Abstract

The excess of solar-neutrino events above 13 MeV that has been recently observed by Superkamiokande can be explained by the vacuum oscillation solution to the Solar Neutrino Problem (SNP). If the boron neutrino flux is 20% smaller than the standard solar model (SSM) prediction and the chlorine signal is assumed 30% (or 3.4σ) higher than the measured one, there exists a vacuum oscillation solution to SNP that reproduces both the observed spectrum of the recoil electrons, including the high energy distortion, and the other measured neutrino rates. The most distinct signature of this solution is a semi-annual seasonal variation of the 7Be neutrino flux with maximal amplitude. While the temporal series of the GALLEX and Homestake signals suggest that such a seasonal variation could be present, future detectors (BOREXINO, LENS and probably GNO) will be able to test it.
wait for future Superkamiokande data, where such possible systematic effects will be further elaborated. The data from the SNO detector, which will come in the operation soon, e.g., see Ref. [4], can shed light on this excess.

Another possible explanation of this excess [5,6] is that the Hep neutrino flux might be significantly larger (about a factor 10–20) than the SSM prediction. The Hep flux depends on solar properties, such as the $^3\text{He}$ abundance and the temperature, and on $S_{13}$, the zero-energy astrophysical $S$-factor of the $p + ^3\text{He} \rightarrow ^4\text{He} + e^+ + \nu$ reaction. Both SSM based [7] and model-independent [8] approaches give a robust prediction for the ratio $\Phi_\nu(\text{Hep})/S_{13}$. Therefore, this scenario implies a cross-section larger by a factor 10–20 than the present calculations (for reviews see [7,9]). Such a large correction to the calculation does not seem likely, though it is not excluded. A large Hep neutrino flux remains a possible explanation of the excess. The signature of Hep neutrinos, the presence of electrons above the maximum boron neutrino energy, can be tested by the SNO experiment.

The Superkamiokande collaboration noticed [1] that vacuum oscillations with large $\Delta m^2$ explain the observed high-energy excess. However, the same Ref. [1] emphasizes that those oscillation parameters that reproduce the excess do not solve the Solar Neutrino Problem (SNP), i.e., they do not explain the global rates observed by the four solar neutrino experiments. In Ref. [1] it was demonstrated that if the SSM prediction for the boron neutrino flux is reduced by factor $f_B = 0.8$ and the chlorine experimental signal is arbitrarily assumed to be larger by a factor $f_{CL} = 1.3$, the vacuum oscillation solution to SNP (global rates) corresponds to $\Delta m^2 = 4.2 \cdot 10^{-10} \text{ eV}^2$ and $\sin^2 2\theta = 0.93$: this choice of parameters reproduces also the excess of high-energy recoil electrons in the Superkamiokande spectrum [1]. In this paper we shall further elaborate upon this specific vacuum oscillation solution. For the sake of conciseness, we shall refer to this solution ($\Delta m^2 = 4.2 \cdot 10^{-10} \text{ eV}^2$ and $\sin^2 2\theta = 0.93$) as HEE (High-Energy Excess) VO.

We shall start with a short description of relevant features of those vacuum oscillation solutions, whose parameters fit all global rates; these solutions will be indicated altogether as VO.

Vacuum oscillations can reconcile the SSM with the observed rates of all three kinds of solar neutrino experiments (for reviews see [11–14]). A recent detailed study [15–19] of VO solutions shows that global fits to the data result in oscillation parameters within the ranges $5 \cdot 10^{-11} \text{ eV}^2 \leq \Delta m^2 \leq 1 \cdot 10^{-10} \text{ eV}^2$ and $0.7 \leq \sin^2 2\theta \leq 1$ for oscillations between active neutrinos. The large range of $\sin^2 2\theta$ is mainly caused by uncertainties in the B-neutrino flux, though other uncertainties contribute too; $\Delta m^2$ is much less sensitive to changes of the B-neutrino flux. These effects have been explicitly investigated in Refs. [20,17]. In the SSM the B-neutrino flux uncertainties (+19%, −14%, [21]) are mainly caused by the uncertainties in $S_{17}$ (the $p$-Be cross section is poorly known) and by the strong temperature dependence of this flux. The above uncertainties are only $1\sigma$ errors and the actual discrepancy could be larger, especially due to the $S_{17}$ factor. This large uncertainty of the B-neutrino flux has motivated several authors to consider the boron flux as $\Phi_B = f_B \Phi^{SSM}_B$ with $f_B$ as a free parameter [20,13,17].

