Vacuum oscillations and the distorted solar neutrino spectrum observed by Superkamiokande

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Abstract

The excess of solar-neutrino events above 13 MeV that has been recently observed by Superkamiokande can be explained by vacuum oscillations (VO). If the boron neutrino flux is 20% smaller than the standard solar model (SSM) prediction and the chlorine signal is assumed 30% (or 3.5σ) higher than the measured one, there exists a VO solution that reproduces both the observed boron neutrino spectrum, including the high energy distortion, and the other measured neutrino rates. This solution is already testable by the predicted anomalous seasonal variation of the gallium signal. Its most distinct signature, a large anomalous seasonal variation of $^7$Be neutrino flux, can be easily observed by the future detectors, BOREXINO and LENS.

Superkamiokande [1] has recently observed an excess of solar-neutrino events at energy higher than 13 MeV. This excess cannot be interpreted as a distortion of the boron neutrino spectrum due to neutrino oscillations [2], if one restricts oneself to the standard oscillation solutions that explain the observed gallium, chlorine and water-cerenkov neutrino rates.

It is tempting to think that this excess is a result of low statistics at the end of the boron neutrino spectrum. On the other hand, all systematic errors are reduced at higher energies: the background decreases, the detection efficiency increases, and the recoil electron direction is better determined. The data from the SNO detector, which is in the operation now (e.g., see [3]), can shed light on this excess.

Another possible explanation [4,5] is that the hep neutrino flux might be significantly larger (about a factor 20–30) than the SSM prediction. The hep flux depends on solar
properties, such as the $^3$He abundance and the temperature, and on $S_{13}$, the zero-energy astrophysical $S$-factor of the $p + ^3$He $\rightarrow ^4$He $+ e^+ + \nu$. Both SSM based \cite{5} and model-independent \cite{6} approaches give a robust prediction for ratio $\Phi_{\nu}(\text{hep})/S_{13}$. Therefore, this scenario implies a cross-section larger by a factor 20–30 than the present calculations (for reviews see \cite{5,4}). Such a huge mistake in the calculation does not seem likely, though the required large cross-section does not contradict to the “first principle physics” \cite{4}.

In this letter we propose another explanation of the observed excess based on the distortion of spectrum by vacuum oscillations.

Combined with the SSM, VO can explain the observed rates of all three solar neutrino experiments (for reviews see \cite{8–11}). We shall refer to these models as Standard Vacuum Oscillation (SVO) solutions. A recent detailed study \cite{12–16} of SVO solutions shows that global fits to the data result in oscillation parameters within the ranges $5 \cdot 10^{-11}$ eV$^2 \leq \Delta m^2 \leq 1 \cdot 10^{-10}$ eV$^2$ and $0.7 \leq \sin^22\theta \leq 1$ for oscillations between the active neutrino components. A large range for $\sin^22\theta$ is caused by uncertainties in the B-neutrino flux. This effect has been explicitly investigated in Refs. \cite{17,14}. In the SSM the B-neutrino flux uncertainties ($+19\%$, $-14\%$, \cite{18}) are 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 given for $1\sigma$ errors and they could be larger, especially due to the $S_{17}$ factor. Motivated by it, several authors considered the boron flux as $\Phi_B = f_B \Phi_{SSM}^B$ with $f_B$ as a free parameter \cite{2,17,12,14}.

A signature of VO is the anomalous seasonal variation of the neutrino flux \cite{13,11}. The variation of the distance between the Sun and the Earth affects the detected flux, apart from a trivial geometrical factor, because of the dependence of the survival probability $P(\nu_e \rightarrow \nu_e)$ on the distance. This effect is absent for the MSW solutions. The anomalous seasonal variation is the strongest for the Be-neutrino flux \cite{20–22,16}.

The seasonal variations for $\Delta m^2$ larger than the values allowed by the SVO solutions were analyzed recently in Ref. \cite{23}. 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. \cite{24}. A clear discussion of the seasonal variation effect has been presented in Ref. \cite{25}.

To explain the distortion of spectrum observed in 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 3.5$\sigma$ increase could have a statistical origin or might imply a small systematic error in the Homestake experiment, though we do not have any concrete argument in favor of such “theoretical assumption”.

In our calculations, we shall use neutrino fluxes from the BP98 model \cite{18} with the B-neutrino flux rescaled as $\Phi_B = f_B \Phi_{SSM}^B$. For the chlorine rate we adopt the recent Homestake data \cite{26} multiplied by a factor $f_{Cl} = 2.56 f_{Cl} \pm 0.16 \pm 0.15$ SNU. For the gallium rate we use the average of the GALLEX \cite{27} and SAGE \cite{28} results: $72.5 \pm 5.7$ SNU. Finally, we take the Superkamiokande result \cite{1}: $(2.46 \pm 0.09) \cdot 10^6$ cm$^{-2}$s$^{-1}$. For each pair $f_B$ and $f_{Cl}$ we find the VO solution, i.e., the parameters $(\Delta m^2, \sin^22\theta)$, that explains 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 $(\Delta m^2 = 4.2 \cdot 10^{-10}$ eV$^2, \sin^22\theta = 0.93)$ give a good fit to all rates ($\chi^2/\text{d.o.f.} = 3.0/3$). On the other hand, the same oscillation parameters give a good fit \cite{1} to the distorted Superkamiokande
spectrum. More generally, this choice of oscillation parameters gives rates in agreement with the experiments for \(0.77 \leq f_B \leq 0.83\) and \(1.3 \leq f_{Cl} \leq 1.55\).

