SOLAR NEUTRINO DATA, NEUTRINO MAGNETIC MOMENTS
AND FLAVOR MIXING

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Abstract

The results of all currently operating solar neutrino experiments are analyzed in
the framework of the resonant neutrino spin–flavor precession scenario including the
effects of neutrino mixing. Nine different profiles of the solar magnetic field are used
in the calculations. It is shown that the available experimental data can be accounted
for within the considered scenario. The Ga–Ge data lead to an upper limit on the
neutrino mixing angle: \( \sin^2 \theta_0 < 0.25 \). One can discriminate between small mixing
angle (\( \sin^2 \theta_0 \lesssim 0.1 \)) and moderate mixing angle solutions by studying the solar \( \bar{\nu}_e \) flux
which is predicted to be sizeable for moderate mixing angles. The expected signals
due to \( \bar{\nu}_e \) in the SNO, Super–Kamiokande and Borexino experiments are calculated
and found to be detectable for \( \sin^2 \theta_0 \gtrsim 0.1 \).

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1 Introduction

The solar neutrino problem, i.e. the discrepancy between the solar neutrino observations \[1, 2, 3, 4, 5\] and the solar model predictions \[6, 7, 8, 9, 10\] remains one of the major unresolved puzzles of modern particle physics and astrophysics. Although at present an astrophysical solution of the problem is not completely ruled out, it is rather unlikely to be the true cause of the discrepancy provided the results of the Cl–Ar \[1,2\], Kamiokande \[3\], and the Ga–Ge \[4,5\] experiments are correct \[11, 9\].

There are several possible neutrino–physics solutions of the solar neutrino problem, the most popular one being resonant neutrino transitions in the matter of the sun (the MSW effect \[14\]). In this paper we concentrate, however, on another type of solutions related to the hypothesis of existence of relatively large magnetic or transition magnetic moments of neutrinos. In this case neutrino spin precession \[16, 17, 18\] can occur in the magnetic field of the sun, converting a fraction of the solar $\nu_eL$’s into $\nu_eR$ or into $\nu_{\mu R}$, $\nu_{\tau R}$, $\bar{\nu}_{\mu R}$ or $\bar{\nu}_{\tau R}$. Although $\bar{\nu}_{\mu R}$ and $\bar{\nu}_{\tau R}$ are not sterile, they cannot be observed in the Cl–Ar (Homestake), and the Ga–Ge (SAGE and GALLEX) experiments, and can only be detected with a small cross section in the Kamiokande experiment. Spin–flavor precession of neutrinos can be resonantly enhanced in the matter of the sun \[17, 18\], in direct analogy with the MSW effect.

Resonant spin–flavor precession (RSFP) of neutrinos can account for both the deficiency of solar neutrinos and the time variations of the solar neutrino flux in anticorrelation with the solar activity, for which there are some indications in the Homestake data \[12, 13\]. Such an anticorrelation can be related to the fact that the magnetic field of the sun is strongest in the periods of active sun.

The Homestake data is fitted better using the hypothesis of a time–dependent signal than that of a constant one: analyses performed exploiting different statistical methods produced fairly large values of the coefficient of correlation between the data and sunspot
number \cite{12, 13}. These analyses were completed, however, before 1990 and so did not take into account the data available from the more recent Homestake runs 109–126. The data from the runs 109–126 do not exhibit a tendency to vary with time, similarly to the data from the runs 19–59. A recent analysis of Stanev \cite{19}, which updated the one of ref. \cite{13}, included the results from the runs 109–126. It showed that this leads to the correlation coefficient being decreased by an order of magnitude as compared to the previously obtained one, but the correlation probability still remains large: the confidence level of the correlation with the sunspot number \(s\) is 0.96 instead of 0.996, and that of the correlation with \(s|z|\), where \(z\) is the latitude of the line of sight, is 0.99 instead of 0.9993. The correlation with the 22-yr cycle is even better than the correlation with the 11-yr one. Therefore, the possibility that the solar neutrino flux anticorrelates with solar activity still persists and deserves a further study.

