IMPLICATIONS OF GALLIUM SOLAR NEUTRINO DATA FOR THE RESONANT SPIN-FLAVOR PRECESSION SCENARIO

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Abstract

We consider the implications of the recent results of SAGE and GALLEX experiments for the solution of the solar neutrino problem in the framework of the resonant neutrino spin-flavor precession scenario. It is shown that this scenario is consistent with all the existing solar neutrino data including the gallium results. The quality of the fit of the data depends crucially on the magnetic field profile used which makes it possible to get information about the magnetic field in the solar interior. In particular, the magnetic field in the core of the sun must not be too strong ($\lesssim 3 \times 10^6$ G). The detection rate in the gallium detectors turns out to be especially sensitive to the magnitude of $\Delta m^2$. Predictions for forthcoming solar-neutrino experiments are made.

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1 Introduction

One of the conceivable solutions of the solar neutrino problem [1, 2, 3, 4] is related to the possible existence of magnetic [5, 6, 7, 8] or transition [4, 8] magnetic moments of electron neutrinos. If these magnetic moments are sufficiently large, a significant fraction of the left-handed solar $\nu_e$ will precess into right-handed neutrinos or antineutrinos of the same or different flavor in the strong toroidal magnetic field of the convective zone of the sun. The resulting neutrinos are sterile or almost sterile for currently operating neutrino detectors. It has been pointed out [10, 11, 12] that the spin-flavor precession due to transition magnetic moments of neutrinos, in which neutrino helicity and flavor are rotated simultaneously, can be resonantly enhanced in matter, very much in the same manner as the neutrino oscillations [13, 14]. Neutrino spin precession and resonant spin-flavor precession (RSFP) can explain the observed deficiency of solar neutrinos [1, 2] as compared to the predictions of the standard solar model (SSM) [15, 16, 17]. They can also account for time variations of the solar neutrino flux in anticorrelation with the solar activity for which there are indications in the chlorine experiment of Davis and his collaborators [1]. This follows from the drastic field-strength dependence of the precession probability and the fact that the toroidal magnetic field of the sun is strongest at maxima of solar activity.

Although the chlorine data seem to exhibit a strong time variation of the $\nu_e$ detection rate $Q$, $Q_{max}/Q_{min} \approx 2-4$, no such time dependence has been observed in the Kamiokande II experiment [2]. The Kamiokande II results do not exclude, however, small ($\lesssim 30\%$) time variations of the solar neutrino signal. The question of whether it is possible to reconcile large time variations of the signal in the Homestake $^{37}$Cl experiment with small time variations allowed by the water Čerenkov detector has been addressed in a number of papers [18, 19, 20, 21, 22]. It has been shown that the Homestake and Kamiokande data can be naturally reconciled in the framework of the RSFP scenario. The key point is that the Homestake and Kamiokande II detectors are sensitive to different regions of the solar neutrino spectrum: the energy threshold in the Homestake experiment is 0.814 MeV so that it is able to detect
high energy $^8$B and the intermediate energy $^7$Be and $pep$ neutrinos; at the same time the energy threshold in the Kamiokande II experiment was 7.5 MeV and so it was only sensitive to the higher-energy fraction of the $^8$B neutrinos. Due to the strong energy dependence of the probability of the RSFP, the flux of lower-energy neutrinos can exhibit stronger time variations (i.e. stronger magnetic field dependence) than the flux of the higher-energy ones. Another point is that the Homestake experiment utilizes the $\nu_e - ^{37}$Cl charged current reaction, while in the Kamiokande detector $\nu - e$ scattering which is mediated by both charged and neutral-current weak interactions is used. If there are no sterile neutrinos the RSFP converts solar $\nu_{eL}$ into $\bar{\nu}_{\mu R}$ or $\bar{\nu}_{\tau R}$ which are not observed in the chlorine detector but can be detected (though with a smaller cross section than $\nu_e$) in water Čerenkov experiments. This also reduces the possible time variation effect in the Kamiokande II detector.

