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Correlation between Solar Neutrino Flux and Solar Magnetic Activity for Majorana Neutrinos

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Abstract

We study the interplay between solar neutrino event rates and solar magnetic field in both the Kamiokande-II and the ^{37}Cl experiments, in a framework with resonant spin-flavor precession. An interesting difference in the correlation in these two experiments arises especially due to the presence of $\nu_e \rightarrow \bar{\nu}_\mu \rightarrow \bar{\nu}_e$ for Majorana neutrinos. The conversion rate is sizable for parameters, $\Delta m^2 < 10^{-7} \text{ eV}^2$, $\sin^2 2\theta > 0.5$ and the Zeeman energy $\mu_B > 10^{-10}$ ($\mu_B \cdot 1\text{kG}$) with μ_B being the Bohr magneton. The detection of characteristic $\bar{\nu}_e$ signals in the Kamiokande-II is also discussed.

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The observation of solar neutrino flux via the reaction of $\nu_e + {}^{37}\text{Cl} \rightarrow e^- + {}^{37}\text{Ar}$ averaged over 20 years, $(2.1 \pm 0.3 \text{ SNU})$ ($1 \text{ SNU} = 10^{-36} \text{ captures/s/atom}$)[1], indicates a substantial depletion by a factor 3-4 with respect to the standard solar model (SSM) prediction $(7.9 \pm 2.5 \text{ SNU})$ (3σ errors)[2]. This discrepancy between experiment and theory is called the solar neutrino problem which has been a fundamental question of enough challenge concerning both astrophysics and neutrino physics. The depletion of the solar neutrino flux has recently been confirmed by the Kamiokande-II experiment with a totally independent method using a large water Cherenkov detector[3]. The observed flux of ${}^8\text{B}$ solar neutrinos was $0.46 \pm 0.13(\text{stat.}) \pm 0.08(\text{sys.})$ [3] of the SSM prediction[2]. Davis has pointed out that the neutrino capture rate of the ${}^{37}\text{Cl}$ experiment was inclusively anti-correlated with the sunspot number with 11 - year cycle[1], which in turn is the manifestation of solar magnetic activity. A plausible explanation to this time variation of the solar neutrino flux was proposed by Okun, Voloshin and Vysotsky[4] who revamped the idea of Cisneros[5]. According to their scenario, if an electron neutrino has a large Dirac type magnetic moment, its helicity is flipped from left-handed to right-handed (spin-precession) in traversing through the solar magnetic field. Right-handed neutrinos do not have weak interactions with matter in the framework of the standard electroweak model, thus the detector being blind to them. In order to obtain a factor of 2 suppression of the solar neutrino flux, a neutrino magnetic moment is constrained in $\mu_{\nu_e} \cong (0.3 - 1.0) \times 10^{-10} \mu_B$, when the magnitude of solar magnetic field is assumed to be (1-5) kG in the convective zone of the thickness $2 \times 10^{10} \text{ cm}$. Such a large magnetic moment is still consistent with the direct experimental bound of $\mu_{\nu_e} \leq 4 \times 10^{-10} \mu_B$ [6], but the upper range is slightly inconsistent with the astrophysical arguments of $\mu_{\nu_e} \leq 8.5 \times 10^{-11} \mu_B$ [7]. However, in view of our very poor knowledge concerning magnetic fields inside the sun, the neutrino spin precession mechanism is still a viable solution to the ${}^{37}\text{Cl}$ data. Furthermore the claimed very stringent limit on the magnetic moment[8] set by the observation of SN1987A neutrinos may be evaded in several ways[9]. Forthcoming solar neutrino observations will provide a significant test on such time correlation, since the present solar activity is in transit from the minimum(~ 1986) to the maximum in 1991-1992.

In this timely period, it is worthwhile to test the mechanism of spin-precession by analysing the time variation of neutrino flux in both of the Kamiokande-II and the ${}^{37}\text{Cl}$ experiments. An interesting question is if there appears some difference in the behavior of time variation in these two experiments. We will see below that the presence of Majorana type magnetic moment of neutrinos really causes such different behavior.

