Mikheyev-Smirnov-Wolfenstein solution of the solar neutrino problem. Also there is no apparent upturn of the energy spectrum ($R \equiv N_{obs}/N_{SSM}$) at low energies in SNO and Super-Kamiokande. Both these facts can be explained if a light, $\Delta m_{01}^2 \sim (0.2-2)\times 10^{-5}$ eV^2, sterile neutrino exists which mixes very weakly with active neutrinos: $\sin^2 2\alpha \sim (10^{-5}-10^{-3})$. We perform both the analytical and numerical study of the conversion effects in the system of two active neutrinos with the LMA parameters and one weakly mixed sterile neutrino. The presence of sterile neutrino leads to a dip in the survival probability in the intermediate energy range $E=(0.5-5)$ MeV thus suppressing the Be, or/and pep, CNO, as well as B electron neutrino fluxes. Apart from diminishing Q_{Ar} it leads to decrease of the Ge-production rate and may lead to the decrease of the BOREXINO signal as well as the CC/NC ratio at SNO. Future studies of the solar neutrinos by SNO, SK, BOREXINO, and KamLAND as well as by the new low energy experiments will allow us to check this possibility.

DOI: 10.1103/PhysRevD.69.113002 PACS number(s): 26.65.+t, 14.60.Lm, 14.60.Pq, 95.85.Ry

I. INTRODUCTION

In the assumption of *CPT* invariance the first KamLAND result [1] and the results of the SNO salt phase [2] confirm the large mixing angle (LMA) Mikheyev-Smirnov-Wolfenstein (MSW) solution of the solar neutrino problem [3–5]. Is the LMA solution complete? If there are observations, which of them may indicate some deviation from the LMA?

According to the recent analysis, the LMA MSW solution describes all the data very well [6,7]: pulls of predictions from experimental results are below 1σ for all but the Homestake experiment [7]. The generic prediction of the LMA for the Ar production rate is

$$Q_{Ar} = 2.9\text{–}3.1 \ \ \text{SNU},^1 \tag{1}$$

which is about 2σ higher than the Homestake result [8]. This pull can be (i) just a statistical fluctuation; (ii) some systematics which may be related to the claimed long term time variations of the Homestake signal [8]; (iii) a consequence of higher fluxes predicted by the standard solar model (SSM) [9];[2] (iv) some physics beyond the LMA.

Another generic prediction of the LMA is the "upturn" of the energy spectrum at low energies (the upturn of ratio of the observed and the SSM predicted numbers of events). According to the LMA, the survival probability should increase with decrease of energy below (6–8) MeV [5]. For the best-fit point the upturn can be as large as 10–15% between 8 and 5 MeV [10,7]. Neither Super-Kamiokande (SK) [11] nor SNO [12] show the upturn, though the present sensitivity is not enough to make a statistically significant statement.

There are also claims that the solar neutrino data have time variations with small periods [13]. If true, this cannot be explained in the context of the LMA solution.

Are these observations related? Do they indicate some new physics in the low-energy part of the solar neutrino spectrum? In this paper we show that both the lower Ar-production rate and the absence of (or weaker) upturn of the spectrum can be explained by the effect of new (sterile) neutrino (for recent related discussion, see Ref. [14]). This is the short version of the paper placed in hep-ph in the e-print ArXiv [15].

II. STERILE NEUTRINO MIXING AND CONVERSION PROBABILITIES

Let us consider the system of two active neutrinos, ν_e and ν_a, and one sterile neutrino, ν_s, which mix in the mass eigenstates ν_1, ν_2, and ν_0:

$$\nu_0 = \cos\alpha\,\nu_s + \sin\alpha(\cos\theta\,\nu_e - \sin\theta\,\nu_a),$$

$$\nu_1 = \cos\alpha(\cos\theta\,\nu_e - \sin\theta\,\nu_a) - \sin\alpha\,\nu_s,$$

$$\nu_2 = \sin\theta\,\nu_e + \cos\theta\,\nu_a. \tag{2}$$

[1]SNU (Solar Neutrino Unit)$=10^{-36}$ interactions per target atom per second.

[2]For instance, the CNO-neutrino fluxes have rather large uncertainties. According to the SSM and in the LMA context they contribute to Q_{Ar} about 0.25 SNU, so that reduction of the CNO fluxes by a factor of 2 (which is within 2σ of the estimated uncertainties) leads to reduction of the Ar-production rate by $\Delta Q_{Ar} \sim 0.12$ SNU.