In the present paper we perform a detailed numerical calculation of the $^{37}$Cl, Kamiokande and $^{71}$Ga detection rates in the framework of the RSFP scenario and confront them with the existing solar neutrino data including the recent results of the gallium experiments. We show that the current solar neutrino observations can be perfectly well described on the basis of the RSFP hypothesis. The time dependence of the detection rates turns out to be very sensitive to the magnetic field profile used which can make it possible to discriminate between various magnetic field configurations and get an information about the magnetic field in the solar interior. We briefly also consider the implications of our results for the forthcoming solar-neutrino experiments. In particular, strong time variations of the $^7$Be neutrino signal is predicted.

2 General features of the RSFP

For simplicity, we shall consider the RSFP of $\nu_e$ into $\bar{\nu}_\mu$ disregarding possible neutrino mixing and assuming that the direction of the transverse magnetic field does not change along the neutrino trajectory. By lifting these assumptions one can enlarge the number of parameters
of the problem and therefore facilitate fitting the data; however, as we shall see, a sufficiently
good fit can be achieved without introducing additional parameters.

We shall consider the Majorana neutrino case which is more promising for the simult-
aneous fit of the Homestake and Kamiokande II data. Under the assumptions made, \( \nu_e \) and \( \nu_\mu \) are neutrinos with definite masses in vacuum \( (m_1 \text{ and } m_2) \) and transition magnetic
moment \( \mu_{e\mu} \). To make the paper self-contained, we recall here the main featur es of the
RSFP [10, 11, 12, 28]. The evolution of the \((\nu_eL, \bar{\nu}_\mu R)\) system in matter and magnetic field
is described by the Schroedinger-like equation

\[
\frac{d}{dt}
\begin{pmatrix}
\nu_{eL} \\
\bar{\nu}_{\mu R}
\end{pmatrix}
= 
\begin{pmatrix}
\sqrt{2}G_F(N_e - N_n/2) + \frac{m_1^2}{2E} & \mu_{e\mu}B_\perp \\
\mu_{e\mu}B_\perp & \sqrt{2}G_F(N_n/2) + \frac{m_2^2}{2E}
\end{pmatrix}
\begin{pmatrix}
\nu_{eL} \\
\bar{\nu}_{\mu R}
\end{pmatrix}
\]  

(1)

Here \( N_e \) and \( N_n \) are the electron and neutron number densities and \( G_F \) is the Fermi constant.
The mixing angle of \( \nu_{eL} \) and \( \bar{\nu}_{\mu R} \) in matter and magnetic field is defined as

\[
\tan 2\theta_m = \frac{2\mu_{e\mu}B_\perp}{\sqrt{2}G_F(N_e - N_n) - \frac{\Delta m^2}{2E}}
\]  

(2)

where \( \Delta m^2 \equiv m_2^2 - m_1^2 \). The precession length \( l \) is given by

\[
l = 2\pi \left\{ \left[ \sqrt{2}G_F(N_e - N_n) - \frac{\Delta m^2}{2E} \right]^2 + (2\mu_{e\mu}B_\perp)^2 \right\}^{-1/2}
\]  

(3)

The resonance density is a density at which the mixing angle \( \theta_m \) becomes \( \pi/4 \):

\[
\sqrt{2}G_F(N_e - N_n)|_{\text{res}} = \frac{\Delta m^2}{2E}
\]  

(4)

The efficiency of the \( \nu_{eL} \to \bar{\nu}_{\mu R} \) transition is basically determined by the degree of its adi-
abaticity. The corresponding adiabaticity parameter depends both on the neutrino energy
and the magnetic field strength at the resonance \( B_{\perp \text{res}} \):

\[
\lambda \equiv \pi \frac{\Delta r}{l_{\text{res}}} = 8 \frac{E}{\Delta m^2} (\mu_{e\mu}B_{\perp \text{res}})^2 L_\rho
\]  

(5)

Here \( \Delta r \) is the resonance width, \( l_{\text{res}} = \pi / \mu_{e\mu}B_{\perp \text{res}} \) is the precession length at the resonance
and \( L_\rho \equiv |(N_e - N_n)_{\text{res}}/ \frac{d}{dt}(N_e - N_n)_{\text{res}}| \) is the characteristic length over which matter density
varies significantly in the sun. For the RSFP transition to be almost complete, one should have $\lambda \gg 1$; however, the transitions can proceed with an appreciable probability even for $\lambda \sim 1$.