A signature of vacuum oscillation is the anomalous seasonal variation of the neutrino flux at low energies [22,12]. The distance between the Sun and the Earth varies during the year by about 3% affecting the detected flux both because of the $1/r^2$ geometrical factor and because of the dependence of the survival probability $P(\nu_e \rightarrow \nu_e)$ on the distance. The
second effect is absent for MSW solutions. Nevertheless, the MSW solution also predicts seasonal variations of neutrino flux, which are connected with the day/night effect and are caused by the longer winter nights (for recent calculations see [23,24] and references to earlier works therein). The MSW seasonal variations are weaker than the VO ones at low energies. In the case of VO, the monochromatic Be-neutrinos are expected to show the strongest seasonal variations [25–27,19]; on the contrary, Be-neutrinos should show very small seasonal variations in the case of MSW oscillations. Since Be-neutrinos are monochromatic, their flux shows the entire seasonal variation predicted by VO; the effect is reduced for the other fluxes due to the averaging over the different phases of neutrinos with different energies within the interval of observation, \( \Delta E \).

Seasonal variations for \( \Delta m^2 \) larger than the values allowed by VO solutions were recently analyzed in Ref. [28]. The authors found some significant consequences such as energy dependence and correlation with distortion of the spectrum. The latter effect was also discussed earlier in Ref. [29]. In relation to the chlorine signal, seasonal variations were analysed in early work [30]. A clear discussion of the seasonal variation effect has been presented in Refs. [31].

To explain the excess in electron spectrum observed by Superkamiokande we allow a boron neutrino flux 15–20% smaller than the SSM prediction, and we allow that the chlorine signal be about 30% larger than the Homestake observation. This assumed 3.4\( \sigma \) increase could have a combined statistical and systematic origin though we do not have any concrete argument in favor of such systematic error in the Homestake experiment.

In our calculation, we shall use neutrino fluxes from the BP98 model [21] with the B-neutrino flux rescaled as \( \Phi_B = f_B \Phi_{SSM}^B \).

For the chlorine rate we assume \( R_{Cl} = 2.56 f_{Cl} \) SNU (the Homestake experiment gives the rate \([32]\) 2.56 ± 0.16 ± 0.16 SNU). It is easy to see that for \( f_{Cl} = 1.3 \) the assumed signal 3.33 SNU is 3.4\( \sigma \) higher than one given by Homestake (systematic and statistical error are incoherently combined).

For the gallium rate we use the average of the GALLEX [33] and SAGE [34] results: 72.5 ± 5.7 SNU. Finally, we take the Superkamiokande result [1]: (2.46 ± 0.09) \( \times 10^6 \) cm\(^{-2}\)s\(^{-1}\). For each pair \( f_B \) and \( f_{Cl} \) we find the VO solution, i.e., the parameters \( (\Delta m^2, \sin^2 2\theta) \), that explain the observed rates, and then we calculate the corresponding boron neutrino spectrum.

For example, for \( f_B = 0.8 \) and \( f_{Cl} = 1.3 \) the oscillation parameters \( (\Delta m^2 = 4.2 \times 10^{-10} \text{ eV}^2, \sin^2 2\theta = 0.93) \) give a good fit to all rates \( (\chi^2/\text{d.o.f.} = 3.0/3) \): This is not the best fit point, which has \( \chi^2 \approx 0 \), therefore the 3 d.o.f. are the three experimental rates. On the other hand, the spectrum with these oscillation parameters reproduces [1] the excess of high-energy events observed in the Superkamiokande spectrum. More generally, this choice of oscillation parameters gives rates in agreement with the experiments at the 2\( \sigma \) level for \( 0.77 \leq f_B \leq 0.83 \) and \( 1.3 \leq f_{Cl} \leq 1.55 \).