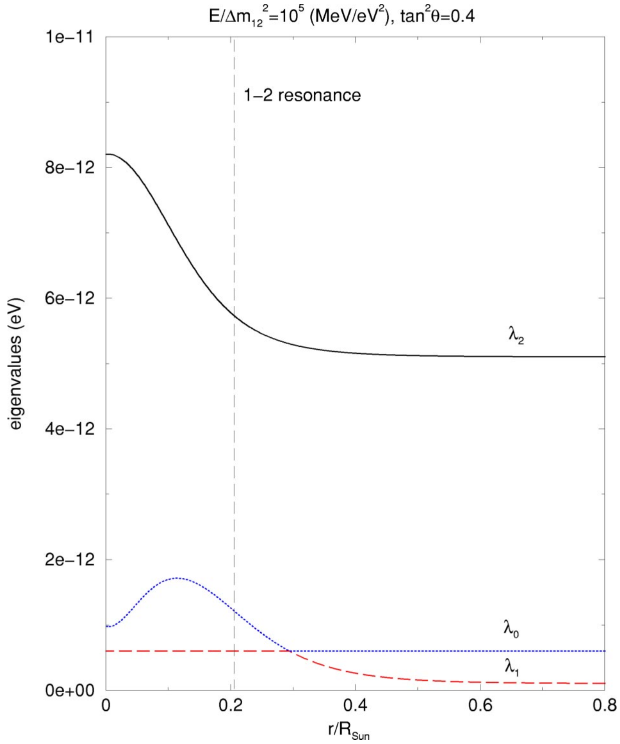

FIG. 1. The level crossing scheme. The mass eigenvalues as functions of the distance from the center of the Sun for $E/\Delta m_{12}^2 = 10^5$ eV^2 and $\tan^2\theta = 0.4$. The mass ratio is taken to be $R_\Delta = \Delta m_{01}^2/\Delta m_{12}^2 = 0.10$. Also shown is the position of 1-2 resonance (dashed vertical line).

The states ν_e and ν_a are characterized by the LMA oscillation parameters θ and Δm_{12}^2. They mix in the mass eigenstates ν_1 and ν_2 with the eigenvalues m_1 and m_2. The sterile neutrino is mainly present in the mass eigenstate ν_0 (mass m_0). It mixes weakly ($\sin\alpha \ll 1$) with active neutrinos in the mass eigenstate ν_1.[3] We will assume first that $m_2 > m_0 > m_1$ and consider the oscillation parameters of ν_s in the intervals:

$$\Delta m_{01}^2 = m_0^2 - m_1^2 = (0.2\text{–}2)\times 10^{-5}\ \ \text{eV}^2,$$

$$\sin^2 2\alpha \sim 10^{-5} - 3\times 10^{-3}. \tag{3}$$

Let $\nu_{1m}, \nu_{2m}, \nu_{0m}$ be the eigenstates, and $\lambda_1, \lambda_2, \lambda_0$ the corresponding eigenvalues of the 3ν system in matter. We denote the ratio of mass squared differences as

$$R_\Delta \equiv \frac{\Delta m_{01}^2}{\Delta m_{21}^2}. \tag{4}$$

The level crossing scheme, that is, the dependence of λ_i ($i = 0,1,2$) on the distance inside the Sun (or on the density), is shown in Fig. 1. It can be constructed analytically considering mixing of the sterile neutrino (the s mixing) as a small perturbation.

(i) In the absence of s mixing we have the usual LMA system of two active neutrinos with eigenstates ν_{1m}^{LMA}, ν_{2m}^{LMA}, and the eigenvalues λ_1^{LMA} and λ_2^{LMA} which we will call the LMA levels:

$$\lambda_1^{LMA} = \frac{m_1^2 + m_2^2}{4E} + \frac{V_e + V_a}{2} - \sqrt{\left(\frac{\Delta m_{21}^2}{4E}\cos 2\theta - \frac{V_e - V_a}{2}\right)^2 + \left(\frac{\Delta m_{21}^2}{4E}\sin 2\theta\right)^2}, \tag{5}$$

and λ_2^{LMA} has a similar expression with a plus sign in front of the square root. Here $V_e = \sqrt{2}G_F(n_e - 0.5 n_n)$, and $V_a = -0.5\sqrt{2}G_F n_n$ are the matter potentials for the electron and nonelectron active neutrinos, respectively; n_e and n_n are the number densities of the electrons and neutrons. For the sterile neutrino we have $V_s = 0$. The 1-2 (LMA) resonance condition determines the LMA resonance energy:

$$E_a = \frac{\Delta m_{21}^2 \cos 2\theta}{2(V_e - V_a)}. \tag{6}$$

(ii) Let us turn on the ν_s mixing. In the assumption $m_1 < m_0 < m_2$ the sterile neutrino level λ_s crosses λ_1^{LMA} only. The level λ_2^{LMA} essentially decouples. It is not affected by the s mixing, and $\lambda_2 \approx \lambda_2^{LMA}$. Evolution of the corresponding eigenstate ν_{2m} is strongly adiabatic.

(iii) In general, the sterile level λ_s, as the function of density, crosses λ_1^{LMA} twice: above and below the 1-2 resonance density. Effects of the higher (in density) level crossing can be neglected since the neutrinos of relevant energies are produced below the resonance (in the density scale).

The Hamiltonian of the $(\nu_{1m}^{LMA} - \nu_s)$ subsystem can be obtained diagonalizing the $\nu_e - \nu_a$ block of the 3ν Hamiltonian, and then neglecting small 1-3 element. As a result,

$$H = \begin{pmatrix} \lambda_1^{LMA} & \frac{\Delta m_{01}^2}{4E}\sin 2\alpha\cos(\theta - \theta_m) \\ \frac{\Delta m_{01}^2}{4E}\sin 2\alpha\cos(\theta - \theta_m) & \frac{m_1^2 + m_0^2}{4E} + \frac{\Delta m_{01}^2}{4E}\cos 2\alpha \end{pmatrix}, \tag{7}$$

where λ_1^{LMA} is given in Eq. (5). The $1-s$ resonance condition,

$$\lambda_1^{LMA}(\Delta m_{21}^2/E, \theta, V_e, V_a) = \frac{m_1^2 + m_0^2}{4E} + \frac{\Delta m_{01}^2 \cos 2\alpha}{4E}, \tag{8}$$

determines the s-resonance energy,

[3]The introduction of mixing with the third active neutrino is straightforward. This mixing (if not zero) can produce a small averaged oscillation effect and in what follows it will be neglected.

$$E_s=\frac{0.5m_1^2+\Delta m_{01}^2\cos^2\alpha}{V_e+V_a}\,\frac{1-R_\Delta}{1-2R_\Delta+\xi\cos 2\theta+\sqrt{(1-2R_\Delta+\xi\cos 2\theta)^2-4R_\Delta(1-R_\Delta)(\xi^2-1)}},\tag{9}$$

where $\xi\equiv(V_e-V_a)/(V_e+V_a)=n_e/(n_e-n_n)$.