In a non-uniform magnetic field, the field strength at resonance $B_{\perp \text{res}}$ depends on the resonance coordinate and so, through eq. (4), on the neutrino energy. Thus, the energy dependence of the adiabaticity parameter $\lambda$ in eq. (5) is, in general, more complicated than just $\lambda \sim E$, and is determined also by the magnetic field profile inside the sun.

3 Calculation of detection rates

We have numerically integrated eq. (1) to find the $\nu_{eL}$ survival probability in the sun. It was then used to calculate the neutrino detection rates for the Homestake, Kamiokande II and gallium experiments utilizing the solar density profiles, solar neutrino spectra and cross sections of $\nu_e$ capture on $^{37}$Cl and $^{71}$Ga from ref. [15], as well as realistic detection efficiency of Kamiokande II experiment and standard-model $\nu - e$ cross sections.

Unfortunately, very little is known about the structure of the magnetic field inside the sun so that one is forced to use various more or less "plausible" magnetic field configurations. In our calculations we assumed the transverse magnetic field profiles to consist of two separate spherically symmetric pieces: constant nonuniform internal magnetic field with its scale defined by the parameter $B_1$ and magnetic field in the convective zone $B_c(x)$, characterized by the overall scale $B_0$ which can vary in time with changing solar activity $[29, 19]$

$$B_{\perp}(x) = \begin{cases} 
B_1 \left( \frac{0.1}{0.1+x} \right)^2, & 0 \leq x < x_0, \\
B_c(x), & x_0 \leq x < x_{\max}
\end{cases}$$

where $x \equiv r/R_\odot$, $r$ being the distance from the center of the sun and $R_\odot$ being the solar
radius. For the convective-zone magnetic field $B_c(x)$ we used the following profiles:

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

(7)

with $x_0 = 0.65, 0.7$ and $0.75, x_c = 0.75$ and $0.85, B_f = 0$ and $100$ G,

$$B_c^{(n)}(x) = B_0 \left[1 - \left(\frac{x - 0.7}{0.3}\right)^n\right], \quad x_{\text{max}} = 1$$

(8)

with $n=2, 6$ and $8$, and

$$B_c(x) = B_0 / \{1 + \exp[(x - 0.95)/0.01]\}, \quad x_{\text{max}} = 1.3.$$  

(9)

It is not clear whether or not there is a strong magnetic field in the inner regions of the sun and so one has no idea about the possible magnitude of $B_1$; in our calculations we treated it as a free parameter. As to the maximum value of the convective zone magnetic field, fields of the order of a few kG or a few tens of kG are usually considered possible. There are, however, arguments based on the helioseismology data that it can achieve as large values as a few MG [30]. The typical values of $B_0$ we used were of the order of a few tens of kG.

The magnetic field strength enters the evolution equation (1) being multiplied by the neutrino transition magnetic moment $\mu_{e\mu}$. The existing upper limits on the magnetic moment of the electron neutrino include the laboratory bound $\mu_{\nu_e} \leq (3 - 4) \times 10^{-10} \mu_B$ ($\mu_B$ is the electron Bohr magneton) from the reactor $\bar{\nu}_e$ experiments [23], as well as astrophysical, cosmological and supernova 1987A bounds. The cosmological and supernova bounds do not apply to transition magnetic moments of Majorana neutrinos which are of major interest to us. The astrophysical bounds come from the limits on the energy loss rates of white dwarfs and helium stars, which yield $\mu_{\nu_e} \leq 10^{-11} \mu_B$ [24]; recently even more stringent bounds have been obtained from the analysis of the data on helium stars, $\mu_{\nu_e} \leq 3 \times 10^{-12} \mu_B$ [25] and $\mu_{\nu_e} \leq 10^{-12} \mu_B$ [26]. One should notice that besides the upper limits on neutrino magnetic moments there is also an astrophysical "prediction" for the transition magnetic moment
\( \mu_{\nu_e \nu_\tau} \) (or \( \mu_{\nu_\mu \nu_\mu} \)) \( \approx 10^{-14} \mu_B \) from the decaying neutrino hypothesis \(^2\). For neutrino magnetic moments of this magnitude to be relevant to the solar neutrino problem, one would need convective zone magnetic field of the order of 10 MG. In our calculations we have taken \( \mu_{e\mu} = 10^{-11} \mu_B \) where \( \mu_B \) is the electron Bohr magneton. The results for any other value of \( \mu_{e\mu} \) can be readily obtained by simply rescaling the magnetic field strength.