At the same time, the Kamiokande group did not observe time variations of the solar neutrino signal in their experiment, which allowed them to put an upper limit on the possible magnitude of the effect, \(\Delta Q/Q < 30\%\) at 90\% c.l. \cite{3}. Thus, the question naturally arises as to whether one can reconcile a relatively strong time variation of the signal in the Homestake experiment with a small (or no) time variation of the Kamiokande event rate.

Recently, it has been shown \cite{20} (see also \cite{21, 22}) that the RSFP scenario is capable of accounting for all the existing solar neutrino data, including their time structure or lack of such a structure. In particular, it can naturally reconcile sizeable time variations of the signal in the Homestake experiment with small time variations allowed by the Kamiokande data. The key points here are that \cite{23, 24, 25, 20} i) the two experiments are sensitive to slightly different parts of the solar neutrino spectrum, and ii) the RSFP can convert left–handed \(\nu_e\) into right–handed \(\bar{\nu}_\mu\) (or \(\bar{\nu}_\tau\)) which are sterile for the Homestake experiment, but do contribute to the event rate in the Kamiokande experiment through their neutral–current interaction with electrons.

\footnote{As is well known, the sunspot number provides a quantitative measure of the solar activity.}
The RSFP mechanism can also explain mild suppression of the signal in the Ga–Ge experiments. Most of the GALLEX and SAGE data have been taken during the period of high solar activity. Therefore one could expect a strong suppression of the signals in these experiments, which has not been observed. This disfavors the ordinary spin precession scenario since it is neutrino-energy independent and so predicts universal suppression and time variation of the signals in all solar neutrino experiments. On the contrary, the RSFP is strongly neutrino-energy dependent which naturally leads to different degrees of suppression and time variation of the event rates in different experiments. In particular, the \( pp \) neutrinos which are expected to give the major contribution to the signal in the Ga–Ge experiments, have low energies and so should encounter the RSFP resonance at higher densities than the \( ^8B \) and \( ^7Be \) neutrinos (the resonant density is inversely proportional to neutrino energy).

We know that the magnetic field does exist and may be quite strong in the convective zone of the sun \((0.7R_\odot \lesssim r \lesssim R_\odot)\). If the \(^8B \) and \(^7Be \) neutrinos experience the RSFP conversion in the convective zone (which is needed to account for the Homestake and Kamiokande data), the \( pp \) neutrinos will encounter the RSFP resonance somewhere in the radiation zone or in the core of the sun. However, it is not clear if a sufficiently strong magnetic field can exist deep in the sun, i.e. in the radiation zone or in the solar core. If the inner magnetic field of the sun is week, the RSFP will not be efficient there and the \( pp \) neutrinos will leave the sun intact, in accordance with the observations of GALLEX and SAGE. One can turn the argument around and ask the following question: What is the maximal allowed inner magnetic field which is not in conflict with the Ga–Ge data? The answer turns out to be \( (B_i)_{\text{max}} \approx 3 \times 10^6 \) G assuming neutrino transition magnetic moment \( \mu = 10^{-11}\mu_B \) \[20\].

Recently, we have analyzed all the available solar neutrino data in the framework of the RSFP disregarding the neutrino flavor mixing \[20\]. In the present paper we extend our previous study to include neutrino mixing and oscillation effects. Our motivation for that was as follows:

(1) RSFP requires non-vanishing flavor-off-diagonal neutrino magnetic moments, i.e.,
implies lepton flavor non-conservation. In general, one should therefore consider the RSFP
and neutrino oscillations (including the MSW effect) jointly. The results of ref. [20] are
only valid in the small neutrino mixing angle limit.

(2) It has been shown in [20] that all the existing solar neutrino data can be fitted within
the RSFP scenario for certain model magnetic field profiles and certain values of neutrino
parameters $\mu$ and $\Delta m^2$. It would be interesting to see how the neutrino mixing modifies
these results.

(3) In ref. [26] it has been suggested that the combined action of the RSFP and MSW
effect in the convective zone of the sun can relax by a factor of 2–3 the lower limit on the
product $\mu B_\perp$ of the neutrino magnetic moment and solar magnetic field strength required
to account for the data. The main idea was that the MSW effect can assist the RSFP to
cause the time variations of the neutrino flux by improving the adiabaticity of the RSFP
(this can occur when the RSFP and MSW resonances overlap). It would be interesting to
confront this idea with the new experimental data.

