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The effect of random magnetic fields in solar neutrino spin-flavor precession

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We study the effect of random magnetic fields in the spin-flavor precession of solar neutrinos in a three generation context, when a non-vanishing transition magnetic moment is assumed. While this kind of precession is strongly constrained when the magnetic moment involves the first family, such constraints do not apply if we suppose a transition magnetic moment between the second and third families. In this scenario we can have a large non-electron anti-neutrino flux arriving on Earth, which can lead to some interesting phenomenological consequences, as, for instance, the suppression of day-night asymmetry. We have analyzed the high energy solar neutrino data and the KamLAND experiment to constrain the solar mixing angle, $\tan\theta_\odot$, and solar mass difference, $\Delta m^2_\odot$, and we have found a larger shift of allowed values.

1. Several years of solar neutrino observations [1]-[9] confirmed the Large Mixing Angle (LMA) realization of the MSW phenomenon as the explanation to the solar neutrino anomaly and rule out several other possible solutions to the solar neutrino problem based on exotic phenomena [10], like as the resonant spin-flip conversion [11]-[17] induced by neutrino interactions with solar magnetic fields through a non-vanishing neutrino magnetic moment.

Nevertheless exotic phenomena can generate sub-leading effects which are still allowed by present solar neutrino data. Such effects can add new features to this picture, in particular, changing the determination of the neutrino oscillation parameters. Examples of these sub-leading effects were analyzed in [18], where random fluctuations of solar matter were considered, or in [19, 20], where non-standard neutrino interactions induced a different determination of the oscillation parameters necessary for a solution to the solar neutrino anomaly. Here we study another possible sub-leading effect: the consequences of neutrino interaction with *random* solar magnetic fields through a non-vanishing magnetic moment [21].

The random magnetic scenario was previously studied [22]-[28] but always assuming a magnetic moment linking the electron neutrino with the muon and tau anti-neutrino families. This kind of assumption produces electron anti-neutrinos as a consequence of the spin-flavor precession, due the large mixing angles $\theta_\odot$ and θ_{atm}, the first one coming from solar neutrino analysis and the second one from atmospheric neutrino data. Since the solar electron anti-neutrino flux is strongly constrained by data [30, 31, 27, 32, 28], that analysis puts severe limits on the size of the spin-flavor conversion induced by magnetic moment. Recently also a limit for anti-non-electron neutrinos was quoted [17], but these limits are weak and does not impose any constrain in our analysis.

In this scenario, the spin-flavor precession is very small for typical values of magnetic field in the Sun. However, it was recently pointed out [27, 28] that random magnetic field could enhance this conversion. Consequently, stronger limits for the neutrino magnetic momentum μ was obtained, typically, $0.78 - 1.2 \times 10^{-10}\mu_B$ [28]

A conveniently chosen non-vanishing magnetic moment in the muon-tau sector leads to a very different scenario. Tau anti-neutrinos are produced through $\nu_\mu \to \bar{\nu}_\tau$ conversion, and assuming a vanishing mixing angle θ_{13}, the production of electron anti-neutrino is kept very small. The final solar neutrino flux can be a mixing of ν_e, ν_μ, ν_τ, $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$, which can have some interesting phenomenological consequences. The more direct one would be a correlation between the solar magnetic field and the proportion between the different neutrino families. Also the regeneration effect will be modified due to a different proportion of active neutrinos in the solar mass eigenstates, in analogy with the effect of a non-vanishing θ_{13} [29].

We analyze here the scenario where neutrinos interact with *random* solar magnetic fields trough a non-vanishing magnetic moment between muon and anti-tau-neutrinos as a sub-leading effect in the context of LMA solution to the solar neutrino anomaly. We combine the results of this analysis with the constrains coming from the KamLAND observations.

In order to appreciate the resulting modifications of these ideas on the LMA solution to the solar neutrino anomaly, we start working in a 6×6 matrix formalism, with $\nu = (\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau)^T$ where we include, besides the usual mass induced oscillation, magnetic moment terms between second and third families.

The system evolution can than be divided in two parts: first the simple MSW conversion in the production region of solar neutrinos, where we can take the formulas for the two families conversion, as presented, for instance, in [34]. For $r/R_{Sun} > 0.7$ the magnetic field starts to act on the system and then the conversion probabilities will depend of the neutrino magnetic momentum μ.

The random features will be introduced, following Ref [33], considering the relative size of coherent length of the magnetic field that we call L_0 and the neutrino oscillation length, $\lambda_\nu \equiv \pi \frac{4E}{\Delta m^2_{21}}$. The condition to have a decoupling between the LMA MSW oscillations and the spin-flip induced by random magnetic fields is defined as $\lambda_\nu >> L_0$. The random character can be written using the matrix density formalism $\rho_{ij} \equiv |\nu_i >< \nu_j|, i, j = 1, .., 3$ resulting, after some algebra detailed in Ref. [21]: $\rho_{11} = \rho_{22} = \rho_{33} = \rho_{44} = \rho_{55} = \rho_{66}/2 = \rho_{88}/3 = -2k, \rho_{38} = \rho_{83} = 2\sqrt{3}k$, where: $k =< (\mu \bar{B}_x)^2 > L_0 =< (\mu \bar{B}_y)^2 > L_0$, and $\bar{B}_{x,y}$ are the random components of the magnetic field, which we take to be proportional to the regular one, and L_0 is the coherence length of the random magnetic field.