4 Results and discussion

Let us first recall the experimental situation. The observed chlorine detection rates in the minima of solar activity were \( 4.1 \pm 0.9 \) SNU (cycle 21) and \( 4.2 \pm 0.75 \) SNU (cycle 22) \(^1\); those in solar maxima were \( 0.4 \pm 0.2 \) SNU (cycle 21) and \( 1.2 \pm 0.6 \) SNU (cycle 22). The average detection rate in the chlorine experiment is \( Q_{\text{ave}} = 2.28 \pm 0.23 \) SNU \(^1\). This should be compared with the SSM prediction \( (Q_{\text{SSM}})_{\text{Cl}} = 8.0 \pm 3.0 \) SNU (effective ”3\( \sigma \)” error) \(^17\).

The Kamiokande II Collaboration reported the value for the ratio of the observed and the SSM detection rates \( R \equiv Q/Q_{\text{SSM}} = 0.46 \pm 0.05(\text{stat.}) \pm 0.06(\text{syst.}) \), the allowed time variation of \( R_b \) being \(< 30\% \) \(^3\). Taking into account the first reported data of the Kamiokande III experiment would just shift the central value of \( R \) to 0.49 \(^31\). As was emphasized above, there was no indication of possible time dependence of the signal in the Kamiokande II experiment; however, time variation in the range \( R \approx 0.3 - 0.7 \) is not excluded (at the 1\( \sigma \) level).

By now, the results of two gallium solar neutrino experiments are available. The combined SAGE result for 1990-1991 is \( 58^{+17}_{-24}(\text{stat.}) \pm 14(\text{syst.}) \) SNU which is in agreement with the GALLEX data for 1991-1992 of \( 83 \pm 19(\text{stat.}) \pm 8(\text{syst.}) \) SNU \(^4\).

It is interesting to note that the SAGE results for 1990 and 1991 were \( 20^{+15}_{-20} \pm 32 \) and \( 85^{+22}_{-32} \pm 20 \) SNU respectively, i.e. they exhibited the tendency to increase with time while the solar activity was decreasing. Although this is by no means sufficient to conclude that the

\(^{11} \) SNU (Solar Neutrino Unit) = \( 10^{-36} \) events/target atom/s.
observed signal was varying in time, the data compare favorably with such an assumption.

Let us now turn to the results of our calculations which are presented in figs. 1–5. It can be seen from fig. 1 that for the "triangle" convective-zone magnetic field of eq. (7) with $x_0=0.70$, $x_c = 0.85$, $x_{max} = 1$, $B_f = 0$ and no inner field, all the available solar-neutrino data can be perfectly well fitted for $\Delta m^2 \sim 7 \times 10^{-9} \text{eV}^2$. For the parameter of the convective-zone magnetic field $B_0$ varying between 25 and 50 kG, the detection rate in the chlorine experiment changes between 4.5 and 1.5 SNU. For the same range of $B_0$ the ratio $R$ measured in the Kamiokande II experiment varies between 0.65 and 0.35, which is within the experimentally allowed domain. The calculated germanium production rate in gallium experiments varies between 100 and 73 SNU; the latter value, corresponding to high solar activity periods, is in a very good agreement with both SAGE and GALLEX results.

The combined results of the calculations of the $^{37}$Cl, Kamiokande and $^{71}$Ga detection rates are presented in the form of iso-SNU (iso-suppression) contour plot in fig. 2. In this figure, the shaded areas correspond to the allowed values of the parameters which are chosen so that the maximum and minimum detection rates in the chlorine experiment range, respectively, between 3.6 and 4.8 SNU, and 1.9 and 1.5 SNU. For the gallium signal at the maximum of solar activity, the whole range between 62 and 104 SNU was allowed. This corresponds to $1\sigma$ errors except for the minimum signal in the chlorine data $(Q_{Cl})_{min}$, for which the quoted errors seem to be underestimated, and therefore we considered as large $(Q_{Cl})_{min}$ as 1.9 SNU possible; we were unable to get values of $(Q_{Cl})$ below 1.5 SNU with the magnetic field configurations we used. Notice that the available gallium results should be considered as "low-signal" ones since both SAGE and GALLEX were in fact taking data during the period of high solar activity. For the Kamiokande experiment, it is difficult to choose the allowed ranges of $R$ for high and low solar activity periods. We have taken the maximum signal/SSM ratio to vary in the range 0.58–0.68, and minimum one, in the range 0.3–0.4. The numbers 0.68 and 0.30 correspond to the observed maximal

\[ \text{This, of course, is only true if we want to fit all three data sets simultaneously.} \]
and minimal values of \( R \) (including 1\( \sigma \) errors for the corresponding runs); the width of the allowed \( R \) regions \( \Delta R = 0.1 \) was taken rather arbitrarily.

