RESONANT SPIN-FLAVOR PRECESSION OF NEUTRINOS AS A POSSIBLE SOLUTION TO THE SOLAR NEUTRINO PROBLEM

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Abstract

Recent developments of the resonant neutrino spin-flavor precession scenario and its applications to the solar neutrino problem are reviewed. We discuss in particular the possibilities of reconciliation of strong time variations of the solar neutrino flux observed in the Homestake $^{37}$Cl experiment with little or no time variation seen in the Kamiokande II experiment.

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1 Introduction

There are two issues in the solar neutrino problem:

(1) the deficiency of solar neutrinos observed in the Homestake [1], Kamiokande II [2] and, most recently, SAGE [3] experiments;

(2) time variation of the solar neutrino flux in anticorrelation with solar activity (11-yr variations) for which there is a strong indication in the chlorine experiment of Davis and his collaborators but which is not seen in the Kamiokande data.

In this talk I will discuss mainly the second issue with the emphasis on various possibilities of conciliation of the strong time variations in the Homestake experiment with no or little variation in Kamiokande II.

The most natural explanation of the time variation of the solar neutrino flux is related to the possible existence of a large magnetic or electric dipole moments of neutrinos, $\mu \sim 10^{-11}\mu_B$. As was pointed out by Vysotsky, Voloshin and Okun (VVO) [4, 5], strong toroidal magnetic field in the convective zone of the sun $B_\perp$ could then rotate left-handed electron neutrinos $\nu_{eL}$ into right-handed $\nu_{eR}$ which escape the detection. In the periods of quiet sun the solar magnetic field is much weaker and the neutrino spin precession is less efficient which explains the 11-yr variation of the neutrino flux.

Subsequently, it was noted [5, 6] that the matter effects can suppress the neutrino spin precession. The reason for this is that $\nu_{eL}$ and $\nu_{eR}$ are not degenerate in matter since $\nu_{eL}$ interact with medium whereas $\nu_{eR}$ are sterile, and their energy splitting reduces the precession probability. It was also shown [7] that, unlike in the MSW effect case, the adiabaticity may play a bad role for the VVO effect resulting in a reflip of neutrino spin and thus reducing the probability of $\nu_{eL} \rightarrow \nu_{eR}$ transition. In order to break the adiabaticity, the precession length should be large as compared to the characteristic lengths over which matter density and magnetic field vary significantly, which gives an upper bound on $\mu B_\perp$. This parameter should be also bounded from below in order for the precession phase not to
be too small. Therefore one gets a rather narrow range of allowed values of $\mu B_\perp$.

Another interesting possibility is the neutrino spin-flavor precession (SFP) due to the interaction of flavor-off-diagonal (transition) magnetic or electric dipole moments of neutrinos $\mu_{ij}$ with transverse magnetic fields $B_\perp$. The SFP is the rotation of neutrino spin with its flavor being simultaneously changed. Such a process can occur even for Majorana neutrinos since the $CPT$ invariance does not preclude the transition magnetic dipole moments of Majorana particles. Until recently, the neutrino SFP has not attracted much attention because it was expected to be suppressed by the energy splitting of the neutrinos of different species. If the "Zeeman energy" $\mu_{ij}B_\perp$ is small as compared to the kinetic energy difference $\Delta m^2_{ij}/2E$, the SFP probability is heavily suppressed. However, in 1988 it was noted independently by the present author and by Lim and Marciano that in matter the situation can change drastically. Since $\nu_{eL}$ and right-handed neutrinos or antineutrinos of another flavor interact with matter differently, the difference of their potential energies can cancel their kinetic energy difference resulting in a resonant amplification of the SFP. Therefore in matter the SFP of neutrinos can be enhanced, unlike the VVO neutrino spin precession. The resonant spin-flavor precession (RSFP) of neutrinos has also some more advantages as compared to the VVO mechanism:

- the adiabaticity plays a good role for the RSFP increasing the conversion probability, and therefore the $\mu_{ij}B_\perp$ should be bounded only from below; the required magnitude of this parameter is a factor of $2 - 3$ smaller than that for the VVO effect;

- some energy dependence of the neutrino conversion seems to be necessary to reconcile the Homestake and Kamiokande II data (see below). The RSFP probability has the desired energy dependence whereas the VVO neutrino spin precession is energy independent.