Once neutrino interactions with matter within the solar interior are taken into account, the spin-precession shows a tendency to be suppressed[10,11,12]. In ref.[11], however, it was shown that the matter effect on the other hand enables to have the resonant enhancement of spin-flavor precessions like $\nu_{eL} \rightarrow \nu_{\mu R}$ or $\nu_{eL} \rightarrow \bar{\nu}_{\mu}$ ($(\nu_{\mu L})^c$ is referred to as $\bar{\nu}_{\mu}$), where not only the spin but also the flavor of neutrino changes. In addition, it should be noticed that the spin-flavor precession is only possible way of spin rotation in the case neutrinos have Majorana type magnetic moments, which have anti-symmetric flavor indices.

In this paper let us focus our attention on the interplay between solar neutrino flux and the solar magnetic fields for Majorana neutrinos, in the framework developed in ref.[11]. The possibility of detecting signals of anti-neutrinos produced by such Majorana magnetic moments is also addressed.

The main reason why only Majorana case is discussed is that only in this case we expect some remarkable difference in the variation of solar neutrino event rate in two kinds of experiments. In fact, we will expect similar time variation of solar neutrino flux in the two experiments provided neutrinos have Dirac type ($\Delta L = 0$, L : lepton number) magnetic moments. This is simply because the right-handed neutrinos produced through the magnetic moments are sterile any way, thus escaping the detection in both experiments. The detailed numerical analysis for Dirac neutrinos was already discussed in ref.[12]. For Majorana neutrinos, however, anti-neutrinos yielded through $|\Delta L| = 2$ (resonant) spin-flavor precessions, $\nu_{eL} \rightarrow \bar{\nu}_\mu$ (or $\bar{\nu}_e$ if mixing angle is sizable), are no longer sterile and contribute to the event rate in the Kamiokande-II detector, while the ^{37}Cl experiment fails to detect them. Table 1 summarizes the cross sections of neutrino scatterings inside water[13]. We find there that the cross section of inverse beta decay $\bar{\nu}_e p(\text{free}) \rightarrow e^+ n$ is almost 100 times larger than that of $\nu_e e^- \rightarrow \nu_e e^-$ for $E_\nu = 10$ MeV, while $\nu_e e^- \rightarrow \nu_e e^-$ and $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$ are dominant processes in elastic scatterings. Thus, if a large conversion rate of $\nu_e \rightarrow \bar{\nu}_e$ is realized for some range of neutrino parameters, some effects of such solar $\bar{\nu}_e$ flux in a water Cherenkov detector can be observed. It can also provide different time variation of solar neutrino flux in two experiments, whose confirmation would be a fascinating test about the type of neutrino, Majorana or Dirac.

We will work in a two generation model with Majorana type magnetic moment. There are potentially two possible routes for "effective" $\nu_e \rightarrow \bar{\nu}_e$ conversion (the direct transition due to magnetic moment does not exist for Majorana neutrino); One is $\nu_e \rightarrow \nu_\mu$ through the MSW matter oscillation and subsequently $\nu_\mu \rightarrow \bar{\nu}_e$ by μB . The other is $\nu_e \rightarrow \bar{\nu}_\mu$ by spin-flavor precession followed by $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ due to flavor mixing *à la* vacuum oscillation (the MSW resonance is not operative for anti-neutrinos). To examine the propagation of neutrinos in the sun, the evolution equation for ν_e , ν_μ , $\bar{\nu}_e$ and $\bar{\nu}_\mu$ [11],

$$i \frac{d}{dt} \begin{bmatrix} \nu_e \\ \nu_\mu \\ \bar{\nu}_e \\ \bar{\nu}_\mu \end{bmatrix} = \begin{bmatrix} a_{\nu_e} & \frac{\Delta m^2}{4E_\nu} \sin 2\theta & 0 & \mu B \\ \frac{\Delta m^2}{4E_\nu} \sin 2\theta & \frac{\Delta m^2}{2E_\nu} \cos 2\theta + a_{\nu_\mu} & -\mu B & 0 \\ 0 & -\mu B & -a_{\nu_e} & \frac{\Delta m^2}{4E_\nu} \sin 2\theta \\ \mu B & 0 & \frac{\Delta m^2}{4E_\nu} \sin 2\theta & \frac{\Delta m^2}{2E_\nu} \cos 2\theta - a_{\nu_\mu} \end{bmatrix} \begin{bmatrix} \nu_e \\ \nu_\mu \\ \bar{\nu}_e \\ \bar{\nu}_\mu \end{bmatrix}$$