The allowed ranges of the parameters which follow from fig. 2 correspond to

\[
\Delta m^2 \simeq (4 \times 10^{-9} - 2 \times 10^{-8}) \text{eV}^2, \quad (B_0)_{\text{min}} \simeq 28 \text{kG}, \quad (B_0)_{\text{max}} \simeq 50 \text{kG} \tag{10}
\]

We see from the figure that for the high signal (low \( B_0 \)) domain, the \(^{37}\text{Cl}\) and Kamiokande data mainly constrain the allowed magnitudes of the convective-zone magnetic field \( B_0 \), i.e. the horizontal size of the allowed strip. At the same time, for certain values of \( B_0 \) the \(^{71}\text{Ga}\) data constrain (from below) the vertical size of the strip, i.e. the allowed values of \( \Delta m^2 \).

For the low signal \((B_0 \sim 50 \text{kG})\) domain of the allowed parameter space, the values of \( B_0 \) are constrained by the chlorine data while the upper and the lower limits on \( \Delta m^2 \) are determined by the Kamiokande and gallium data respectively. This shows that the gallium experiments are especially sensitive to the magnitude of \( \Delta m^2 \).

Similar results are obtained if one takes \( x_0 = 0.75 \) instead of 0.70 in the magnetic field profile of eq. (7). All the other magnetic-field configurations that we used in our calculations either resulted in very poor fits of the experimental results or completely failed to reproduce the chlorine, Kamiokande and gallium data simultaneously. For example, one can fit the data with the magnetic field in the convective zone of eq. (8) with \( n = 6 \) provided there is a moderate inner field \((B_1 = 2 \times 10^6 \text{ G})\). However, the allowed range of \( \Delta m^2 \) turns out to be extremely narrow (fig. 3) and is likely to disappear with improving accuracy of the data.

In refs. [20] and [21] numerical calculations of the Homestake and Kamiokande detection rates in the framework of the RSFP scenario have been performed. Satisfactory description of the results of these experiments has been achieved, but the predicted gallium signal in solar maximum for the parameter range they found was \( \sim 20-30 \text{ SNU} \) which is considerably lower than the positive results obtained by SAGE and GALLEX Collaborations. It is easy to understand why the gallium detection rates in the periods of high solar activity predicted

\(^3\text{The shaded areas at larger values of } B_0 \text{ correspond to direct correlation of neutrino signals with solar activity instead of anticorrelation.}\)
in refs. [20, 21] were too small, whereas the results of our calculations are in good agreement with the data. The main contribution to the signal in the gallium experiments comes from the low-energy $pp$ neutrinos which, according to eq. (4), encounter the resonance at higher density than the $^7$Be and $^8$B neutrinos. For them the resonant region can lie in the radiation zone and the efficiency of the RSFP will drastically depend on the magnitude of the inner magnetic field of the sun. If this field is absent, as in the calculations the results of which are shown in figs. 1 and 2, or just not too strong, as in the field configuration of eq. (8) with $n=6$ and $B_1 = 2 \times 10^6$ G, the $pp$ neutrinos either leave the sun unscathed or experience very weak conversion. Therefore, in this case one can expect unsuppressed $pp$ signal in the gallium experiments in good agreement with observations. Note that the authors of ref. [20] assumed very strong inner magnetic field ($B_1 = 2 \times 10^7$ G).

The resonant density depends on the magnitude of $\Delta m^2$ as well, so for small enough $\Delta m^2$ the $pp$ neutrinos can also undergo resonant transitions in the convective zone. As a consequence, the $pp$ neutrino flux can be heavily suppressed even in the absence of strong inner magnetic field. In this case the $^7$Be, $pep$ and $^8$B neutrinos will undergo resonant conversion closer to the surface of the sun and the Homestake and Kamiokande II data can only be reproduced if the convective-zone magnetic field $B_c(r)$ does not decrease too fast with increasing $r$. In ref. [21] the value of $\Delta m^2$ was chosen to be rather small ($\Delta m^2 \simeq 5 \times 10^{-9}$ eV$^2$) so that a significant fraction of $pp$ neutrinos experienced resonant transition in the convective zone.