Let us find the ν_e survival probability. According to Eq. (2) the initial neutrino state can be written in terms of the matter eigenstates ν_{im} as

$$\nu_e=\sin\theta_m^0\nu_{2m}+\cos\theta_m^0(\cos\alpha_m^0\nu_{1m}+\sin\alpha_m^0\nu_{0m}),\tag{10}$$

where θ_m^0 and α_m^0 are the mixing angles in matter in the neutrino production point.

Using the level crossing scheme we can describe the propagation of neutrinos from the production point to the surface of the Sun. ν_{2m} evolves adiabatically, so that $\nu_{2m}\to\nu_2$. Evolution of the two other eigenstates is, in general, nonadiabatic, so that

$$\nu_{1m}\to A_{11}\nu_1+A_{01}\nu_0,\quad \nu_{0m}\to A_{10}\nu_1+A_{00}\nu_0,\tag{11}$$

where A_{ij} are the transition amplitudes which satisfy the following equalities: $|A_{01}|^2=|A_{10}|^2=1-|A_{00}|^2=1-|A_{11}|^2\equiv P_2$. They can be found by solving the evolution equation with the Hamiltonian (7). P_2 is the two neutrino jump probability in the system $\nu_{1m}-\nu_s$.

Using Eqs. (10), (11) we can write the final neutrino state as

$$\nu_f=\sin\theta_m^0\nu_2 e^{i\phi_2}+\cos\theta_m^0[\cos\alpha_m^0(A_{11}\nu_1+A_{01}\nu_0)+\sin\alpha_m^0(A_{10}\nu_1+A_{00}\nu_0)],\tag{12}$$

where ϕ_2 is the phase acquired by ν_{2m}. Then the survival probability equals

$$P_{ee}\equiv|\langle\nu_e|\nu_f\rangle|^2\approx\sin^2\theta_m^0\sin^2\theta+\cos^2\theta_m^0\cos^2\theta[\cos^2\alpha_m^0-P_2\cos 2\alpha_m^0].\tag{13}$$

Here we have neglected a small admixture of ν_e in ν_0: $\langle\nu_e|\nu_0\rangle\approx 0$. Also we have taken into account that the coherence of the mass eigenstates is lost on the way from the Sun to the Earth due to a spread of the wave packets and averaging effects.

Similarly we obtain the transition probability of the electron to sterile neutrino:

$$P_{es}\equiv|\langle\nu_s|\nu_f\rangle|^2\approx\cos^2\theta_m^0[\sin^2\alpha_m^0+P_2\cos 2\alpha_m^0].\tag{14}$$

At the intermediate energies, $E\sim E_s(n_c)$, crossing the s resonance can be adiabatic so that $P_2=0$, and moreover, the initial angle can be equal to $\alpha_m^0\approx\pi/2$. Since the s resonance is very narrow this equality is realized already at energies slightly above $E_s(n_c)$. In this case we get from Eq. (13)

$$P_{ee}\approx\sin^2\theta_m^0\sin^2\theta.\tag{15}$$

If also $E\ll E_a(n_c)$, so that $\theta_m^0\approx\theta$, Eq. (15) leads to

$$P_{min}=P_{ee}\approx\sin^4\theta.\tag{16}$$

P_{min} is the absolute minimum of the survival probability which can be achieved in the system. In general, $P_{ee}>\sin^4\theta$, since E is not small in comparison with E_a ($\sin\theta_m^0>\sin\theta$) and/or the adiabaticity is broken.

In Fig. 2 we show results of numerical computations of the ν_e survival probability P_{ee}, and the survival probability of active neutrinos $(1-P_{es})$ as functions of energy. We have performed a complete integration of the evolution equations for the 3ν system and also made averaging over the produc-