To analyze if the values used for the parameter k are reasonable, we can write it in convenient units:

$$k = 1.710^{-17}\text{eV} \left[\frac{\mu}{10^{-11}\mu_B}\right]^2 \left[\frac{B}{1MG}\right]^2 \left[\frac{L_0}{1km}\right] \quad .$$

If we take the neutrino oscillation parameters from the best fit point of the standard solar neutrino analysis, $(\tan^2\theta_\odot, \Delta m^2_\odot) = (0.4, 8\times 10^{-5}\ \text{eV}^2)$, we have that the oscillation length for a 10 MeV neutrino is $\lambda_\nu \sim 200$ km.

Taking the marginal allowed value of $L_0 = 10$ km, in order to have $k = 10^{-14}$ eV, we should have $B \sim 10$ MG, which is hardly acceptable. Lower values of neutrino energy will decrease the neutrino oscillation length, making it more difficult to fulfill the necessary conditions. In this sense, the values of $k = 10^{-15}$ eV seems more feasible in a realistic scenario. From these considerations the range of k quantity is bounded to be between $10^{-15} < k < 10^{-14}$ eV.

2. The effect of the random magnetic field in the LMA region can be seen in Fig. 1. As the parameter k increases, the electronic survival probability decreases. This effect can be compensated by a higher value of neutrino mixing angle, moving the allowed region to the right in left panel of Fig. 1.

For larger values of k, all probabilities tend to $1/3$, with a weak dependence of the mixing angle. Since the Super-Kamiokande and SNO results are in accordance with this probability, in this scenario even maximal mixing is allowed. But also a interesting phenomenon occurs. Now a significant part of the total neutrino flux does not take part in regeneration effect in Earth. Actually, if we have exactly a equally equipartition of ν_e, ν_μ and $\bar{\nu}_\tau$ fluxes the regeneration effect vanishes, regardless of the neutrino mass difference Δm^2.

The right panel of Fig. 1 presents the KamLAND allowed regions, for 95% C.L., 99% C.L. and 3σ. Maximal

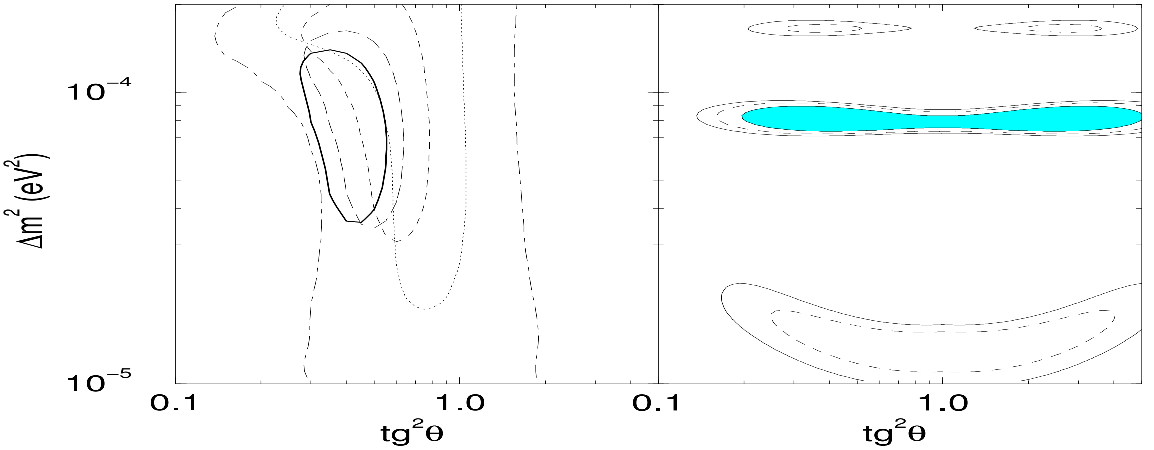

Figure 1. The LMA compatibility region for SNO+SK data (left panel) and the KamLAND allowed region (right panel). In left panel, the black line stands for no magnetic field, the long-dashed line for $k = 10^{-15.5}$ eV, the short-dashed line for $k = 10^{-15}$ eV, the dotted line for $k = 10^{-14.5}$ eV and the dot-dashed line for $k = 10^{-14}$ eV. In the right panel the allowed regions stands for 95% C.L., 99% C.L. and 3σ for respectively the filled, dashed and black curves.

mixing is allowed at 62.1% C.L., and low values of Δm^2 are still consistent with data at 99% C.L.. This last region is inconsistent with solar neutrino experiments because it predicts a too strong regeneration effect, not seen by data.

In the present context, the regeneration effect can be suppressed for large values of k. As a result, lower values of Δm^2 are allowed, and a new region of compatibility between solar and KamLAND data appears. In other contexts of non-standard neutrino physics [18, 20], we have called this region very-low LMA.

3. The results of our analysis of SNO+SK compatibility region indicate that in the presence of solar random magnetic fields the allowed region for Δm^2 becomes larger while higher values of θ_{12} are found.

This is a consequence of the fact that, in a three neutrino family context, an electron-neutrino survival probability of $P \sim 1/3$ is possible, even for $\tan^2\theta_{12} \sim 1$. In fact, when the random components of the solar magnetic field is large enough in such way that $k = 10^{-14}$ eV, values around $\Delta m^2 \approx 10^{-5}\mathrm{eV}^2$ are included in the region allowed by solar neutrino observations. Furthermore, different proportion of neutrinos and anti-neutrinos suppresses the regeneration effect of the solar neutrinos crossing the Earth matter. As a consequence, a totally new region of compatibility between solar neutrinos and KamLAND, which we call very-low LMA, appears at 99% C.L. for small values of $\Delta m^2_{21} \sim [1-2] \times 10^{-5}$ eV^2 and maximal mixing.

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