In Fig. 1 we present the neutrino-induced electron spectra for the vacuum oscillation solutions as the ratio to the SSM unmodified spectrum [21]. The dotted and dashed curves show two spectra corresponding to the VO solutions of Ref. [1] and Ref. [18], respectively. The solid line shows the VO oscillation solution that is discussed in this paper (HEE VO) corresponding to \( \Delta m^2 = 4.2 \times 10^{-10} \text{ eV}^2 \) and \( \sin^2 2\theta = 0.93 \) \( (f_B = 0.8 \) and \( f_{Cl} = 1.3) \).

The role of the two parameters, \( f_B \) and \( f_{Cl} \), for the best fit of the spectrum is different:
while $f_B$ mostly changes $\sin^2 2\theta$, $f_{Cl}$ affects $\Delta m^2$ and, therefore, the spectrum. Values of $f_{Cl}$ as low as 1.2 already give a bad fit to the observed spectrum.

The anomalous seasonal variations of Be-neutrino flux and of the gallium signal are shown in the Fig. 2 (see also [10]). Anomalous seasonal variation is described by the survival probability of the electron neutrino $P(\nu_e \rightarrow \nu_e)$. For Be-neutrinos with energy $E = 0.862$ MeV the survival probability (the suppression factor for electron neutrinos) is given by

$$ P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 a}{4E} \left( 1 + e \cos \frac{2\pi t}{T} \right) \right),$$

(1)

where $a = 1.496 \cdot 10^{13}$ cm is the semimajor axis, $e = 0.01675$ is the eccentricity of the Earth’s orbit, and $T = 1$ yr is the orbital period. The phase in Eq. (1) is such that $t = 0$ corresponds to the aphelion. In Fig. 2 the solid and dashed curves show the variation of the Be-neutrino flux for the HEE VO and VO [4] cases, respectively. The case of the HEE VO (solid curve) is dramatically different from the VO case: there are two maxima and minima during one year and the survival probability oscillates between $1 - \sin^2 2\theta \approx 0.14$ and 1. The explanation is obvious: the HEE VO solution has a large $\Delta m^2$, which results in a phase $\Delta m^2 a/(4E) \approx 93$, large enough to produce two full harmonics during one year, when the phase changes by about 3% due to the factor $(1 + e \cos 2\pi t/T)$. The flat central maximum with a shallow local minimum has a trivial origin: the extrema of $P(\nu_e \rightarrow \nu_e)$ in Eq. (1) correspond to phases $k\pi/2$, where $k$ are integers, and to the phases with $\cos 2\pi t/T = \pm 1$. The accidental proximity of these phases can result in three nearby extrema. The shallow minimum in Fig. 2 disappears with small changes in $\Delta m^2$.

The phases of maxima and minima in terms of $t/T$ are not fixed in the HEE VO solution, because tiny changes of $\Delta m^2$ shift their positions: e.g., 1% change in $\Delta m^2$ shifts the position of an extremum by more than one month (see Eq. (1)).

As one can see from Fig. 2, the HEE VO solution predicts that the beryllium electron neutrinos should arrive almost unsuppressed during about four months in a year!

According to the SSM, beryllium neutrinos contribute 34.4 SNU out of the total gallium signal of 129 SNU. Therefore, the strong $^7$Be neutrino oscillation predicted by the HEE VO solution also implies an appreciable variation of total gallium signal. In Fig. 2 the dotted curve shows this variation corresponding to the HEE VO solution, which can be compared with the weaker variation corresponding to the best-fit VO solution (dashed-dotted curve). It is possible that the HEE VO variation could already be partially testable by the existing gallium data, and this possibility will significantly increase when the results from GNO with its larger statistics are available.