Although the above arguments disfavor the VVO effect as a solution of the solar neutrino problem, they do not rule it out, given the uncertainties of the experimental data.

\footnote{The VVO neutrino spin rotation can also be resonantly enhanced provided the magnetic field twists along the neutrino trajectory, see \cite{11, 12} and below.}
2 General features of RSFP of neutrinos

The RSFP of neutrinos is analogous to the resonant neutrino oscillations [13, 14], but differs from the latter in a number of important respects. The main features of this effect have been discussed in detail in my talk at the last Moriond meeting [15], and so I will just briefly mention them here.

The magnetic-field induced mixing of $\nu_{eL}$ and $\nu_{\mu R}(\bar{\nu}_{\mu R})$ can be described by the mixing angle $\theta$,

$$\tan 2\theta = \frac{2\mu_{e\mu}B_\perp}{\sqrt{2}G_F(N_e - \alpha N_n - \frac{\Delta m^2_{e\mu}}{2E}\cos 2\theta_0}$$  \hspace{1cm} (1)

Here $N_e$ and $N_n$ are the electron and neutron number densities, $\alpha = 1/2$ for Dirac neutrinos and 1 for Majorana neutrinos, $G_F$ is the Fermi constant, and $\theta_0$ is the ordinary neutrino mixing angle in vacuum. The resonant density is defined as a density at which the mixing angle $\theta$ becomes $\pi/4$:

$$\sqrt{2}G_F(N_e - \alpha N_n)_{|r} = \frac{\Delta m^2_{e\mu}}{2E}\cos 2\theta_0$$ \hspace{1cm} (2)

The efficiency of the $\nu_{eL} \rightarrow \nu_{\mu R}(\bar{\nu}_{\mu R})$ transition is defined by the degree of the adiabaticity which depends on both the neutrino energy and magnetic field strength at the resonance:

$$\lambda \equiv \frac{\Delta r}{l_r} = 8\frac{E}{\Delta m^2_{e\mu}}(\mu_{e\mu}B_{\perp r})^2L_\rho$$ \hspace{1cm} (3)

Here

$$\Delta r = \frac{8E\mu_{e\mu}B_{\perp r}}{\Delta m^2_{e\mu}}L_\rho$$ \hspace{1cm} (4)

is the resonance width, $l_r = \pi/\mu_{e\mu}B_\perp$ is the precession length at the resonance and $L_\rho$ is the characteristic length over which matter density varies significantly in the sun. For the RSFP to be efficient, $\lambda$ should be $> 1$. In non-uniform magnetic field the field strength at resonance $B_{\perp r}$ depends on the resonance coordinate and so, through eq. (2), on neutrino energy. Therefore the energy dependence of the adiabaticity parameter $\lambda$ in eq. (3) is, in general, more complicated than just $\lambda \sim E$, and is defined by the magnetic field profile.
inside the sun. The main difficulty in the analyses of the RSFP as a possible solution of the solar neutrino problem is that this profile is essentially unknown, so that one is forced to use various more or less plausible magnetic field configurations.

In the adiabatic regime ($\lambda \gg 1$), the $\nu_{eL}$ survival probability is

$$ P(\nu_{eL} \rightarrow \nu_{eL}) = \frac{1}{2} \cos 2\theta_i \cos 2\theta_f + \frac{1}{2} \sin 2\theta_i \sin 2\theta_f \cos \int_{t_i}^{t_f} \Delta E(t) \, dt $$

(5)

where

$$ \Delta E = \sqrt{\left[ \sqrt{2} G_F (N_e - \alpha N_n) - \frac{\Delta m_{\mu\mu}^2}{2} \cos 2\theta_0 \right]^2 + (2\mu_{e\mu} B_\perp)^2} $$

(6)