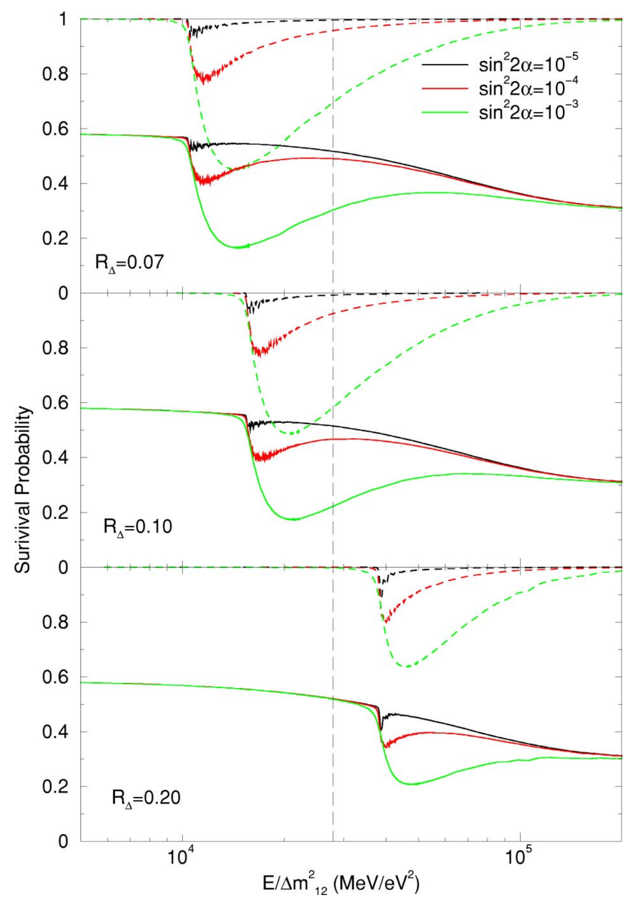

FIG. 2. The survival probability of the electron neutrinos P_{ee} (solid line) and survival probability of the active neutrinos $1-P_{es}$ (dashed line) as functions of $E/\Delta m_{12}^2$ for different values of the sterile-active mixing parameter $\sin^2 2\alpha$. We take $\tan^2\theta=0.4$. Also shown is the position of the 1-2 resonance for the central density of the Sun (vertical dashed line). For $\Delta m_{12}^2=7.1\times10^{-5}$ eV^2 the Be line is at $E/\Delta m_{12}^2=1.2\times10^4$ MeV/eV^2, the pep-neutrino line is at $E/\Delta m_{12}^2=2\times10^4$ MeV/eV^2; the lowest (observable) energy, $E=5$ MeV, and the highest energy of boron neutrino spectrum ($\sim$14 MeV) are at $E/\Delta m_{12}^2=7\times10^4$ MeV/eV^2 and 2×10^5 MeV/eV^2, correspondingly.

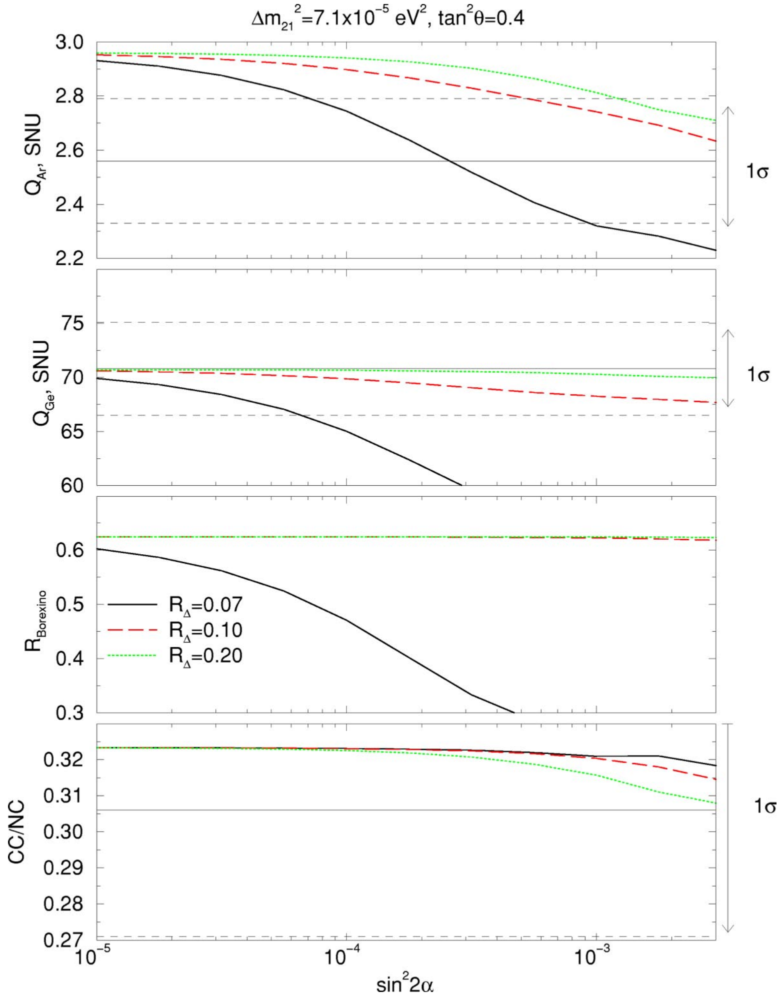

FIG. 3. The Ar-production rate (upper panel), the Ge-production rate (second panel), the suppression factor for the BOREXINO signal, and the CC/NC ratio at SNO as functions of $\sin^2 2\alpha$, for $\tan^2\theta = 0.4$ and $\Delta m^2_{21} = 7.1\times 10^{-5}$ eV^2.

tion region of the Sun. The analytical consideration allows us to understand immediately the numerical results.

The effect of s mixing is reduced to the appearance of a dip in the LMA energy profile. A size of the dip equals

$$\Delta P_{ee} \equiv P^{LMA}_{ee} - P_{ee} = P_{es}\cos^2\theta, \tag{17}$$

where $P_{ee}(E)^{LMA} = P_{ee}(E)(P_2=0, \alpha^0_m=0)$ is the LMA adiabatic probability. To obtain the last equality in Eq. (17) we used expressions for P_{ee} from Eq. (13), and P_{es} from Eq. (14). Since $\cos^2\theta < 1$ (the best-fit value of LMA mixing, $\cos^2\theta = 0.714$) according to Eq. (17) a change of the ν_e survival probability due to mixing with ν_s is weaker than the transition to sterile neutrino P_{es}. The relation (17) is well reproduced in Fig. 2.

