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New limits on neutrino magnetic moment through nonvanishing 13-mixing

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The relatively large value of the neutrino mixing angle θ_{13} set by recent measurements allows us to use solar neutrinos to set a limit on the neutrino magnetic moment involving the second and third flavor families, μ_{23} . The existence of a random magnetic field in the solar convective zone can produce a significant antineutrino flux when a nonvanishing neutrino magnetic moment is assumed. Even if we consider a vanishing neutrino magnetic moment involving the first family, electron antineutrinos are indirectly produced through the mixing between the first and third families and $\mu_{23} \neq 0$. Using KamLAND limits on the solar flux of electron antineutrino, we set the limit $\mu_{23} < 0.95 \times 10^{-11} \mu_B$ as a reasonable assumption on the behavior of solar magnetic fields. This is the first time that a limit on μ_{23} has been established in the literature directly from neutrino interactions with magnetic fields, and, interestingly enough, is comparable with the limits on the neutrino magnetic moment involving the first family and with the ones coming from modifications to the electroweak cross section.

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I. INTRODUCTION

In a recent paper [1] we performed an analysis of how a nonvanishing neutrino transition magnetic moment involving the second and third families, μ_{23} , could affect the flavor conversion of solar neutrinos. At that time we assumed a vanishing θ_{13} , which allowed to produce a large flux of nonelectronic antineutrinos, and our model was not limited by the absence of electron antineutrinos $\bar{\nu}_e$ in the solar neutrino flux, as required by KamLAND [2].

However, in that paper it was argued that a nonvanishing θ_{13} would open a channel for the production of electron antineutrinos, and thus a limit on μ_{23} could be established from the absence of a signal of $\bar{\nu}_e$ in the solar neutrino flux. Since recent data indicates a relatively large value for this angle, we examine such limits in light of these new measurements.

II. CONVERSION PROBABILITIES

To calculate the probability that an electron neutrino produced at the Sun evolves into an electron antineutrino in the presence of magnetic fields through a transition

magnetic moment, in principle we would have to work using a 6×6 evolution matrix formalism, involving $\nu_a = (\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau)^T$. But the system can be simplified in specific cases. For instance, in Ref. [1] we assumed a vanishing value for θ_{13} and a magnetic moment linking the second and third flavor families, and the system was decoupled into two 3×3 systems. All neutrino oscillations could only populate one of these systems, and the electron antineutrino was not produced. In the next subsection we will present the main analytical steps taken in Ref. [1], before presenting our analysis with new assumptions.

A. Vanishing θ_{13} and the magnetic moment between flavor families μ_{23}

In Ref. [1] we performed the following procedure to decouple the electron antineutrino flavor from the oscillation analysis. By rotating out the 23-mixing with the definition $\nu' = U_{23}^{-1} \nu$, the system was decoupled into two systems, which can be presented with a convenient reordering of eigenstates as

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu'_\mu \\ \bar{\nu}'_\tau \\ \bar{\nu}_e \\ \bar{\nu}'_\mu \\ \nu'_\tau \end{pmatrix} = \begin{pmatrix} [A] & 0 \\ 0 & [\tilde{A}] \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu'_\mu \\ \bar{\nu}'_\tau \\ \bar{\nu}_e \\ \bar{\nu}'_\mu \\ \nu'_\tau \end{pmatrix}, \quad (1)$$

where

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$$A = \begin{pmatrix} -\delta \cos 2\theta_{12} + V_{CC} + V_{NC} & \delta \sin 2\theta_{12} & 0 \\ \delta \sin 2\theta_{12} & \delta \cos 2\theta_{12} + V_{NC} & \mu_{23}B \\ 0 & \mu_{23}B & \Delta - V_{NC} \end{pmatrix} \quad (2)$$

and \tilde{A} is the same as A with a change of sign on matter potentials. Also, $\delta = \Delta m_{21}^2/4E$, $\Delta = (\Delta m_{32}^2 + \Delta m_{31}^2)/4E$, and V_{CC} and V_{NC} are the charged-current and neutral-current interaction potentials with matter.