was calculated numerically, making use of Runge-Kutta-Gill technique. The matter potentials a_{ν_e} and a_{ν_μ} experienced by ν_e and ν_μ are given by $G_F(2N_e - N_n)/\sqrt{2}$ and $G_F(-N_n)/\sqrt{2}$, respectively ($G_F = 1.16636 \times 10^{-5} \text{ GeV}^{-2}$ and N_f = the fermion number density). The same

density profiles of N_e and N_n as in ref. [11] were used. Free parameters in the present calculation are a mass difference (Δm^2), a mixing angle (θ), a Zeeman energy (μB); the product of a transition magnetic moment μ (thanks to the Majorana property only one moment is allowed) and the solar magnetic field (B) which is assumed to distribute uniformly over the radiation and convection zones in the sun. The vacuum oscillation outside the sun can be computed by the analytic formula of eq.(5.2) in ref. [14]. The calculation of the evolution equation covers the parameter ranges in $\Delta m^2 = (10^{-3} - 10^{-9}) \text{ eV}^2$ and $\sin^2 2\theta = (10^{-4} - 1)$.

One naively expect that spin-flavor precession like $\nu_e \rightarrow \bar{\nu}_\mu$ is effective only when the Zeeman energy overcome the energy level gap due to mass difference of neutrinos: $\mu B > \Delta m^2/2E_\nu$. This condition requires $\Delta m^2 < 10^{-8} \text{ eV}^2$ for $\mu = 10^{-10} \mu_B$, $B = 1 \text{ kG}$ and $E_\nu = 10 \text{ MeV}$. However, when the neutrino weak interaction with matter is switched on, it can compensate for the energy gap, thus making a resonant spin-flavor precession possible[11]. In fact, the present calculation shows that the conversion probability of ν_e to $\bar{\nu}_\mu$ which is given rise to by magnetic interactions becomes large in $\Delta m^2 < 10^{-6} \text{ eV}^2$. Therefore, for investigating the behavior of neutrino propagation, we pick up 3 oscillation points : (α) $\Delta m^2 = 10^{-6.5} \text{ eV}^2$, $\sin^2 2\theta = 0.1$, (β) $\Delta m^2 = 10^{-7.25} \text{ eV}^2$, $\sin^2 2\theta = 0.56$ and (γ) $\Delta m^2 = 10^{-9} \text{ eV}^2$, $\sin^2 2\theta = 1$. These three sets of parameters have been chosen so that expected solar neutrino fluxes for "average" solar magnetic field, $\mu_{10} B_1 = 1$ in units of ($10^{-10} \mu_B$) and (1 kG), are all consistent with the observed fluxes of (3 - 4) SNU in the ^{37}Cl and $\sim 50\%$ of SSM in the Kamiokande-II experiments in essentially the same data taking interval[3].