In Fig. 1 we present the spectra of the VO solutions as the ratio to the SSM unmodified spectrum [18]. The dotted and dashed curves show two spectra corresponding to the SVO solutions of Ref. [2] and Ref. [15], respectively. The solid line shows the spectrum-distorted vacuum oscillation (DVO) solution that corresponds 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 DVO spectrum differs from SVO at low \((E \approx 5-6 \text{ MeV})\) and high \((E > 13 \text{ MeV})\) energies. Both deviations can be tested by future Superkamiokande and SNO data.

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 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. Anomalous seasonal variation is described by the survival probability of the electron neutrino \(P(\nu_e \rightarrow \nu_e)\). For Be-neutrinos with energy \(E = 0.862 \text{ MeV}\) the survival probability (the suppression factor) is given by

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

where \(a = 1.496 \times 10^{13} \text{ cm}\) is the semimajor axis, \(e = 0.01675\) is the eccentricity of the Earth’s orbit, and \(T = 1 \text{ yr}\) 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 DVO and SVO [2] cases, respectively. The case of the DVO (solid curve) is dramatically different from the SVO 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 DVO 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 trigonometric explanation (for some parameters this accidental shallow minimum turns into maximum). The phases of maxima and minima are not fixed in the DVO solution, because tiny changes of \(\Delta m^2\) shift their positions.

Therefore, the DVO 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 \(^7\text{Be}\) neutrino oscillation predicted by the DVO solution also implies an appreciable variation of total gallium signal. In Fig. 2 the dotted curve shows this variation corresponding to the DVO solution, which can be compared with the weaker variation corresponding to the SVO solution (dashed-dotted curve). It is possible that the DVO variation could already be tested by the existing gallium data, and this possibility will significantly increase when the new results from GNO with enlarged mass are available.

In Fig. 3 the predicted time variation of the gallium signal is compared with GALLEX data (M. Cribier cited in [27]). 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 with the proper phase. The phase of the oscillation and the averaged flux have been chosen to fit the data. The fit by the theoretical curve has $\chi^2/d.o.f. = 0.85/4$; the fit by a time-independent signal is also good: $\chi^2/d.o.f. = 1.36/5$. Because of limited statistics, we do not interpret the good agreement seen in Fig. 3 as a proof of DVO solution, though one might consider it as some indication.

The anomalous seasonal variation of Be-neutrino flux predicted by the DVO solution can be reliably observed by the future BOREXINO [29] and LENS [30] detectors. Additionally, LENS, which should measure the flux and spectrum of $pp$ neutrinos, will be able to observe the suppression of $pp$ neutrino flux, $P(\nu_e \to \nu_e) = 1 - (1/2) \sin^2 2\theta = 0.53$, which is another signature of VO solutions.

In conclusion, a B-neutrino flux 20% lower than in the SSM (easily allowed by the present uncertainties) and the assumption of chlorine signal 30% ($3.5\sigma$) higher than the Homestake data result in a VO solution with a distorted neutrino spectrum that fits the one recently observed by Superkamiokande. This solution predicts strong seasonal variation of $^7$Be-neutrino flux, which would be seen by future experiments, and appreciable gallium-signal variation, which is compared in Fig. 3 with existing data.

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FIGURES

FIG. 1. Ratio of the VO spectrum to the SSM spectrum. The solid curve corresponds to the DVO 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 SVO solutions of Refs. [15] and [2], respectively. Energy resolution is taken into account everywhere. The data points show the Superkamiokande results [1].

FIG. 2. Anomalous seasonal variations of the beryllium neutrino flux and gallium signal for the SVO and DVO solutions. The survival probability \( P(\nu_e \rightarrow \nu_e) \) for Be neutrinos (suppression factor) is given for the DVO (solid curve) and the SVO (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 DVO (SVO [2]) solution.

FIG. 3. Seasonal time variation predicted by the DVO solution in comparison with the GALLEX data. The theoretical dependence includes oscillations and 7\% geometrical variations. The phase of the oscillation (undefined in DVO) and the mean rate (chosen in DVO as averaged rate of GALLEX and SAGE) has been chosen here to fit the data. The fit by the DVO solution gives \( \chi^2/\text{d.o.f.} = 0.85/4 \) and the fit by a time-independent signal gives \( \chi^2/\text{d.o.f.} = 1.36/5 \).
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$^7\text{Be}$ suppression, $P(\nu_e \rightarrow \nu_e)$

Gallium signal (SNU)