Since all neutrinos in the Sun are produced as electron neutrinos and the two systems are completely decoupled, no $\bar{\nu}_e$'s were produced. For a regular magnetic field in the convective zone of the order of 100 kG and for magnetic moments of the order of $10^{-11} \mu_B$, we do not expect any transition to antineutrinos, since

$$\mu_{23}B \sim 5.8 \times 10^{-15} \text{ eV} \ll \Delta|_{E=10 \text{ MeV}} \sim 10^{-10} \text{ eV}. \quad (3)$$

However, random fluctuations of magnetic fields in the convective zone are expected and promote the population of antineutrino-state families [1]. This is implemented through symmetric entries in the Liouville equation, which induces decoherence, raising the $\nu \rightarrow \bar{\nu}$ conversion probability, as presented in Ref. [1] and reintroduced in the next section.

B. Nonvanishing θ_{13} and the magnetic moment between mass families μ_{23}

We currently cannot assume a vanishing θ_{13} , which was measured with a relatively large value [3–5]. Thus, we cannot decouple the system as in Ref. [1], and we have to solve the full 6×6 evolution equation. In this work, we will also slightly change our choice of magnetic moment by including it in the mass basis, μ_{23} , which is a more fundamental choice regarding nonstandard models.

Rotating out both mixing angles θ_{13} and θ_{23} , we obtain the following evolution matrix in the basis $\nu' = U_{13}^{-1}U_{23}^{-1}\nu$:

$$i \frac{d}{dt} \begin{pmatrix} \nu'_e \\ \nu'_\mu \\ \nu'_\tau \\ \bar{\nu}'_e \\ \bar{\nu}'_\mu \\ \bar{\nu}'_\tau \end{pmatrix} = \begin{pmatrix} H_{3 \times 3} & M \\ M & \bar{H}_{3 \times 3} \end{pmatrix} \begin{pmatrix} \nu'_e \\ \nu'_\mu \\ \nu'_\tau \\ \bar{\nu}'_e \\ \bar{\nu}'_\mu \\ \bar{\nu}'_\tau \end{pmatrix}, \quad (4)$$

where

$$H_{3 \times 3} = \begin{pmatrix} -\delta \cos 2\theta_{12} + V_{CC} + V_{NC} & \delta \sin 2\theta_{12} & -s_{13}c_{13}V_{CC} \\ \delta \sin 2\theta_{12} & \delta \cos 2\theta_{12} + V_{NC} & 0 \\ -s_{13}c_{13}V_{CC} & 0 & \Delta + V_{NC} \end{pmatrix}$$

and

$$M = \begin{pmatrix} 0 & 0 & s_{12}\mu_{23}B \\ 0 & 0 & c_{12}\mu_{23}B \\ s_{12}\mu_{23}B & c_{12}\mu_{23}B & 0 \end{pmatrix},$$

where $s_{13} = \sin \theta_{13}$ and $c_{13} = \cos \theta_{13}$, and $\bar{H}_{3 \times 3}$ is obtained from $H_{3 \times 3}$ by changing the sign of the matter potentials.

We proceed with the usual approximation done when θ_{13} is included in the solar neutrino analysis, which is to

disregard the terms proportional to $\sin \theta_{13}$ in the evolution equation, since for the entire solar neutrino evolution

$$s_{13}c_{13}V_{CC} \ll \Delta.$$

The third neutrino family is produced in solar nuclear reactions due to its mixing with the electron neutrino, but it evolves completely decoupled from the first two neutrino families.