Here $\theta_i$ and $\theta_f$ are the mixing angles (1) at the neutrino production point and on the surface of the sun respectively. If the $\nu_{eL}$ are produced at a density which is much higher than the resonant one, $\theta_i \approx 0$ and the survival probability (4) becomes

$$ P(\nu_{eL} \rightarrow \nu_{eL}) \approx \cos^2 \theta_f $$

(7)

Since the magnetic field becomes very weak at the sun’s surface, the mixing angle $\theta_f \approx \pi/2$, and so the $\nu_{eL}$ survival probability is very small in the adiabatic regime. The adiabaticity parameter $\lambda$ in eq. (3) depends drastically on the magnetic field strength at resonance, which gives a natural explanation of time variations of the solar magnetic flux in anticorrelation with solar activity.

The RSFP requires non-vanishing flavor-off-diagonal magnetic dipole moments of neutrinos and so is only possible if the neutrino flavor is not conserved. Therefore neutrino oscillations must also take place, and in general one should consider the SFP and oscillations of neutrinos jointly. This have been done in a number of papers both analytically $[16, 17]$ and numerically $[10, 16, 18, 19, 17]$. It was shown that a subtle interplay between the RSFP and the MSW resonant neutrino oscillations can occur. In particular, although the resonant neutrino oscillations cannot give rise to the time variations of the solar neutrino flux, they can assist the RSFP to do so by improving the adiabaticity of the latter $[17]$.

Note that for the MSW effect the adiabaticity parameter is inversely proportional to $E$ $[13]$. 

4
Neutrino spin precession in twisting magnetic fields

If the magnetic field changes its direction along the neutrino trajectory, this can result in new interesting phenomena. In particular, new kinds of resonant neutrino conversions become possible, the energy dependence of the conversion probability can be significantly distorted and the lower limit on the value of $\mu B_\perp$ required to account for the solar neutrino problem can be slightly relaxed \[11, 12\]. Moreover, if the neutrino oscillations are also taken into account, the transitions $\nu_e \rightarrow \bar{\nu}_e$ can become resonant, and the order of the RSFP and MSW resonances can be interchanged \[20\].

Since the main features of the resonant neutrino spin-flip transitions in twisting magnetic fields are discussed in some detail in the contributions of Krastev and Toshev in this volume, I will confine myself to a new development which was not covered in their talks.

A few years ago, Vidal and Wudka \[21\] claimed that the field rotation effects can greatly enhance the neutrino spin-flip probability and reduce the needed value of $\mu B_\perp$ by a few orders of magnitudes. In \[11, 12\] it was shown that this result is incorrect and typically the required value of $\mu B_\perp$ can only be reduced by a factor 2–3 (see also \[22, 23\] in which the process without matter effects was considered). However, in these papers it was not proved that there cannot exist a rotating field configuration giving stronger enhancement of the spin-flip probability and larger gain in the $\mu B_\perp$ parameter. Recently, Moretti \[24\] has found a severe constraint on the transition probability which eliminates even this possibility. The effective Hamiltonian describing the evolution of the system of left handed $\nu_{eL}$ and right handed neutrino of the same or another flavor $\nu_R$ in a twisting magnetic field is

$$H = \begin{pmatrix} V(t)/2 & \mu B_\perp e^{i\phi(t)} \\ \mu B_\perp e^{-i\phi(t)} & -V(t)/2 \end{pmatrix}$$

(8)

where $V(t)$ is just the denominator of the r.h.s. of eq. (1), and the angle $\phi(t)$ defines the direction of the magnetic field in the plane orthogonal to the neutrino momentum. The
transition probability \( P(\nu_{eL} \rightarrow \nu_{R}) \) turns out to have the following upper bound \[24\]:

\[
P(\nu_{eL} \rightarrow \nu_{R}; t) \leq \mu \int_0^t B_{\perp}(t') dt'
\]  \text{(9)}

The analogous result can also be obtained for the neutrino oscillations in matter as well as for the evolution of any other two-level system.