The combined action of the RSFP and the MSW effect on solar neutrinos has been con-
sidered in a number of papers [18, 27, 28]. However, the data of the Ga–Ge experiments were
not available at that time. In the present paper we analyze all the existing solar–neutrino
data including those of the gallium detectors. We also give predictions for the forthcoming
solar neutrino experiments paying special attention to the possibility of detection of $\bar{\nu}_e$’s
coming from the sun.

2 Neutrino propagation in the sun and solar magnetic
fields

We consider transitions of solar neutrinos in the two-flavor approximation assuming massive
neutrinos to be Majorana particles with a transition magnetic moment $\mu$ and taking into
account the neutrino mixing and matter effects in the sun. The neutrino basis is taken to be $(\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu)$. The transverse (toroidal) magnetic field of the convective zone of the sun $B_\perp$ is assumed to have a fixed direction. The evolution equation for such a neutrino system was given in [18].

Unfortunately, very little is known about the magnetic field of the sun. Not only its profile is unknown, but even its strength is in fact very uncertain. Energy balance consideration yield only rather loose bounds on the solar magnetic fields strength. One is therefore forced to use various more or less “plausible” model magnetic field configurations. With a very precise data on the flux and spectrum of solar neutrinos and independent information about the neutrino magnetic moments one could in principle solve the inverse problem and get an information about the solar magnetic field. At the moment the only way to proceed is to compute the signals in various solar–neutrino detectors and to compare them with the data. This approach allows one even now to discard certain magnetic field configurations which fail to simultaneously account for all the existing data.

We have calculated the neutrino signals in the Homestake, Ga–Ge and Kamiokande experiments using nine different model magnetic field profiles in the convective zone, assuming that the field is absent in the radiation zone and in the core of the sun. It was also assumed that the magnetic field strength varies in time in direct correlation with solar activity. The minimum and maximum magnetic field strengths were fixed to reproduce the apparent time variations of the Homestake signal (see [20] for more details). In most of the cases we have considered it was assumed that the solar magnetic field vanishes at the surface of the sun. The only exception was the magnetic field configuration COSH (see below) in which the magnetic field was assumed to die off exponentially. We therefore integrated the evolution equation numerically taking into account neutrino flavor oscillations $(\nu_{eL} \leftrightarrow \nu_{\mu L}$ and $\bar{\nu}_{eR} \leftrightarrow \bar{\nu}_{\mu R}$) along the whole neutrino path between the core of the sun and the earth and spin–flavor transitions $(\nu_{eL} \leftrightarrow \bar{\nu}_{\mu R}$ and $\bar{\nu}_{eR} \leftrightarrow \nu_{\mu R}$) only in the convective zone of the

2The case of magnetic field which rotates in the transverse plane along the neutrino trajectory (“twisting” magnetic field) has been considered in [29] [21] [30].
sun, $0.7R_\odot \lesssim r \lesssim R_\odot$; for for the COSH magnetic field configuration the integration of the evolution equations describing the RSFP was extended until $r = 1.3R_\odot$.

The magnetic field configurations used were:

$$B_{\perp}(x) = B_0 \left[ 1 - \left( \frac{x - 0.7}{0.3} \right)^n \right], \quad 0.7 \leq x \leq 1,$$

where $x \equiv r/R_\odot$ and $n=2, 6, 8$ and $10$ (hereafter referred to as MAG$n$ configurations);

$$B_{\perp}(x) = B_0 \left[ 1 - \left( \frac{x - 0.9}{0.1} \right)^6 \right], \quad 0.8 \leq x \leq 1,$$

(MAG69 configuration); the same as eq. (2) with an additional horizontal line $B_{\perp} = B_0/2$ between the point $x = 0.7$ and the point where this horizontal line touches the profile of eq. (2), i.e.