Disregarding such a term in the evolution matrix and rearranging the neutrino families like in Eq. (1), we again obtain an equation identical to Eq. (1) but with $\nu_e \rightarrow \nu'_e$ and

$$A = \begin{pmatrix} -\delta \cos 2\theta_{12} + c_{13}^2 V_{CC} + V_{NC} & \delta \sin 2\theta_{12} & s_{12}\mu_{23}B \\ \delta \sin 2\theta_{12} & \delta \cos 2\theta_{12} + V_{NC} & c_{12}\mu_{23}B \\ s_{12}\mu_{23}B & c_{12}\mu_{23}B & \Delta - V_{NC} \end{pmatrix}, \quad (5)$$

which in the limit $\theta_{13} = 0$ is only different from Eq. (2) due to the fact that now we are considering a transition magnetic moment between mass eigenstates.

III. RESULTS

As in Ref. [1], we will assume that the magnetic field is composed of a regular part and a random part. Again, for a regular magnetic field we do not expect significant production of antineutrinos. However, assuming a random component of the magnetic field, antineutrinos can be produced through different channels.

Since we will have an initial flux of ν'_e and ν'_τ , we will have two channels of electron antineutrino production through the neutrino magnetic moment,

$$\nu'_e \rightarrow \bar{\nu}'_\tau, \quad (6)$$

$$\nu'_\tau \rightarrow \bar{\nu}'_e, \quad (7)$$

and the electron antineutrino conversion probability can be written as

$$P(\nu_e \rightarrow \bar{\nu}_e) = s_{13}^2 c_{13}^2 [P(\nu'_e \rightarrow \bar{\nu}'_\tau) + P(\nu'_\tau \rightarrow \bar{\nu}'_e)].$$

Writing the probability in terms of the probabilities in the Sun's convective and radiation zones and averaging out interference terms, we have

$$P(\nu_e \rightarrow \bar{\nu}_e) = s_{13}^2 c_{13}^2 \left[\sum_{i=1,2} P^{\text{rad}}(\nu'_e \rightarrow \nu_i) P^{\text{conv}}(\nu_i \rightarrow \bar{\nu}'_\tau) + P^{\text{conv}}(\nu_3 \rightarrow \bar{\nu}'_e) \right],$$

where we assumed that $P^{\text{rad}}(\nu'_e \rightarrow \nu_3) = 0$ and $P^{\text{conv}}(\nu'_\tau \rightarrow \nu_3) = 1$. Finally, since matter effects are negligible in the convective zone, we can replace

$$P^{\text{conv}}(\nu_3 \rightarrow \bar{\nu}'_e) = 1 - P^{\text{conv}}(\nu_1 \rightarrow \bar{\nu}'_\tau) - P^{\text{conv}}(\nu_2 \rightarrow \bar{\nu}'_\tau),$$

and after some rearrangement we obtain

$$P(\nu_e \rightarrow \bar{\nu}_e) = s_{13}^2 c_{13}^2 [1 - (1 - P^{\text{rad}}(\nu'_e \rightarrow \nu_1)) P^{\text{conv}}(\nu_1 \rightarrow \bar{\nu}'_\tau) - (1 - P^{\text{rad}}(\nu'_e \rightarrow \nu_2)) P^{\text{conv}}(\nu_2 \rightarrow \bar{\nu}'_\tau)].$$

KamLAND [2] sets the strongest limit on the electronic antineutrino flux from the Sun, given by $\phi(\bar{\nu}_e) < 3.7 \times 10^2 \text{ cm}^{-2} \text{ s}^{-1}$, which written in terms of a production probability and using the solar model [6] provides an antineutrino appearance probability limit of $P < 2.8 \times 10^{-4}$. Although using the neutrino flux predictions of new solar models (e.g., Ref. [7]) would slightly change this number, we will use it in the remainder of this paper in accordance with the KamLAND results.