A position of the dip (its low-energy edge) is given by the resonance energy taken at the central density of the Sun $E_s(n_c)$ [Eq. (9)]. With an increase of Δm^2_{01} the dip shifts to higher energies.

III. OBSERVABLES AND RESTRICTIONS. THREE SCENARIOS

As follows from Fig. 2, selecting appropriately the values of R_Δ and α (and therefore position and form of the dip) one can easily obtain a significant suppression of Q_{Ar} as well as the upturn of the spectrum (see Fig. 3). There are, however, restrictions which follow from other experimental results (see Ref. [15] for more details).

1. Ar-production rate versus Ge-production rate. A decrease of Q_{Ar} is accompanied by a decrease of Q_{Ge} (Fig. 3). Since the LMA prediction for Q_{Ge} is close to the central experimental value [16,17] a possible decrease of Q_{Ge} is restricted.

The changes of rates are correlated:

$$\Delta Q_{Ge} = A(R_\Delta, \alpha)\cdot \Delta Q_{Ar}, \tag{18}$$

where A is the constant which depends on the oscillation parameters. If the Be-(ν_e) line is suppressed only, we would have $A^{Be} \approx 30$. If the neutrino fluxes at the intermediate energies are affected only, then $A^{int} \sim 18$, for the boron neutrino flux we find the smallest value $A^B \sim 2$.

In principle, the decrease of the Ge-production rate can be compensated by an increase of the survival probability for the pp neutrinos. The increase of $P_{ee}(pp)$ requires the decrease of mixing. However, a decrease of $\sin^2\theta$ is restricted by the high-energy data (SK, SNO).

2. The Ar-production rate versus the rates at SNO and SuperKamiokande. For large R_Δ and $\sin\alpha$ the restriction appears from the charged current (CC)–event rate at SNO as well as from the rate of events at SK and the spectra. With a decrease of Q_{Ar} the rate [CC] decreases: we find

$$\Delta[\mathrm{CC}]=0.2\Delta Q_{Ar}, \tag{19}$$

and this relation does not depend on the absolute value of the boron neutrino flux. Also the spectral information does not allow us to strongly suppress Q_{Ar}.

Three phenomenologically different scenarios can be realized depending on the oscillation parameters, and therefore on the position and form of the dip. Three panels in Fig. 3, which correspond to different values of R_Δ, illustrate these scenarios.

(i) Narrow dip at low energies: the Be line is in the dip. This corresponds to $\sin^2 2\alpha<10^{-4}$ and $R_\Delta<0.08$ or

$$0.5E_{Be}<E_s(n_c)<E_{Be}, \tag{20}$$

where $E_{Be}=0.86$ MeV is the energy of the Be neutrinos (first panel in Fig. 2 and solid line in Fig. 3). The lower bound (20) implies that the *pp*-neutrino flux is not affected. In this case the Be line is suppressed most strongly; the ν_e fluxes of the intermediate energies (pep and CNO neutrinos) are suppressed weaker and the low-energy part of the boron neutrino spectrum measured by SK and SNO is practically unaffected (see Fig. 3).

The best compromise solution would correspond to $\sin^2 2\alpha\sim 7\times10^{-5}$, when Q_{Ar} is 1σ above the observation, and Q_{Ge} is 1σ below the observation. In this case the BOREXINO rate reduces from 0.61 down to 0.48 of the SSM rate.

For $E_s(n_c)$ being substantially smaller than E_{Be}, the Be line is on the nonadiabatic edge of the dip and its suppression is weaker. In this case larger values of $\sin\alpha$ are allowed.

(ii) The dip at the intermediate energies:

$$E_{Be}<E_s(n_c)<1.4\ \ \mathrm{MeV} \tag{21}$$

(see the second panel in Fig. 2 and the dashed lines in Fig. 3). The Be line is out of the dip and therefore unaffected. A decrease of Q_{Ar} occurs due to suppression of the ν_e components of the pep- and CNO-neutrino fluxes.

A decrease of Q_{Ar} is accompanying by smaller decrease of Q_{Ge} in comparison with the previous case. The value $Q_{Ar}=2.8$ SNU, which is 1σ above the observation, can be achieved by just 0.4σ reduction of Q_{Ge}. The BOREXINO signal due to the Be flux is unchanged, and also the observable part of the boron neutrino flux is affected very weakly. $\Delta(\mathrm{CC/NC})\sim 0.002$.

The optimal fit would correspond to $\sin^2\alpha=10^{-3}$, when Q_{Ar} is diminished down to 2.75 SNU, at the same time $Q_{Ge}=68$ SNU and CC/NC$=3.22$ in agreement with the latest data [2].

(iii) The dip at high energies:

$$E_s(n_c)>1.6\ \ \mathrm{MeV} \tag{22}$$

(see Fig. 2, the panel for $R_\Delta=0.2$, and the dotted lines in Fig. 3). Q_{Ar} is diminished due to the suppression of the low-energy part of the boron neutrino spectrum. For $\sin^2\alpha=10^{-3}$, we find $\Delta Q_{Ar}=0.17$ SNU. At the same time a decrease of the Ge-production rate is very small: $\Delta Q_{Ge}\sim 0.5$ SNU which corresponds to $A=(2–3)$ in Eq. (18).