From the above results it follows that

(1) in the vicinity of $\Delta m^2 \simeq (6 - 8) \times 10^{-8}$ eV$^2$ the gallium detection rate should exhibit strong dependence on the value of $\Delta m^2$ since for smaller $\Delta m^2$ an appreciable fraction of $pp$ neutrinos will have the resonance in the convective zone, whereas for larger $\Delta m^2$ most of them will encounter the resonance in the radiation zone where the magnetic field need not be strong

$^4$The border-line value of $\Delta m^2$ depends, of course, on whether or not the magnetic field is strong near
(2) the gallium detection rate is very sensitive to the magnitude of the inner magnetic field of the sun and can be used to set an upper limit on it;

(3) while Homestake and Kamiokande II data can well be reproduced with a wide class of magnetic field configurations, the simultaneous fit of the results of all three kinds of experiments, the chlorine, water Čerenkov and the gallium ones, is very sensitive to the solar magnetic field profile used. This stems from the fact that these experiments are sensitive to neutrinos of different energies which experience the RSFP transitions at different distances from the center of the sun and therefore probe the magnetic field distribution $B_\perp(r)$ in the wide range of $r$.

The first point is illustrated by figs. 1c and 2 which show that the dependence of $Q_{Ga}$ on $\Delta m^2$ is much stronger than in the case of chlorine and Kamiokande detection rates. The second point is illustrated by fig. 4 in which all the three detection rates are shown as functions of $B_1$ and $B_0$ for a fixed value of $\Delta m^2$. One can see that for $B_1 \gtrsim 3 \times 10^6$ G the predicted gallium detection rate is too small. The third point is confirmed by our calculations with various magnetic field profiles. As we already mentioned, only two magnetic field configurations gave acceptable fits of the data. With most other configurations it was not difficult to fit the chlorine and Kamiokande results, but not all three data sets simultaneously.

In fig. 5 the magnetic field dependence of the suppression factors of the $pp$, $pep$, $^7$Be and $^8$B neutrino contributions to the gallium detection rate is illustrated (the suppression factors for the $pep$, $^7$Be and $^8$B neutrino contributions to $Q_{Cl}$ are practically the same). One can see that the $^7$Be flux is expected to exhibit a strong time variation, between $\simeq 0.6 \times (SSM\ prediction)$ in the low solar activity periods and $\simeq 0.1 \times (SSM\ prediction)$ at high activity. This should be clearly seen in the forthcoming Borexino experiment which is intended for detecting the $^7$Be neutrino signal. Strong time dependence of the $^7$Be neutrino flux is what one expects on general grounds from the condition of having stronger time variations for the bottom of the convective zone. For our field configurations of eq. (7) for which $B_\perp(x)$ achieves its maximum in the center of the convective zone this value can be somewhat smaller.
the chlorine detection rate than for the Kamiokande one\footnote{One should note that for our magnetic field configuration of eq. (8) with $n = 6$ and $B_1 = 2 \times 10^6$ G the predicted $^7$Be flux is almost constant since the $\Delta m^2$ value which fits the data is rather large and the $^7$Be neutrinos encounter the resonance in the radiation zone where the magnetic field is constant in time. However, as we already mentioned, the allowed $\Delta m^2$ range is extremely narrow in this case.}

Let us briefly discuss the predictions for the other solar neutrino experiments. In the gallium detectors, the signal should experience moderate time variation, the signal at minimum solar activity being about 100-110 SNU. In the SNO experiment, time variation of the signal in the charged-current channel should be similar to that in the chlorine detector; in addition, the neutrino spectrum measured in this channel should be distorted. In the neutral-current channel one should see unsuppressed constant signal (the signal can be somewhat suppressed if the SSM overestimates the $^8$B flux or if there are neutrino oscillations along with the RSFP).

