Spin flavor precession and solar neutrino data

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Abstract. The current status of spin flavor precession (SFP) in the Sun is reviewed. It is shown that this mechanism is disfavored as a leading solution to the solar neutrino problem. The case of SFP as a sub-leading solution is also discussed. For this case, the recent KamLAND constraint on solar anti-neutrino flux provides a stringent constraint on the neutrino magnetic moment down to $\mu_{\nu} \leq 5 \times 10^{-12} \mu_B$.

1. Introduction

After the solar data reported by SNO [1, 2] and KamLAND [3], the solar neutrino problem has been solved, favoring the MSW-LMA solution [4]. Different solutions that were possible before these experiments are now ruled out as a leading effect. However, some of these solutions can still be considered as a sub-leading effect. This is the case for the spin flavor precession mechanism [5] (SFP), which suppose a non-zero neutrino magnetic moment. For the case of Majorana neutrinos [6], SFP would lead to a non-zero anti-neutrino flux that could be detected at present detectors such as Super-Kamiokande, KamLAND and SNO. A future positive signal for anti-neutrinos from the Sun would be a hint for the Majorana nature of the neutrinos, alternative to the laboratory searches were the most promising experiment is the neutrinoless double beta decay [7] (although some other possibilities has been discussed in the literature [8]).

In this work we review the present status of SFP in the Sun (the case of Supernovae has also been studied recently [9, 10]) using the most recent results on solar neutrino experiments. In order to get a result for SFP mechanism in the Sun, a model for the magnetic fields inside the Sun is necessary; we also discuss here this models, both for the case of regular magnetic fields, as well as for random magnetic fields. It is shown that, for the case of random magnetic fields, the recent solar anti-neutrino flux limit hints for a constraint on the transition neutrino magnetic moment down to the level of $\mu_{\nu} \leq 5 \times 10^{-12} \mu_B$.

2. SFP for Regular Magnetic Field Profiles in the Sun

In order to analyze the solar neutrino data using the SFP mechanism is necessary to have a model for the magnetic field inside the Sun; in this section we will concentrate first on such a model for the case of regular magnetic field profiles.
2.1. Regular magnetic field profiles

It is commonly accepted that magnetic fields measured at the surface of the Sun are weaker than within the convective zone interior where this field is supposed to be generated. It is known by observational data that the mean field value over the solar disk is of the order of 1 Gauss while in the solar spots magnetic field strength reaches 1 kG.

The origin of these solar magnetic fields can be explained in solar magnetohydrodynamics (MHD, for short) from the dynamo mechanism at the bottom of the convective zone or, to be more specific, in the overshoot layer, where magnetic fields may be as strong as 300 kG [11]. Although several MHD dynamo solutions have been known since long time ago [12], the corresponding magnetic field profiles are rather complicated and difficult to extract. For this reason there have been many attempts to mimic MHD properties through the use of ad hoc magnetic field profiles [13, 14, 15, 16]. (A completely different approach is to consider a magnetic field located at the solar core, or in the radiative zone [17, 18], but these models are not so well motivated as those based on the MHD dynamo theory).

An alternative approach is to consider fully self-consistent solutions to the MHD equations inside the Sun. In order to do this we start with the case of stationary solutions, which are known analytically in terms of relatively simple functions [19]. In this way a family of simple and well-motivated magnetic field profiles is obtained, without the full complexity that a dynamo model implies. To follow this approach we can consider the solutions to the equation for a static MHD plasma configuration in a gravitational field given by the equilibrium of the pressure force, the Lorentz force and the gravitational force

\[ \nabla p - \frac{1}{c} \mathbf{j} \times \mathbf{B} + \rho \nabla \Phi = 0, \]

where \( p \) is the pressure, \( \mathbf{j} = (c/4\pi) \nabla \times \mathbf{B} \) is the electric current, \( \mathbf{B} \) is the static magnetic field under consideration, \( \rho \) is the matter density and \( \Phi \) is the gravitational potential.

For this model the magnetic field will be given by a family of solutions that depends on \( z_k \), the roots of the spherical Bessel function \( f_{5/2} = \sqrt{z} J_{5/2}(z) \) [19].

One advantage of this method is that now we have several profiles that are in accordance with the picture given by the MHD dynamo mechanism. After analyzing the solar neutrino data we get to the conclusion [20] that any of these profiles will give a similar fit to the data, because the resulting neutrino survival probabilities will be very similar for any of these profiles.