The propagation behaviors of $\nu_e, \nu_\mu, \bar{\nu}_e$ and $\bar{\nu}_\mu$ for parameters (α) and (β) are presented in figs. 1a and 1b. A large suppression of ν_e and enhancement of ν_μ due to the MSW effect are displayed in these figures. Just after the MSW resonance, some fractions of remained ν_e 's are converted to $\bar{\nu}_\mu$'s by a level crossing responsible for resonant spin-flavor precession in the outer region of the sun ($> 0.7 R_\odot$). The strength of this conversion (ν_e to $\bar{\nu}_\mu$) really depends on Δm^2 : about 4 % for $\Delta m^2 = 10^{-6.5} \text{ eV}^2$ (fig. 1a) and 12% for $\Delta m^2 = 10^{-7.25} \text{ eV}^2$ (fig. 1b). Figures also show that the successive appearance of $\bar{\nu}_e$ which is a main interest in our work comes from the vacuum oscillation of $\bar{\nu}_\mu$ to $\bar{\nu}_e$ outside the sun. Therefore, oscillation parameters with large mixing angles lead to a large fraction of $\bar{\nu}_e$, through a path $\nu_e \rightarrow \bar{\nu}_\mu \rightarrow \bar{\nu}_e$. Interestingly, no contribution from the other possible conversion process $\nu_e \rightarrow \nu_\mu \rightarrow \bar{\nu}_e$ is found in the surveyed parameter region of $\Delta m^2 = 10^{-3}$ to 10^{-9} eV^2 and $\sin^2 2\theta = 10^{-4}$ to 1. This is clearly the reflection of the fact that level crossing responsible for $\nu_\mu \rightarrow \bar{\nu}_e$ is absent inside the sun (see fig. 2 in ref.[11]). Thus, $\nu_e \rightarrow \bar{\nu}_\mu \rightarrow \bar{\nu}_e$ is effectively only possible way to get a large portion of $\bar{\nu}_e$.

In the Kamiokande-II experiment, neutrinos can be observed by detecting electrons from neutrino-electron elastic scatterings, $\nu_x(\bar{\nu}_x)e^- \rightarrow \nu_x(\bar{\nu}_x)e^-$ together with the informations of the neutrino arrival time, the direction and the energy spectrum. The solar neutrino flux is extracted from fitting the $\cos \theta_{Sun}$ distribution of electrons with a flat background plus expected angular distribution (peak at $\cos \theta_{Sun} = 1$) of the solar neutrino signals[3]. If the spin-flavor precession of neutrinos would be real effect, neutrinos $\nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$ converted from

ν_e make appreciable contributions to the elastic scattering peak in the $\cos \theta_{Sun}$ distribution, depending on their cross sections (see table 1) and energy distributions of electrons. The ^8B solar neutrino flux expected in the Kamiokande-II detector was calculated for oscillation parameters (α) , (β) and (γ) as a function of μB (fig. 2a), taking the Kamiokande-II detection efficiency for low energy electrons into account. The gross structure of fig. 2a tells that the spin-flavor precession effect becomes obvious in $\mu_{10}B_1 > 1$. The variation of solar neutrino flux is predicted to be from $\sim 50\%$ of the SSM to $(20-40)\%$ of the SSM, corresponding to the change of the magnitude of solar magnetic field by $\mu_{10}B_1 = 0.1 - 10$. A drastic reduction ($50\% \rightarrow 20\%$ of the SSM) by a factor of 2.5 is seen for a parameter (α) . However, only a factor of 1.3 reduction (50% to 40% of the SSM) is obtained for parameters (β) and (γ) . This is the consequence of the fact that, as is anticipated, a large $\bar{\nu}_e$ conversion from $\bar{\nu}_\mu$ through vacuum oscillation which is more dominant in parameters, (β) and (γ) than (α) , recovers considerably the event rate through $\bar{\nu}_e e \rightarrow \bar{\nu}_e e$.

Results of corresponding calculation for the ^{37}Cl experiment are shown in fig. 2b, where the event rates are those expected for the SSM with 7.9 SNU neutrino source. Although the way the event rates change as μB varies looks like similar to that in Kamiokande-II, relatively larger reduction rates, 4, 1.5 and 2 for (α) , (β) and (γ) respectively, are obtained for the change $\mu_{10}B_1 = 0.1 - 10$. Furthermore it should be noted that in general the event rates themselves are considerably smaller for large magnetic fields, $\mu_{10}B_1 \geq 5$, compared with those expected in Kamiokande-II; When normalized by the SSM prediction, the difference of event rate between Kamiokande-II and ^{37}Cl is 5% of the SSM for parameter (α) and 10% of the SSM for parameters (β) and (γ) . Such qualitative difference between two experiments stems from the fact that, for Majorana magnetic moment, converted anti-neutrinos do have elastic scattering on electrons. Thus if we get different time variations anti-correlated with solar activity in the two experiments in the same data taking interval, it would be a good indication of the Majorana property of neutrinos.