It is interesting to note that in order to reproduce the existing solar neutrino data, one needs a modest variation of the magnetic field parameter $B_0$, only by a factor of two or so. In reality, the situation can be much more complicated. It is possible that the maximum of the convective-zone magnetic field does not just change in time having fixed spatial position, but rather floats from the bottom of the convective zone to its surface during the solar cycle \footnote{We plan to consider this effect as well as more realistic 3-dimensional magnetic field configurations in a subsequent publication.}. We plan to consider this effect as well as more realistic 3-dimensional magnetic field configurations in a subsequent publication.

As we emphasized above, only the Homestake data seem to exhibit a time variation of the neutrino signal whereas the Kamiokande data do not support this possibility. In our calculations we just fitted the upper and lower values of $Q_{\text{Cl}}$ having in mind that the parameter sets which fit these values for some $(B_0)_{\text{min}}$ and $(B_0)_{\text{max}}$ will also fit all the intermediate $Q_{\text{Cl}}$ for the magnitudes of $B_0$ lying in between these values. A more consistent approach is to perform a $\chi^2$ fit of all the data sets on the run-by-run basis, as, for example, it has been done for Homestake and Kamiokande II data in \cite{34,32}. The results of such an analysis will be presented elsewhere.
In conclusion, we have shown that the results of the $^{37}$Cl, Kamiokande II and $^{71}$Ga solar neutrino experiments can be reproduced assuming that the solar $\nu_e$ undergo resonant spin-flavor precession into $\bar{\nu}_\mu$ or $\bar{\nu}_\tau$ in the magnetic field of the sun. The gallium detection rate turns out to be especially sensitive to the magnitude of the parameter $\Delta m^2$. It also depends drastically on the strength of the inner magnetic field of the sun. Using the positive results of SAGE and GALLEX experiments, we have obtained an upper limit on the strength of such a field: $B_1 \lesssim 3 \times 10^6$ G. Our calculations show that the quality of the combined fit of the data is very sensitive to the magnetic field configuration used, which opens up the possibility of extracting information on the strength and profile of the solar magnetic field from solar neutrino data. We predict very strong time variation of the $^7$Be neutrino flux which should be observable in the Borexino experiment.

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Note added. When this paper was being typed we received a preprint by Krastev in which analogous analysis has been done assuming that the direction of the solar magnetic field varies along the neutrino trajectory. It was shown that in this case a satisfactory description of the data can also be achieved.

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Figure captions

Fig. 1. Predicted detection rates for the chlorine (a), Kamiokande (b) and gallium (c) experiments as functions of convective zone magnetic field parameter $B_0$ for the "triangle" magnetic field configuration of eq. (7) with $x_0 = 0.70$, $x_c = 0.85$, $x_{\text{max}} = 1$, $B_f = 0$ and no inner magnetic field; $\mu_{e\mu} = 10^{-11}\mu_B$ is assumed. The numbers near the curves indicate the values of $\Delta m^2$ in units of $\text{eV}^2$. The groups of closely located curves in figs. 1a and 1b correspond to the values of $\Delta m^2$ in the range $5 \times 10^{-9} - 8 \times 10^{-9} \text{eV}^2$.

Fig. 2. The iso-SNU (iso-suppression) contours for $^{37}\text{Cl}$, Kamiokande and $^{71}\text{Ga}$ experiments in the ($B_0$, $\Delta m^2$) plane. The magnetic field configuration is the same as in fig. 1. The full lines are chlorine iso-SNU curves ($1.5$, $1.9$, $2.2$, $3.6$, $4.8$, $5.2$ and $5.8$ SNU), the dotted lines correspond to the ratio $R=0.30$, $0.40$, $0.58$ and $0.68$ for the Kamiokande experiment, and the dash-dotted lines represent the gallium iso-SNU curves ($62.0$, $83.0$, $104.0$ and $120$ SNU). The shaded areas show the allowed ranges of parameters (see the text).

Fig. 3. Same as fig. 2, but for the magnetic field configuration of eq. (8) with $n = 6$ and $B_1 = 2 \times 10^6$ G.

Fig. 4. The iso-SNU (iso-suppression) contours in the ($B_0$, $B_1$) plane. The magnetic field configuration and the definition of the curves are the same as in fig. 2.

Fig. 5. Suppression factors for neutrinos from the different sources for the gallium experiments as functions of the convective zone magnetic field parameter $B_0$. The magnetic field configuration is the same as that used for fig. 1.