At $\sin^2\alpha=10^{-3}$ there is already significant modification of the observable part of the boron neutrino spectrum and decrease of the total rate at SK and SNO. Also the CC/NC ratio decreases. According to Fig. 3 at $\sin^2 2\alpha=10^{-3}$, we have $\Delta(\mathrm{CC/NC})=0.01$. Further increase of R_Δ will shift the dip to higher energies, where the boron neutrino flux is larger. This, however, will not lead to further decrease of Q_{Ar} since the dip becomes shallow approaching the nonoscillatory region (see Fig. 2). The BOREXINO signal (Be line) is unchanged. So, the main signature of this scenario is a strong suppression of the upturn and even a possibility to bend the spectrum down.

Note that even for large R_Δ the influence of ν_s on the KamLAND results is negligible due to very small mixing. In contrast to the solar neutrinos, for the KamLAND experiment the matter effect on neutrino oscillations is very small and no enhancement of the *s* mixing occurs. Therefore the effect of *s* mixing on oscillation probability is smaller than $\sin^2 2\alpha\sim 10^{-3}$.

IV. FURTHER TESTS

How can one check the described scenarios?

(i) BOREXINO [18] and KamLAND (solar) as well future low-energy experiments [19–25] can establish the suppression of the Be-neutrino flux in comparison with the LMA predictions, if case (i) is realized. In BOREXINO and other experiments based on the νe scattering the ratio of the numbers of events with and without conversion can be written as

$$R_{Borexino}=P_{ee}(1-r)+r-rP_{es}, \tag{23}$$

where $r\equiv\sigma(\nu_\mu e)/\sigma(\nu_e e)$ is the ratio of cross sections. Using Eq. (17) we find an additional suppression of the BOREXINO rate in comparison with the pure LMA case:

$$\Delta R_{Borexino}\equiv R^{LMA}_{Borexino}-R_{Borexino}=(1-r)\Delta P_{ee}+rP_{es} \approx\Delta P_{ee}(1+r\tan^2\theta). \tag{24}$$

According to Fig. 3, $R^{LMA}_{Borexino}$ can be diminished rather significantly. Simultaneously, Q_{Ge} decreases. If we restrict this decrease by 2σ below the experimental results, the bounds $R^{LMA}_{Borexino}>0.4$ and $\Delta R_{Borexino}<0.2$ can be obtained. For the best-fit value of scenario

(i) we find

$$R^{LMA}_{Borexino}\sim 0.5,\quad (\Delta R_{Borexino}\sim 0.1). \tag{25}$$

Clearly, it will be difficult to establish such a difference.

(ii) If the dip is at higher energies and the Be flux is unaffected, one expects significant suppression of the pep

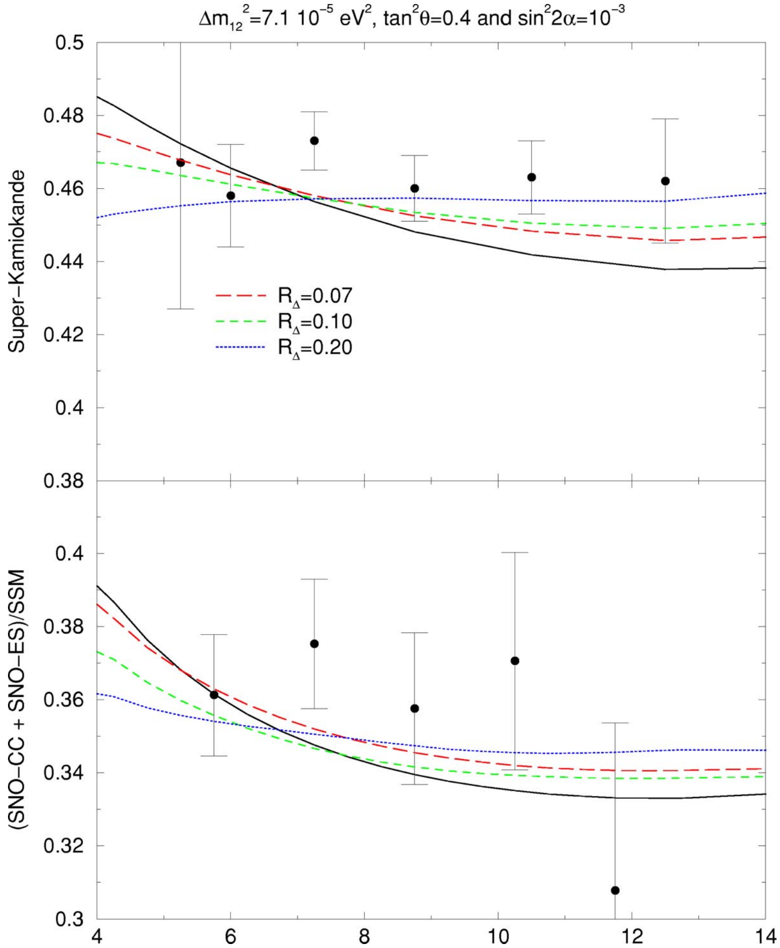

FIG. 4. The spectrum distortion (N^{osc}/N^{SSM}) at Super-Kamiokande (upper panel) and SNO (lower panel) for different values of the mass ratio R_Δ and for the sterile-active mixing $\sin^2 2\alpha = 10^{-3}$. The solid lines correspond to the pure LMA case (no sterile neutrino). Normalization of spectra have been chosen to minimize the χ^2 fit of the spectrum for each case. We show also the Super-Kamiokande and SNO experimental data points with statistical errors only.

and CNO fluxes. Such a possibility can be checked using a combination of measurements from different experiments which are sensitive to different parts of the solar neutrino spectrum. The radiochemical Li experiment [26] which has high sensitivity to the pep- and CNO-neutrino fluxes will be especially useful [27].