$$B_{\perp}(x) = \begin{cases} B_0/2, & 0.7 \leq x \leq 0.811, \\ B_0 \left[ 1 - \left( \frac{x - 0.9}{0.1} \right)^6 \right], & 0.811 \leq x \leq 1, \end{cases}$$

(MAG69+ configuration);

$$B_{\perp}(x) = \begin{cases} B_0 \frac{x - x_0}{x_c - x_0}, & x_0 \leq x < x_c, \\ B_0 - (B_0 - B_f) \frac{x - x_c}{1 - x_c}, & x_c \leq x \leq 1 \end{cases}$$

with $x_0 = 0.7$, $x_c = 0.85$ (LIN2) and 0.9 (LIN9), $B_f = 0$ and 100 G, and

$$B_{\perp}(x) = B_0 / \cosh[20(x - 0.7)], \quad 0.7 \leq x \leq 1.3$$

(COSH configuration).

### 3 Results and discussion

The criteria for choosing the minimum and maximum allowed detection rates (which correspond to high and low convective-zone magnetic field strengths respectively) were the same as in our previous paper [20] except for the following modifications. For the Home-stake experiment, the average signal for all the reported data (runs 18–124) was taken to
be $2.55 \pm 0.25$ SNU instead of $2.3 \pm 0.3$ SNU, the increase being related to the changes of the estimated Ar extraction efficiency (6%) and counting efficiency (3%) \cite{2}; the maximum and minimum values of the signal and the iso-SNU curves were also modified to take these changes of the efficiencies into account. For the detection rate in the Ga–Ge experiments the combined GALLEX result for the first 30 runs, $79 \pm 12$ SNU, was used \cite{4}. The $1\sigma$ and $2\sigma$ iso-SNU curves were redefined in accordance with the reduced error bars. Qualitatively similar results are obtained using the SAGE data \cite{4}.

The main conclusions of our analysis are summarized below.

(1) For small mixing angles, $\sin 2\theta_0 \lesssim 0.1$, the results of our previous study \cite{20} are only slightly modified. The best fit of all the data is achieved with LIN2 magnetic field configuration.

(2) For moderate mixing angles, $\sin 2\theta_0 \gtrsim 0.2$, the magnetic field profile LIN2 which proved to give a good fit of the data for vanishing $\theta_0$, no longer works: it leads to too strong a suppression of the signal in the gallium experiments since the MSW transitions of the low–energy $pp$ neutrinos become adiabatic. Reasonable fit can still be achieved for very large mixing angles, $\sin 2\theta_0 \approx 1$, but in this case a large flux of electron antineutrinos would be produced, in contradiction with an upper limit derived from the Kamiokande and LSD data \cite{31, 32} (see below, point (5)).

(3) Moderate values of $\theta_0$ are allowed for the magnetic field profiles whose maximum is shifted towards the outer regions of the convective zone. For such profiles the RSFP would be efficient for lower values of $\Delta m^2$ (since the resonance would have to take place at lower densities), for which in turn the MSW transitions of the $pp$ neutrinos will be non-adiabatic. As a consequence, the flux of the $pp$ neutrinos will be essentially unsuppressed. We have tried three such new magnetic field configurations (LIN9, MAG69 and MAG69+) and they produced good fits of all the data.

(4) Typical values of the neutrino parameters required to account for the data are $\Delta m^2 \approx (10^{-8}–10^{-7})$ eV$^2$, $\sin 2\theta_0 \lesssim 0.2–0.3$, depending on the magnetic field configuration;
for neutrino transition magnetic moment $\mu = 10^{-11} \mu_B$ the maximum magnetic field in the
total convective zone should vary in time in the range (15–45) kG.

(5) As have been noticed above (points (2) and (3)), some magnetic field configurations
which give a good fit to the data for vanishing $\theta_0$, do not do so for not too small mixing
angles and, conversely, some other profiles which failed to reproduce the data for $\theta_0 = 0$
do give a good fit for moderate $\theta_0$. This is, in fact, a rather unpleasant situation: whether
or not a given magnetic field profile fits the data depends on the neutrino mixing angle
which is unknown. A possible way out of this ambiguity is to look for a flux of $\bar{\nu}_{eR}$’s coming
from the sun. If neutrinos experience the RSFP in the sun and also have flavor mixing,
a flux of electron antineutrinos can be produced which in principle can be detected in the
SNO, Super–Kamiokande and Borexino experiments even in the case of moderate neutrino
mixing angles [18, 27, 33, 34]. We therefore calculated the expected $\bar{\nu}_{eR}$ signals in these
experiments for the magnetic field profiles and the values of neutrino parameters which fit
all the available solar–neutrino data.