4 RSFP and antineutrinos from the sun

If both the SFP and oscillations of neutrinos can occur, this will result in the conversion of a fraction of solar \( \nu_e \) into \( \bar{\nu}_e \) \[10, 16, 25, 26\]. For Majorana neutrinos, the direct \( \nu_e \rightarrow \bar{\nu}_e \) conversions are forbidden since the CPT invariance precludes the diagonal magnetic moment \( \mu_{ee} \). However, this conversion can proceed as a two-step process in either of two ways:

\[
\nu_{eL} \xrightarrow{\text{oscill.}} \nu_{\mu L} \xrightarrow{\text{SFP}} \bar{\nu}_{eR} \quad \text{(10)}
\]

\[
\nu_{eL} \xrightarrow{\text{SFP}} \bar{\nu}_{\mu R} \xrightarrow{\text{oscill.}} \bar{\nu}_{eR} \quad \text{(11)}
\]

One can then consider two possibilities:

(1) both oscillations and SFP take place inside sun \[10, 16, 25\]. The amplitudes of the processes (10) and (11) have opposite signs since the matrix of the magnetic moments of Majorana neutrinos is antisymmetric. Therefore there is a large cancellation between these two amplitudes (the cancellation is exact in the limit of vanishing neutron density \( N_n \)), and the probability of the \( \nu_e \rightarrow \bar{\nu}_e \) conversion inside the sun turns out to be about 3–5% even for large mixing angles \( \theta_0 \) \[16, 25\].

(2) Only the RSFP transition \( \nu_{eL} \rightarrow \bar{\nu}_{\mu R} \) occurs in the sun with an appreciable probability whereas the oscillations of neutrinos proceed mainly in vacuum on their way between the sun and the earth [eq. (11)]. For not too small neutrino mixing angles the probability of the \( \nu_e \rightarrow \bar{\nu}_e \) conversion can then be quite sizable \[26\].

In \[27\] the background events in the Kamiokande II experiment were analysed and a stringent bound on the flux of \( \bar{\nu}_e \) from the sun was obtained: \( \Phi(\bar{\nu}_e) \leq (0.05 - 0.07)\Phi(\nu_e) \).
This poses a limit on the models in which both the RSFP and neutrino oscillations occur: the mixing angle $\theta_0$ should be less than $6 - 8^\circ$. This rules out the models with the large magnetic moments of pseudo Dirac neutrinos including those with only one neutrino generation for which $\theta_0$ is the mixing between $\nu_{eL}$ and sterile $\bar{\nu}_{eL}$ \cite{28, 29}. However, the models with a conserved lepton charges $L_e \pm (L_\mu - L_\tau)$ are not excluded even though the mixing angle is $\pi/4$, since the $\nu_e \rightarrow \bar{\nu}_e$ conversion probability vanishes identically in this case \cite{30}.

The $\bar{\nu}_e$ production due to the combined effect of the RSFP and oscillations of neutrinos can be easily distinguished from the other mechanisms of $\bar{\nu}_e$ generation (like $\nu \rightarrow \bar{\nu} + \text{Majoron}$ decay) since (i) the neutrino flux should vary in time in direct correlation with solar activity, and (ii) the neutrino energy is not degraded in this case \cite{16, 25}. The $\bar{\nu}_e$ flux from the sun of the order of a few per cent of the expected $\nu_e$ flux should be detectable in the forthcoming solar neutrino experiments like BOREXINO, SNO and Super-Kamiokande \cite{25, 26, 31}.

5 Reconciling the Homestake and Kamiokande II data

It has been mentioned above that while there is a strong indication in favor of time variation of the neutrino detection rate in the Homestake data, the Kamiokande experiment does not see such a time variation. It still cannot rule out a small ($\leq 30\%$) time variation. Therefore a question naturally arises as to whether it is possible to reconcile large time variations in the Homestake $^{37}$Cl experiment with small time variation in the water Čerenkov experiment. There are two major differences between these two experiments which could in principle give rise to different time variations of their detection rates:

(1) Homestake experiment utilizes the $\nu_e \rightarrow ^{37}$Cl charged current reaction, while in the Kamiokande detector $\nu - e$ scattering is used which is mediated by both charged and neutral currents;

(2) the energy threshold in the Homestake experiment is 0.814 MeV so that it is sensitive to high energy $^8$B, intermediate energy $^7$Be and partly to low energy pep neutrinos; at the
same time the energy threshold in the Kamiokande II experiment is 7.5 MeV and so it is only sensitive to the high-energy fraction of the \(^8\)B neutrinos.