Precise measurements of Q_{Be} and Q_{Ge} and independent measurements of the B, *pp*, and Be neutrino fluxes and subtraction of their contributions from Q_{Be} and Q_{Ge} will allow us to determine the CNO-electron neutrino fluxes. In other words one will need to perform a combined analysis of results from Ga,Cl,Li experiments as well as the dedicated low-energy experiments [19–25].

(iii) For $R_\Delta \sim 0.1$–0.2 and $\sin^2 2\alpha \sim 10^{-3}$ a significant suppression of the low-energy part of the B-neutrino spectrum is expected. As follows from Fig. 4, at 5 MeV an additional suppression due to sterile neutrino can reach 10–15% both in SK and SNO.

In fact, the spectra with the *s* mixing give a slightly better fit to the data. Notice that there is no turn down of the SNO spectrum even for $R_\Delta = 0.2$ and $\sin^2\theta_{13} = 10^{-3}$ since we add a contribution from the $\nu - e$ scattering to the number of events. Separation of the CC and $\nu - e$ signals would increase the sensitivity. Precision measurements of shape of the spectrum in the low-energy part, $E < 6$–8 MeV, will give crucial checks of the described possibility.

No effects of the sterile neutrino with suggested parameters is expected on the supernovae neutrinos and the big-bang nucleosynthesis [15].

A very small *s* mixing implies that the width of *s* resonance is also very small. In the density scale we have $\Delta n/n = \tan 2\alpha \sim 10^{-2}$. Therefore 1% density perturbations can strongly affect conversion in the *s* resonance [28]. If density perturbations (or density profile) change in time, this will induce time variations of neutrino signals. Since the effect of the *s* resonance is small, one may expect 10% (at most) variations of the Ga- and Ar-production rates.

V. CONCLUSIONS

(i) The low (with respect to the LMA prediction) value of the Ar-production rate measured in the Homestake experiment and/or suppressed upturn of the spectrum at low energies in SK and SNO can be explained by the introduction of the sterile neutrino which mixes very weakly with the active neutrinos. The mixing of sterile neutrino leads to the appearance of the dip in the survival probability in the interval of intermediate energies $E = 0.5$–5 MeV. The survival probability in the nonoscillatory and vacuum ranges is not modified (if the sterile level crosses λ_1^{LMA}).

(ii) Depending on the value of R_Δ, that is, on a position of the dip, three phenomenologically different scenarios are possible: the Be-neutrino line in the dip; strong suppression of the pep- and CNO-neutrino fluxes and the Be-neutrino line out of the dip; suppression of the boron flux only.

The best global fit of the solar neutrino data corresponds to the unsuppressed Be line, but strongly suppressed pep- and CNO-neutrino fluxes. Such a scenario requires $\sin^2 2\alpha \sim 10^{-3}$ and $R_\Delta \sim 0.1$. It predicts also an observable suppression of the upturn of the spectrum at SK and SNO.

The present experimental results as well as relations between observables restrict substantially possible effects of the dip induced by the s mixing.

(iii) The presence of s mixing can be established by future precise measurements of the Be-, pep-, CNO-neutrino fluxes in BOREXINO [18] and KamLAND, as well as by measurements of the low-energy part of the Boron neutrino spectrum ($<5-6$ MeV) in SNO and SK. Study of the solar neutrinos seems to be the only possible way to test the scenarios described in this paper. There are no other observable effects in laboratory experiment, or in astrophysics and cosmology.

Even precise measurements of the high-energy part of the solar neutrino spectrum may not be enough to reconstruct the energy profile of the effect at low energies. So, the low-energy solar experiments are needed and they may lead to important discoveries.

Note added Since the time we posted our paper on hep-ph, some new publications have appeared which are relevant for this study.

(i) A lower value of the cross section $^{14}N(p,\gamma)^{15}O$ measured by the LUNA experiment [29] leads to a decrease of the predictions for the Ar-production rate by $\Delta Q_{Ar} = -0.1$ SNU [30] (see our footnote 1). This reduces a difference of the LMA prediction and the Homestake result by about 0.5σ. Notice that at the same time the Ge-production rate is diminished by $\Delta Q_{Ge} = 2$ SNU.

(ii) Larger values of the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ cross section obtained in the recent measurements lead to a significant increase of the predicted boron neutrino flux. Now the predicted flux is larger than that extracted from the NC event rate measured at SNO: $f_B = 0.88 \pm 0.04(\mathrm{expt}) \pm 0.23(\mathrm{theor})$ [31]. This being confirmed may testify for partial conversion of the produced ν_e to sterile neutrino thus supporting the scenario suggested in this paper.

ACKNOWLEDGMENT

One of us (P.C.H.) would like to thank FAPESP for financial support.

[1] KamLAND Collaboration, K. Eguchi *et al.*, Phys. Rev. Lett. **90**, 021802 (2003).

[2] SNO Collaboration, Q.R. Ahmad *et al.*, Phys. Rev. Lett. **92**, 181301 (2004).