In Fig. 3 the predicted time variation of the gallium signal is compared with GALLEX data (see also [10]). GALLEX data have been analysed according to the time of the year of the exposures and grouped in six two-month bins (M. Cribier cited in [33]): the data points with error bars in Fig. 3 reproduce the result of this analysis. The data give the rates averaged for the same two months every year of observations. The theoretical prediction (solid curve) is plotted with the same averaging. The 7% geometrical variation is included. Both the phase of the time-variation and the average flux have been taken to fit the data. The fit by the theoretical curve has $\chi^2$/d.o.f. = 0.85/4; the fit by a nonoscillating signal is also good: $\chi^2$/d.o.f. = 1.36/5. Because of the limited statistics, we do not interpret the good visual agreement in Fig. 3 as a proof of HEE VO solution, though it is certainly suggestive.
The comparison of the predicted time variation with preliminary data \[3^4\] of the other gallium detector SAGE is shown in Fig. 4. Note that this time we can not choose the phase arbitrary: it is already fixed by the fit to the GALLEX data. Because of the larger fluctuations of the SAGE data (compare Fig. 3 and Fig. 4) the agreement with the predicted variation is worse.

In Fig. 5 the predicted variation is compared with the Homestake data (see Ref. \[30\] for an earlier analysis of indications for seasonal oscillations in the Homestake data). The phase of the theoretical dependence is kept fixed at the value fitted to the GALLEX data. As for the GALLEX data we find that the HEE VO theoretical curve gives a better fit \((\chi^2/d.o.f.=1.4/5)\) than the time-independent signal, which however cannot be excluded \((\chi^2/d.o.f.=3.1/5)\). This agreement is further strengthened by the fact that the phase of time dependence was not chosen to fit the Homestake data, since it was already fixed by the GALLEX data. One should consider this agreement as additional indication for the HEE VO solution.

Finally, in Fig. 6 (Fig. 7) we compare the time variation of the Superkamiokande signal for recoil electrons with energies higher than 10 MeV (11.5 MeV) with the HEE VO predictions. The fit of the data is good: \(\chi^2/d.o.f.=2.7/7\) \((\chi^2/d.o.f.=5.1/7)\). Similar calculations were done by the Superkamiokande collaboration \[33\], by A. Smirnov (private communication) and by M. Maris and S. Petcov \[38\].

While the agreement between the HEE VO solution and each single observational datum on seasonal variations might appear accidental and not statistically significant, the combined agreement with all data on seasonal variations, as shown in Figs. 3–7 (total \(\chi^2/d.o.f. = 34.7/41\)), appears to be quite a suggestion in favour of the HEE VO solution.

As in our previous work \[10\], we prefer not to make a global fit in terms of \(\chi^2/d.o.f.\) to all available data (rates, spectrum and time variations). The large number of degrees of freedom can hide a discrepancy with some particular data, especially if it corresponds to only one degree of freedom, like the chlorine rate in our case. A small \(\chi^2\) is only a necessary condition for the correct model. One can find such a global fit in the paper by Barger and Whisnant \[39\], which appeared after this work was completed. The authors study the VO solution with \(\Delta m^2 = 4.42 \times 10^{-10} \text{ eV}^2\) and \(\sin^2 2\theta = 0.93\), \(i.e.,\) parameters close the ones we consider. They find this solution as the global best fit to the rates, spectrum and time dependence of SuperKamiokande signal \((\chi^2 = 39\) for 26 degrees of freedom).