Another interesting possibility is to detect $\bar{\nu}_e$ via its inelastic scattering. To see the importance, we have calculated the event rates of $\bar{\nu}_e p(\text{free}) \rightarrow e^+ n$ reaction expected in the Kamiokande-II detector changing $\mu_{10}B_1$ from 0.1 to 50. The results are shown in fig. 3, where the event rates are normalized by the $\nu_e e^- \rightarrow \nu_e e^-$ event rate predicted from the ^8B solar neutrinos with full flux of the SSM. A sudden increment of a factor (8-15) is seen in strong magnetic fields of $\mu_{10}B_1 = 5 - 10$ for parameters (β) and (γ) ($\sin^2 \theta > 0.5$). Such a large event rate of $\bar{\nu}_e$ predicts possibilities to detect solar $\bar{\nu}_e$ events in Kamiokande-II. The isotropic angular distribution of positrons produced in $\bar{\nu}_e p(\text{free}) \rightarrow e^+ n$ reactions yields additional contribution over the background in the $\cos \theta_{Sun}$ distribution. Compared with the recent Kamiokande-II result concerning $\cos \theta_{Sun}$ distribution (fig.3 in ref. [15]), for instance about 2 times larger "combined" background level will be obtained provided the inelastic scattering event rate gains factor 10 enhancement compared with full SSM prediction. Finding time variation of background event level in the $\cos \theta_{Sun}$ distribution is one of evidences for the $\bar{\nu}_e$ flux from the sun.

More decisive evidence of solar $\bar{\nu}_e$ signals can be obtained from the energy distribution of positrons. The positron energy is determined by $E_\nu - (M_n - M_p)$, where M_n and M_p are neutron and proton mass. Therefore, positrons produced in $\bar{\nu}_e p(\text{free}) \rightarrow e^+ n$ reactions carry the original energy information of solar ν_e . This is in clear contrast with the nearly uniform energy distribution ($E_e < E_\nu$) of scattered electrons in $\nu_x(\bar{\nu}_x)e^- \rightarrow \nu_x(\bar{\nu}_x)e^-$ process. Energy distributions of these positrons for $(0.5 - 10) \mu_{10} B_1$ in the Kamiokande-II detector were calculated and are shown in figs. 4a, 4b, and 4c, corresponding to parameters $(\alpha), (\beta)$, and (γ) . For comparison the energy distribution of low energy events observed in Kamiokande-II (fig. 2 in ref. [15]) is also plotted in fig. 4. Here, the same event reducing factor due to the event selection cuts in Kamiokande-II was applied to extracting positron energy distributions. One can see clear bumps of $\bar{\nu}_e$ events overriding the Kamiokande-II data taken in the time period of June 1988 through April 1989[15] for parameter points $(\beta), (\gamma)$ and $\mu_{10} B_1 > 1$; namely for small ($\Delta m^2 < 10^{-7} \text{eV}^2$) and large mixing angle ($\sin^2 2\theta > 0.5$). If we see sunspot number data during 1988 - 1989, it is found that the solar activity of this time period is close to the minimum. Therefore, forthcoming Kamiokande-II energy distribution data give the chance to observe the solar $\bar{\nu}_e$ flux based on the resonant spin-flavor precession mechanism. Not just the increase of background events in the $\cos \theta_{Sun}$ distribution, but also the observation of time variation of bump in energy spectrum is the direct evidence of solar $\bar{\nu}_e$ flux. The Kamiokande-II experiment thus provides great opportunity to detect the (anti-) correlation between solar neutrino flux and solar magnetic field.

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Table Captions

Table 1 : Cross sections of low energy neutrinos off electrons and protons.