3. Fit to solar neutrino data: before and after KamLAND

3.1. Neutrino Evolution

The recent SNO data [1, 2] strongly support that solar neutrinos convert to active neutrinos. On the other hand the combined constraints from reactor neutrino experiments [21] and atmospheric neutrino data [22] imply that solar neutrino conversions involve mainly two flavors. It is therefore natural to consider the evolution Hamiltonian describing a system of two flavors of active Majorana neutrinos [23, 5]

\[ i \begin{pmatrix} \dot{\nu}_e L \\ \dot{\nu}_e R \\ \dot{\nu}_\mu L \\ \dot{\nu}_\mu R \end{pmatrix} = \mathcal{H} \begin{pmatrix} \nu_e L \\ \nu_e R \\ \nu_\mu L \\ \nu_\mu R \end{pmatrix}, \]

(2)
In this equation $c_2 = \cos 2\theta$, $s_2 = \sin 2\theta$, $\delta = \Delta m^2/4E$ (assumed to be always positive) are the neutrino oscillation parameters, $\mu = \mu_\nu$ is the neutrino transition magnetic moment; $B_\pm = B_x \pm iB_y$, are the magnetic field components orthogonal to the neutrino momentum; $V_e(t) = G_F \sqrt{2}(N_e(t) - N_n(t)/2)$ and $V_\mu(t) = G_F \sqrt{2}(-N_n(t)/2)$ are the neutrino vector potentials for $\nu_e$ and $\nu_\mu$, in the Sun, given by $N_e(t)$ and $N_n(t)$, the number densities of the electrons and neutrons, respectively. This generalized form takes into account that, in addition to mixing, massive Majorana neutrinos may be endowed with a non-zero transition magnetic moment. In the limit where $\mu B \rightarrow 0$ this system reduces to the widely discussed case of two-flavor oscillations. On the other hand when the mixing vanishes, $\sin 2\theta \rightarrow 0$, one recovers the pure magnetic solutions [13, 14, 15].

The corresponding survival and conversion probabilities $P_{\alpha\beta}$ can be found by numerically solving the evolution equation (2).

3.2. SFP in regular magnetic fields and solar neutrino data.

With the above is possible to analyze the behavior of the neutrino survival probabilities with respect to variations in $\mu B_\perp$ (hereafter, we will use the value $\mu_\nu = 10^{-11}\mu_B$ unless stated opposite) and with respect to the usual oscillation parameters $\Delta m^2$ and $\tan^2\theta$. It can be found [24] that the smallest magnetic field magnitude which leads to a boron neutrino survival probability at the required level lies close to 80 kG. It had also been found that, previous to the KamLAND experiment, there were two limit values of $\tan^2\theta$ giving a good solution to the solar neutrino problem, one in the limit case $\tan^2\theta \rightarrow 0$ (RSFP) and the second one [25] for $\tan^2\theta \rightarrow \infty$ (NRSFP).

Using all the current solar neutrino data [26], including the most recent Super-Kamiokande data sample [27] and the latest results from SNO [2, 28], it is possible to fit the SFP mechanism with the experimental results [24]. However, this mechanism fails to explain reactor neutrino observations at the KamLAND experiment [3].

After adding the KamLAND result to the $\chi^2$ analysis, the RSFP and NRSFP solutions are allowed only at 99.86 % C. L. and 99.88 % C. L., respectively [24]. Thus the spin flavor precession solution to the solar neutrino problem can not be reconciled with the KamLAND data and is therefore rejected as a leading solution.

However, even with the recent SNO salt results [1] which confirm the simplest three-neutrino oscillation picture [29], a neutrino magnetic moment could still play a role as a sub-leading effect. For instance, it is possible to look for distortions in the neutrino survival probability due to the effect of a non-zero neutrino magnetic moment, or, with the recent constraints on the solar anti-neutrino flux, for an appearance of anti-neutrinos due to the same non-zero neutrino magnetic moment.

The chances to limit the possibility of sub-leading SFP component in the neutrino conversion mechanism, are substantially increased thanks to the latest KamLAND result [30] which greatly improves the expected sensitivity limit on a possible anti-neutrino component in the solar flux from 0.1 % [31] of the solar boron $\nu_e$ flux to $2.8 \times 10^{-2}$ % at the 90 % C.L., about 30 times better than the recent Super-K and SNO limit [32].