In [32, 17] it was noted that if the lower-energy neutrino contributions to the chlorine detection rate are suppressed stronger than that of high-energy neutrinos, the latter can vary in time with smaller amplitude and still fit the Homestake data. In that case one can expect weaker time variations in the Kamiokande II experiment. The desired suppression of the low-energy neutrino flux can be easily explained in the framework of the RSFP scenario as a consequence of flavor-changing spin-flip conversion due to a strong inner magnetic field, the existence of which seems quite plausible [33]. The alternative possibility is the suppression of low-energy neutrinos by the MSW effect when RSFP and the resonant neutrino oscillations operate jointly. Another important point is that due to the RSFP solar \(\nu_e\) are converted into \(\bar{\nu}_\mu^R\) or \(\bar{\nu}_\tau^R\) which are sterile for the chlorine detector but can be detected (though with a smaller cross section) by water Čerenkov detectors. This also reduces the amplitude of the time variation in the Kamiokande II detector. If both these factors are taken into account, it becomes possible to reconcile the Homestake and Kamiokande data; one can expect a low signal in the gallium experiments in this case since they are primarily sensitive to low-energy neutrinos whose flux is supposed to be heavily suppressed [32, 17].

A similar possibility has been recently considered by Babu, Mohapatra and Rothstein [34] and by Ono and Suematsu [35]. They pointed out that due to the energy dependence of the RSFP neutrino conversion probability, lower-energy neutrinos can exhibit stronger time variations (i.e. stronger magnetic field dependence) than the higher-energy ones. In fact, this is very natural in the RSFP scenario: with increasing neutrino energy the width of the resonance increases [see eq. (4)] and at sufficiently high energies it can be a significant fraction of the solar radius. The neutrino production point can then happen to be inside the resonant region, which reduces the conversion efficiency. The different magnetic field dependence of the Homestake and Kamiokande II detection rates is illustrated by the figures
which we borrowed from ref. [33].

Fig. 1. (a) Expected event rate in chlorine as a function of the convective zone magnetic field. Here $\Delta m^2 = 7.8 \times 10^{-9} \text{eV}^2$, the maximal value of the magnetic field in the core $B_1 = 10^7 \text{G}$ and $\mu = 2 \times 10^{-11} \mu_B$. (b) The same as (a) but for the Kamiokande event rate.

It should be noted that the ordinary VVO neutrino spin precession lacks energy dependence which is required to get smaller time variation in the Kamiokande II experiment. Moreover, it converts $\nu_{eL}$ into sterile $\nu_{eR}$ (unless the neutrinos are Zeldovich-Konopinski-Mahmoud particles) which do not contribute to the $\nu - e$ cross section. However, for the VVO scenario yet another possibility of reconciliation of the Homestake and Kamiokande data exists. In order to get sizable magnetic moments of neutrinos, $\mu \approx 10^{-11} \mu_B$, one has to go beyond the Standard Model. Most of the models producing large neutrino magnetic moments are based on various extensions of the Standard Model containing new charged scalars. In these models right-handed sterile neutrinos can interact with electrons via scalar exchange and therefore can contribute to the $\nu - e$ reaction which increases the signal in the Kamiokande II detector and reduces the amplitude of its time variation [36]. Note that the models giving large transition neutrino magnetic moments usually also contain new scalars and therefore the same mechanism can be operative in case of the RSFP as well.
6 Conclusion

We conclude that the resonant neutrino spin-flavor precession mechanism provides a viable explanation of the solar-neutrino problem which complies with all the existing experimental data and yields a number of interesting predictions for the forthcoming experiments.

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