For LIN2 and LIN9 magnetic field profiles defined by eq. (4), it did not make much
difference if we took the surface magnetic field to be 0 or 100 G. The best fit of all the
data for $\sin 2\theta_0 \gtrsim 0.1$ was achieved with LIN9 and MAG69+ magnetic field configurations;
MAG69 profile was also able to reproduce the experimental results but gave somewhat
smaller allowed parameter ranges. In figs. 1–5 we present the results of the numerical
calculations for the MAG69+ profile. More complete account of our results will be presented
elsewhere.

Figs. 1–4 give the calculated iso-SNU/iso-suppression curves for the Homestake, Kamiokande
and Ga–Ge experiments on the planes of the parameters $(B_0, \Delta m^2)$, $(\sin 2\theta_0, \Delta m^2)$
and $(B_0, \sin 2\theta_0)$. From fig. 1 one can see that for $\sin 2\theta_0 = 0.2$ the allowed range of $\Delta m^2$
(which is defined by the right shaded area since it is more restrictive than the left one) is
$\Delta m^2 \approx (1 - 3) \times 10^{-8}$ eV$^2$. In fact, with increasing mixing angle the vertical size of the
right shaded area decreases and for $\sin 2\theta_0 \gtrsim 0.25$ this area disappears. This comes about
because the detection rate in the Ga–Ge experiment becomes too high. The same effect can also be seen in figs. 2, 3 and 4. The allowed minimum and maximum strengths of the convective-zone magnetic field of the sun can be found from fig. 1 to be in the ranges 17–23 kG and 30–50 kG respectively (assuming $\mu = 10^{-11} \mu_B$). This is also illustrated by fig. 4.

In figs. 2 and 3 the allowed ranges of the parameters are given by the lower shaded areas. The upper ones are excluded by the data since for weak field (fig. 2) and strong field (fig. 3) they do not overlap.

One can see from fig. 4 that the MAG69+ profile does not fit the data for zero mixing angle (at least, at the 1\(\sigma\) level). This illustrates the point (5) of the above brief summary of our results.

It follows from our analysis that the mixing angles larger than $\sin^2 \theta_0 \approx 0.25$ are excluded since they would lead to too high a detection rate in the Ga–Ge experiments. This limits the possibility of having oscillations–assisted RSFP suggested in [26]. The gain in the product $\mu B_\perp$ which is required for the RSFP to be efficient turns out to be rather modest: a factor 1.5–2. This can be seen from the fact that for $\theta_0 = 0$ and the value of $\mu$ fixed at $10^{-11} \mu_B$ the allowed range of $B_\perp$ was 30–50 kG [20] whereas for $\sin^2 \theta_0 = 0.25$ and MAG69+ magnetic field configuration it can be as low as 17–30 kG.

As we have already mentioned, the combined action of the RSFP and neutrino oscillations can produce an observable flux of $\bar{\nu}_e$’s from the sun. We have calculated the fluxes and the corresponding signals in SNO, Super–Kamiokande and Borexino detectors for various magnetic field configurations. Fig. 5 shows the energy dependence of the $\nu_e \to \bar{\nu}_e$ transition probabilities $P_2$ and $P_{2}^{\text{NVO}}$. The latter takes into account the $\bar{\nu}_e$ production only inside the sun, i.e. disregards the $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillations in vacuum; it is given just for comparison. One can see that the main source of the $\bar{\nu}_e$’s is vacuum oscillations of $\bar{\nu}_\mu$’s (which are produced in the sun by the RSFP mechanism) into $\bar{\nu}_e$’s. This, however, is only true if the transverse magnetic field of the sun has a fixed direction along the neutrino path. The $\bar{\nu}_e$ flux can be significantly enhanced in twisting magnetic fields [30, 35], and
the $\bar{\nu}_{eR}$ production inside the sun can become more important than their production due to the vacuum oscillations. In fact, in this case one can have a detectable $\bar{\nu}_{eR}$ flux even if the neutrino magnetic moment is too small or the solar magnetic field is too weak to account for the solar neutrino problem [35, 36].