[3] L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978); in Neutrino-78, Purdue Univ. C3, 1978.

[4] S.P. Mikheyev and A.Yu. Smirnov, Yad. Fiz. **42**, 1441 (1985) [Sov. J. Nucl. Phys. **42**, 913 (1985)]; Nuovo Cimento Soc. Ital. Fis., C **9**, 17 (1986); Zh. Éksp. Teor. Fiz. **91**, 7 (1986) [Sov. Phys. JETP **64**, 4 (1986)].

[5] J.N. Bahcall, P.I. Krastev, and A.Yu. Smirnov, Phys. Rev. D **60**, 093001 (1999); M.C. Gonzalez-Garcia, P.C. de Holanda, Carlos Pena-Garay, and J.W.F. Valle, Nucl. Phys. **B573**, 3 (2000).

[6] A.B. Balantekin and H. Yüksel, Phys. Rev. D **68**, 113002 (2003); G.L. Fogli, E. Lisi, A. Marrone, and A. Palazzo, Phys. Lett. B **583**, 149 (2004); M. Maltoni, T. Schwetz, M.A. Tortola, and J.W.F. Valle, Phys. Rev. D **68**, 113010 (2003); P. Aliani, V. Antonelli, M. Picariello, and E. Torrente-Lujan, hep-ph/0309156; P. Creminelli, G. Signorelli, and A. Strumia, J. High Energy Phys. **05**, 052 (2001); A. Bandyopadhyay, S. Choubey, S. Goswami, S.T. Petcov, and D.P. Roy, Phys. Lett. B **583**, 134 (2004).

[7] P.C. de Holanda and A.Yu. Smirnov, hep-ph/0309299.

[8] B.T. Cleveland *et al.*, Astrophys. J. **496**, 505 (1998).

[9] J.N. Bahcall, M.H. Pinsonneault, and S. Basu, Astrophys. J. **555**, 990 (2001).

[10] P.I. Krastev and A.Yu. Smirnov, Phys. Rev. D **65**, 073022 (2002).

[11] Super-Kamiokande Collaboration, S. Fukuda *et al.*, Phys. Rev. Lett. **86**, 5651 (2001); **86**, 5656 (2001).

[12] SNO Collaboration, Q.R. Ahmad *et al.*, Phys. Rev. Lett. **89**, 011301 (2002); **89**, 011302 (2002).

[13] P.A. Sturrock, G. Walther, and M.S. Wheatland, Astrophys. J. **491**, 409 (1997); **507**, 978 (1998); P.A. Sturrock and M.A. Weber, *ibid.* **565**, 1366 (2002); P.A. Sturrock, astro-ph/0304148; hep-ph/0304106; A. Milsztajn, hep-ph/0301252; P.A. Sturrock, Astrophys. J. **594**, 1102 (2003); hep-ph/0304073; D.O. Caldwell and P.A. Sturrock, hep-ph/0305303.

[14] V. Berezinsky, M. Narayan, and F. Vissani, Nucl. Phys. **B658**, 254 (2003); P.C. de Holanda and A.Yu. Smirnov, hep-ph/0211264.

[15] P.C. de Holanda and A.Yu. Smirnov, hep-ph/0307266.

[16] SAGE Collaboration, J.N. Abdurashitov *et al.*, Zh. Éksp. Teor. Fiz. **122**, 211 (2002) [JETP **95**, 181 (2002)].

[17] GNO Collaboration, T.A. Kirsten, Nucl. Phys. B (Proc. Suppl.) **118**, 33 (2003).

[18] BOREXINO Collaboration, G. Alimonti *et al.*, Astropart. Phys. **16**, 073022 (2002).

[19] R.S. Raghavan, Phys. Rev. Lett. **78**, 3618 (1997).

[20] H. Ejiri *et al.*, Phys. Rev. Lett. **85**, 2917 (2000).

[21] Y. Suzuki, Low Nu2 workshop, Tokyo 2000, http://www-sk.icrr.u-tokyo.ac.jp/neutlowe/

[22] B. Lanou, in Low Nu3 Heidelberg, Germany, http://www.mpi-hd.mpg.de/nubis/

[23] D.N. McKinsey and J.M. Doyle, J. Low Temp. Phys. **118**, 153 (2000).

[24] G. Bonvicini *et al.*, eConf.C010630 E603 (2001); Nucl. Instrum. Methods Phys. Res. A **491**, 402 (2002).

[25] C. Broggini, Low Nu3 Heidelberg, Germany, http://www.mpi-hd.mpg.de/nubis/

[26] J.N. Bahcall, Phys. Lett. **13**, 332 (1964); V.A. Kuzmin and G.T. Zatsepin, Proc. Int. Conf. on Cosmic Rays, Jaipur, India,

1965, paper Mu-Nu 36, p. 1023.
[27] See, for recent discussion, A. Kopylov and V. Petukhov, hep-ph/0301016; hep-ph/0306148.
[28] P.I. Krastev and A.Yu. Smirnov, Mod. Phys. Lett. A **6**, 1001 (1991).
[29] LUNA Collaboration, A. Formicola *et al.*, nucl-ex/0312015.
[30] S. Degl'Innocenti, G. Fiorentini, B. Ricci, and F.L. Villante, astro-ph/0312559.
[31] J.N. Bahcall and M.H. Pinsonneault, Phys. Rev. Lett. **92**, 121301 (2004).