Figure Captions

- Fig. 1 :** Behavior how the probabilities of four neutrinos states to be observed change at each point inside the sun. All plots are for $E_\nu = 10$ MeV and $\mu B = 10^{-10} \mu_B \text{ kG}$. a) $\Delta m^2 = 10^{-6.5} \text{ eV}^2$ and $\sin^2 2\theta = 0.1$; b) $\Delta m^2 = 10^{-7.25} \text{ eV}^2$ and $\sin^2 2\theta = 0.56$; The solid, dotted, dash-dotted and dashed lines represent the ν_e , ν_μ , $\bar{\nu}_\mu$, and $\bar{\nu}_e$ probabilities.
- Fig. 2 :** Expected event rates of solar neutrinos as the functions of solar magnetic field, (a) in Kamiokande-II via $\nu_x(\bar{\nu}_x)e^- \rightarrow \nu_x(\bar{\nu}_x)e^-$, (b) in the ^{37}Cl experiment. The circle, square and diamond represent the oscillation parameter points of (α) , (β) , and (γ) described in the text.
- Fig. 3 :** $\bar{\nu}_e p(\text{free}) \rightarrow e^+ n$ event rate of solar $\bar{\nu}_e$ expected in the Kamiokande-II detector. The normalization of the event rate is described in the text. The circle, square and diamond means the same as in fig. 2.
- Fig. 4 :** Expected energy spectra of positrons from $\bar{\nu}_e p(\text{free}) \rightarrow e^+ n$ reactions in the Kamiokande-II detector for different solar magnetic field parameter of $\mu_{10} B_1$, (0.5 - 50). A solid line with data points represents the energy distribution of the Kamiokande-II low energy events[15]. a), b), and c) correspond to parameters of (α) , (β) , and (γ) described in the text.

Table 1

Cross sections of low energy neutrinos off electrons and protons.

reactions	cross sections (cm ²)
elastic scattering on electron	
$\nu_e e^- \rightarrow \nu_e e^-$	$(0.933 \times 10^{-43})[E_\nu/(10 \text{ MeV})]$
$\nu_\mu e^- \rightarrow \nu_\mu e^-$	$(0.159 \times 10^{-43})[E_\nu/(10 \text{ MeV})]$
$\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$	$(0.388 \times 10^{-43})[E_\nu/(10 \text{ MeV})]$
$\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-$	$(0.130 \times 10^{-43})[E_\nu/(10 \text{ MeV})]$
inverse β - decay	
$\bar{\nu}_e p \text{ (free)} \rightarrow e^+ n$	$(9.77 \times 10^{-42})[E_\nu/(10 \text{ MeV})]^2$

Fig. 1 : Behavior how the probabilities of four neutrinos states to be observed change at each point inside the sun. All plots are for $E_\nu = 10$ MeV and $\mu B = 10^{-10} \mu_B \text{ kG}$. a) $\Delta m^2 = 10^{-6.5} \text{ eV}^2$ and $\sin^2 2\theta = 0.1$; b) $\Delta m^2 = 10^{-7.25} \text{ eV}^2$ and $\sin^2 2\theta = 0.56$; The solid, dotted, dash-dotted and dashed lines represent the ν_e , ν_μ , $\bar{\nu}_\mu$, and $\bar{\nu}_e$ probabilities.

Fig. 2 : Expected event rates of solar neutrinos as the functions of solar magnetic field, (a) in Kamiokande-II via $\nu_x(\bar{\nu}_x)e^- \rightarrow \nu_x(\bar{\nu}_x)e^-$, (b) in the ^{37}Cl experiment. The circle, square and diamond represent the oscillation parameter points of (α) , (β) , and (γ) described in the text.

Fig. 3 : $\bar{\nu}_e p(\text{free}) \rightarrow e^+ n$ event rate of solar $\bar{\nu}_e$ expected in the Kamiokande-II detector. The normalization of the event rate is described in the text. The circle, square and diamond means the same as in fig. 2.

Fig. 4 : Expected energy spectra of positrons from $\bar{\nu}_e p(\text{free}) \rightarrow e^+ n$ reactions in the Kamiokande-II detector for different solar magnetic field parameter of $\mu_{10} B_1$, (0.5 - 50). A solid line with data points represents the energy distribution of the Kamiokande-II low energy events[15]. a), b), and c) correspond to parameters of (α) , (β) , and (γ) described in the text.