In fig. 5 also shown are the spectrum of electron antineutrinos as well as that of the initially produced $^8$B neutrinos. Both spectra are normalized to unit integral, the relative normalization factor being 36.5. This means that the total flux of electron antineutrinos for maximum allowed magnetic field is less than 3% of the boron neutrino flux. Electron antineutrinos from the sun could have been detected by the Kamiokande and LSD groups through the $\bar{\nu}_{eR}$–proton capture reaction. Such antineutrinos have not been seen which gave an upper limit on the total flux as well as on the spectrum of solar $\bar{\nu}_{eR}$'s. The integral over the predicted $\bar{\nu}_{eR}$ spectrum taking into account the instrumental energy threshold of Kamiokande experiment $E_{th} = 7.5$ MeV and the threshold of the $\bar{\nu}_{eR}$–proton capture reaction turns out to be 1.46% of the corresponding boron $\nu_{eL}$ flux. This is significantly lower than the upper bound of $\sim (5 - 7)$% derived from the Kamiokande and LSD data in [31, 32]. For the minimum allowed magnetic field strength, $B_0 \approx 20$ kG, the $\bar{\nu}_{eR}$ flux is smaller by about a factor of two. We have also compared the energy spectrum of $\bar{\nu}_{eR}$ with the Kamiokande limit [37] and found that this limit was never violated for the mixing angles $\theta_0$ which fit the experimental data. This means that at the moment the Ga–Ge results give more stringent upper bound on $\theta_0$ than the non-observation of solar $\bar{\nu}_{eR}$’s by the Kamiokande and LSD collaborations.

The forthcoming solar neutrino experiments, such as SNO, Super–Kamiokande and Borexino, are expected to have much higher sensitivity to $\bar{\nu}_{eR}$'s than the Kamiokande experiment. We have calculated expected signals of solar $\bar{\nu}_{eR}$'s in these detectors. For the magnetic field configuration MAG69+, the event rates for $\Delta m^2 = 10^{-8}$ eV$^2$ and several values of $\sin 2\theta_0$ are given in table 1. We have also included the results for the mixing angle $\sin 2\theta_0 = 0.32$ which fits the data within $2\sigma$ errors. The calculated event rates for LIN9
magnetic field configuration are similar to those for MAG69+.
Table 1. Predicted numbers of events per year due to the solar $\bar{\nu}_{eR}$'s in SNO, Super–Kamiokande and Borexino experiments for MAG69+ magnetic field configuration, $\Delta m^2 = 10^{-8}$ eV$^2$, $B_0 = 45$ kG. The (instrumental) $e^+$ energy threshold for SNO and Super–Kamiokande is 5 MeV; for Borexino the expected signal for $E_{\bar{\nu}_e} \geq 5$ MeV is given. For Super–Kamiokande the same $e^+$ detection efficiency as in Kamiokande is assumed, for SNO and Borexino the detection efficiencies were taken to be 1.

|                  | $B_0 = 45$ kG |        | $B_0 = 20$ kG |        |
|------------------|---------------|--------|---------------|--------|
|                  | $\sin 2\theta_0$ | 0.1    | 0.25           | 0.32   |
| SNO              | $(\bar{\nu}_e d \rightarrow nne^+)$ | 13.1   | 82             | 134    |
| Super – Kamiok.  | $(\bar{\nu}_e p \rightarrow ne^+)$ | 1380   | 8600           | 14000  |
| Borexino         | $(\bar{\nu}_e p \rightarrow ne^+)$ | 12     | 74             | 120    |

As few as 5-10 $\bar{\nu}_{eR}$ events/yr in SNO [38] and 20 events/yr in Borexino [33] are probably detectable. It therefore follows from table 1 that for $\sin 2\theta_0 \gtrsim 0.1$ the solar $\bar{\nu}_{eR}$'s can be detected in Super–Kamiokande, SNO and Borexino. The event rates for $B_0 = 20$ kG are about a factor of two smaller than those for $B_0 = 45$ kG. Thus the $\bar{\nu}_{eR}$ flux should vary in time in direct correlation with solar activity (11-yr variations). This time dependence of the flux can facilitate significantly the discrimination between the signal and the background.