In conclusion, the combination of a B-neutrino flux 20% lower than in the SSM (easily allowed by the present uncertainties) and of the assumption that the chlorine signal be 30\% \((3.4\sigma)\) higher than the one presently observed by Homestake results in a vacuum oscillation solution (HEE VO) that fits the electron spectrum recently observed by Superkamiokande. This solution predicts strong seasonal variation of \(^7\text{Be}-\)neutrino flux: some indication to such a variation is already seen in the GALLEX and Homestake data. Seasonal dependence of the Superkamiokande data for electron energies higher than 10 MeV and 11.5 MeV provide further indication in favour of the HEE VO solution. The anomalous seasonal variation of Be-neutrino flux predicted by the HEE VO solution can be reliably observed by the future BOREXINO \[36\] and LENS \[37\] detectors. Additionally, LENS, which should measure the flux and spectrum of \(^7\text{Be}\) neutrinos, will be able to observe the suppression of \(^8\text{B}\) neutrino flux, \(P(\nu_e \rightarrow \nu_e) = 1 - (1/2) \sin^2 2\theta = 0.53\), which is another signature of VO solutions.
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FIGURES

FIG. 1. Ratio of the vacuum oscillation spectra to the SSM spectrum. The solid curve corresponds to the HEE VO solution with $\Delta m^2 = 4.2 \cdot 10^{-10} \text{eV}^2$ and $\sin^2 2\theta = 0.93$. The dashed and dotted curves correspond to the VO solutions of Refs. [18] and [4], respectively. Energy resolution is taken into account. The data points show the 708-day Superkamiokande result.

FIG. 2. Anomalous seasonal variations of the beryllium neutrino flux and gallium signal for the VO and HEE VO solutions. The survival probability $P(\nu_e \rightarrow \nu_e)$ for Be neutrinos is given for the HEE VO (solid curve) and the VO (dashed curve) solutions as function of time ($T$ is an orbital period). The dotted (dash-dotted) curve shows the time variation of gallium signal in SNU for the VO solutions.

FIG. 3. Seasonal variations predicted by the HEE VO solution are compared with the GALLEX data. Theoretical dependence includes oscillations and 7% geometrical effect. The global phase of oscillation (undefined in HEE VO) and the mean rate (taken in HEE VO as the average of the GALLEX and SAGE rates) have been chosen to fit the data. The fit with the HEE VO solution has $\chi^2 / \text{d.o.f.} = 0.87 / 4$, while the no-oscillation fit has $\chi^2 / \text{d.o.f.} = 1.36 / 5$.

FIG. 4. Seasonal variations predicted by the HEE VO solution are compared with the SAGE preliminary data. Theoretical dependence includes oscillations and the 7% geometrical variations. The phase of oscillation has already been fixed by the GALLEX data, while the mean rate has been chosen to fit the data. The fit with the HEE VO solution has $\chi^2 / \text{d.o.f.} = 8.9 / 5$, while a time-independent fit gives $\chi^2 / \text{d.o.f.} = 3.8 / 5$.

FIG. 5. Seasonal variations predicted by the HEE VO solution are compared with the Homestake data binned according to the mean exposure time. Data take into account the 7% geometrical variation. The phase of the oscillation has already been fixed to fit the GALLEX data, while the mean rate has been chosen to fit the data. The fit with the HEE VO solution gives $\chi^2 / \text{d.o.f.} = 1.4 / 5$, while a constant fit (no oscillation) gives $\chi^2 / \text{d.o.f.} = 3.1 / 5$.

FIG. 6. Seasonal variations predicted by the HEE VO solution (solid line) and by the geometrical effect only (dashed line) are compared with the Superkamiokande data for electron recoil-energies $E_e > 10 \text{ MeV}$. The fit with the HEE VO solution gives $\chi^2 / \text{d.o.f.} = 2.7 / 7$, while the one with the geometrical effect only (no oscillation) gives $\chi^2 / \text{d.o.f.} = 2.3 / 7$.

FIG. 7. Seasonal variations predicted by the HEE VO solution (solid line) and by the geometrical effect only (dashed line) are compared with the Superkamiokande data for electron recoil-energies $E_e > 11.5 \text{ MeV}$. The fit with the HEE VO solution gives $\chi^2 / \text{d.o.f.} = 5.1 / 7$, while the one with the geometrical effect only (no oscillation) gives $\chi^2 / \text{d.o.f.} = 6.8 / 7$. 

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Fig. 1

VO spectrum / SSM BBP98 spectrum