The Collaboration has reported that the anti-neutrino flux $\Phi_{\bar{\nu}_e}$ is less than $3.7 \times 10^2$ cm$^{-2}$ s$^{-1}$ at 90 % C. L. In order to obtain a conservative bound on $\mu_\nu B$ we have calculated the minimum $\bar{\nu}_e$ yield as the oscillation parameters vary within the acceptable range (at the 90 % C.L.) for the
pure LMA-MSW case. We have found that for regular magnetic field profiles in the convective zone it is possible to obtain a constraint

$$\mu_\nu \frac{B}{100 \text{kG}} \leq 6.$$  \hspace{1cm} (4)

Note that for a regular field profile we can only constrain the product $\mu_\nu B$, as opposed to the intrinsic neutrino magnetic moment.

4. SFP for Random Magnetic Field Profiles in the Sun

A more interesting picture for SFP scenario is obtained if we consider the case of turbulent random magnetic fields inside the Sun. The reason for this is twofold: (i) we will be able to fix, to some extent, the dependence on the magnetic field, in contrast to previous analysis of the random magnetic field [33, 34], where an extra parameter $L_0$ appeared, characterizing the scale of the random magnetic field cells, and (ii) this model leads to more stringent limits on the neutrino magnetic moment.

In dynamo theory, the mean magnetic field is accompanied by a small-scale random magnetic field of about the solar granule size ($\sim 1000 \text{ km}$) [35] where the rms magnetic field amplitudes in the range of 50-100 kG are reasonable.

We will assume for definiteness that random magnetic field evolution is due to the highly developed steady-state MHD turbulence treated within the Kolmogorov scaling theory [36, 37] i.e. the rms magnetic field $b_l$ is assumed to scale as $b_l \sim l^{1/3}$. This implies that, after fixing the maximum field amplitude, it is straightforward to obtain the rms field at the neutrino oscillation scale, which is about several hundreds kilometers for LMA-MSW case.

For LMA oscillations the MSW conversion occurs well below the CZ resulting in a coherent mixture of two neutrino flavors at the bottom of the convective zone. When neutrinos cross the randomly fluctuating magnetic field of the CZ it is expected that $\nu_eL$ will convert to $\bar{\nu}_\mu R$ and $\nu_\mu L$ will convert to $\bar{\nu}_e R$ as a result of the CZ magnetic field. For the case of random CZ magnetic fields these populations will tend to equilibrate.

The anti-neutrino yield due to this effect will be proportional to [38]

$$\eta \sim 3 \times 10^{-3} \mu_{11}^2 \varepsilon^2 S^2 \left( \frac{7 \times 10^{-5} eV^2}{\Delta m^2} \right)^{5/3} \left( \frac{E}{10 \text{MeV}} \right)^{5/3}$$  \hspace{1cm} (5)

where $\mu_{11}$ is the magnetic moment in units of $10^{-11} \mu_B$, and the ratio $\varepsilon = (b/100 \text{ kG})(L_{\text{max}}/1000 \text{ km})^{1/3}$. $\delta = \Delta m^2/4E$, and $S^2$ is a rms magnetic field profile shape factor that takes values between 0.5 and 1.

Although the ratio $\varepsilon$ is not known precisely, we can obtain as a good estimate [38] that $0.5 < \varepsilon < 1$, with our assumptions. As mentioned, for different profiles we found that the parameter $S^2$ lies in the range between 0.5 and 1. With this in mind, we can see that the product $k = \varepsilon S$ lies in the interval $0.25 < k < 1$. Since the overall $\nu_e \rightarrow \bar{\nu}_e$ conversion probability depends linearly on $\eta$, it follows that, by comparing the resulting $\bar{\nu}_e$ yield to the recent KamLAND bound one can constrain the value of $\mu_\nu$ to within a factor 4. More precisely, we have computed the solar anti-neutrino yield for this random magnetic field model for all allowed values of neutrino oscillation parameters in the LMA-MSW region. The constraint we obtain is better than those that hold for the case of regular magnetic fields. Moreover, from our estimate for the maximum value of $k$, we can obtain an upper bound for $\mu_\nu$ given by $\mu_\nu \leq 5 \times 10^{-12} \mu_B$. 
5. Conclusions

The present status of spin flavor solution has been discussed. We have shown that SFP solution are disfavored as a leading solution to the solar neutrino problem at least at 99.86 % C. L. We have also discussed SFP as a sub-leading solution. In this case, the random magnetic field scenario provides a well-motivated solar MHD model and gives a constraint to the neutrino transition magnetic moment $\mu_\nu \leq 5 \times 10^{-12}$.

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