Besides the observable flux of solar $\bar{\nu}_e$'s, the predictions for the forthcoming solar neutrino experiments do not differ much from those of the RSFP scenario in the absence of neutrino flavor mixing [23, 24, 39]: strong 11-yr variations of the $^7$Be neutrino flux, no suppression and no time variations in the neutral–current events in SNO and moderate time variation ($\lesssim 20 - 30\%$) of the event rate in Super–Kamiokande.

In summary, we have shown that the results of the Homestake, Kamiokande and gallium solar neutrino experiments, including their time structure or lack of such a structure, can be accounted for provided neutrinos undergo resonant spin–flavor precession. We have taken possible flavor mixing of neutrinos into account and demonstrated that the data can only
be reproduced for small enough mixing angles, \( \sin 2\theta_0 \lesssim 0.25 \). Larger mixing angles are excluded by the data of Ga–Ge experiments. The solar magnetic field profiles required to fit the data depend substantially on the neutrino mixing angle. One can discriminate between small mixing angle \( (\sin 2\theta_0 \lesssim 0.1) \) and moderate mixing angle \( (0.1 \lesssim \sin 2\theta_0 \lesssim 0.25) \) solutions by studying the solar \( \bar{\nu}_e \) flux which can be sizeable for moderate mixing angles. We have calculated the expected \( \bar{\nu}_e \) signals in the SNO, Super–Kamiokande and Borexino experiments and showed that they are detectable even for moderate mixing angles.

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Figure captions

Fig. 1. The iso-SNU/iso-suppression contours for the Cl–Ar (Homestake), Kamiokande and Ga–Ge experiments in the \((B_0, \Delta m^2)\) plane for \(\sin 2\theta_0 = 0.2\). MAG69+ magnetic field configuration is used [see eq. (3)]. The full lines are chlorine iso-SNU curves (1.7, 2.1, 2.55, 3.9, 5.2, 5.7 and 6.4 SNU), the dotted lines correspond to the ratio of the signal to the reference solar model prediction \(R\) for the Kamiokande experiment, \(R=0.30, 0.40, 0.58\) and 0.68, and the dash-dotted lines represent the Ga–Ge iso-SNU curves (53, 66, 79, 92 and 105 SNU). The shaded areas show the allowed ranges of parameters (see the text).

Fig. 2. The iso-SNU/iso-suppression contours in the \((\sin 2\theta_0, \Delta m^2)\) plane for \(B_0 = 20\) kG. The magnetic field configuration and the definition of the curves are the same as in fig. 1.

Fig. 3. Same as in fig. 2 but for \(B_0 = 45\) kG.

Fig. 4. The iso-SNU/iso-suppression contours in the \((B_0, \sin 2\theta_0)\) plane for \(\Delta m^2 = 10^{-8}\) eV\(^2\). The magnetic field configuration and the definition of the curves are the same as in figs. 1–3.

Fig. 5. Spectra (in MeV\(^{-1}\)) of \(^8\)B \(\nu_e\)’s (full upper curve) and solar \(\bar{\nu}_e\)’s (dashed upper curve) normalized to unit integral. The latter is calculated with MAG69+ magnetic field profile, \(\Delta m^2 = 10^{-8}\) eV\(^2\), \(\sin 2\theta_0 = 0.25\) and \(B_0 = 40\) kG. The relative normalization factor of the two spectra is 36.5. Also shown are the \(\nu_{eL} \rightarrow \bar{\nu}_{eR}\) transition probabilities \(P_2\) and \(P_2^{NVO}\). In the latter the (anti)neutrino oscillations in vacuum are disregarded (see the text).
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