Considering all recent measurements of $\sin^2 \theta_{13}$ [3–5], we will use a lower bound [8] of $\sin^2 \theta_{13} = 2.0 \times 10^{-2}$ in our analysis. This translates into a limit on antineutrino production of

$$P(\nu'_e \rightarrow \bar{\nu}'_\tau) + P(\nu'_\tau \rightarrow \bar{\nu}'_e) < 1.4 \times 10^{-2}. \quad (8)$$

To calculate the antineutrino production probability we follow the procedure presented in Ref. [1]. The probability is a function of the parameter

$$k = \langle (\mu B_\perp)^2 \rangle L_0, \quad (9)$$

where L_0 is a length scale related to the spatial coherence of the magnetic fluctuations. Rewriting k in convenient units, we have

$$k = 3.4 \times 10^{-17} \left[\frac{\mu}{10^{-11} \mu_B} \right]^2 \left[\frac{B}{100 \text{ kG}} \right] \left[\frac{L_0}{200 \text{ km}} \right] \text{ eV}. \quad (10)$$

To include the random magnetic fields with the same procedure, we should adapt the numerical codes used in Ref. [1] to the new supposition about the neutrino magnetic moment.

The Liouville equation can be written as

$$\frac{d\rho_\mu}{dt} = \sum_{\nu\alpha} (h_\nu f_{\nu\alpha\mu}) \rho_\alpha,$$

where $f_{\nu\alpha\mu}$ are the structure constants of the Gell-Mann matrices and h_ν are the components of the Hamiltonian when written as a combination of such matrices. Explicitly, these coefficients are written as

$$h_0 = \frac{\Delta}{\sqrt{6}} + \frac{V_{CC} + V_{NC}}{\sqrt{6}},$$

$$h_1 = \delta \sin 2\theta_{12},$$

$$h_3 = -\delta \cos 2\theta_{12} + \frac{V_{CC}}{2},$$

$$h_4 = s_{12} \mu_{23} B \cos \alpha, \quad h_5 = -s_{12} \mu_{23} B \sin \alpha,$$

$$h_6 = c_{12} \mu_{23} B \cos \alpha, \quad h_7 = -c_{12} \mu_{23} B \sin \alpha,$$

$$h_8 = -\frac{\Delta}{\sqrt{3}} + \frac{1}{2\sqrt{3}} (V_{CC} + 4V_{NC}),$$

and the evolution equation takes the form

$$\frac{d\rho}{dt} = \tilde{H}\rho$$

with

$$\tilde{H} = \begin{pmatrix} 0 & -2h_3 & 0 & -h_7 & +h_6 & -h_5 & +h_4 & 0 \\ +2h_3 & 0 & -2h_1 & -h_6 & -h_7 & +h_4 & +h_5 & 0 \\ 0 & +2h_1 & 0 & -h_5 & +h_4 & +h_7 & -h_6 & 0 \\ +h_7 & +h_6 & +h_5 & 0 & -h_3 - \sqrt{3}h_8 & 0 & -h_1 & +\sqrt{3}h_5 \\ -h_6 & +h_7 & -h_4 & +h_3 + \sqrt{3}h_8 & 0 & +h_1 & 0 & -\sqrt{3}h_4 \\ +h_5 & -h_4 & -h_7 & 0 & -h_1 & 0 & +h_3 - \sqrt{3}h_8 & +\sqrt{3}h_7 \\ -h_4 & -h_5 & +h_6 & +h_1 & 0 & -h_3 + \sqrt{3}h_8 & 0 & -\sqrt{3}h_6 \\ 0 & 0 & 0 & -\sqrt{3}h_5 & +\sqrt{3}h_4 & -\sqrt{3}h_7 & +\sqrt{3}h_6 & 0 \end{pmatrix}.$$

Following Ref. [1], we write the evolution equation in terms of averaging over multiple coherence lengths:

$$\langle h_i \rho_j \rangle = \langle h_i \rangle \langle \rho_j \rangle + \left\langle \left(\int_{t'}^{t'+\tau/2} h_i(t'') dt'' \right) \dot{\rho}_j(t') \right\rangle,$$

where $\langle \rangle$ means an averaging over t' in the range $t \pm \tau/2$, and $\tau \gg L_0$. Using the Liouville equation to replace $\dot{\rho}_j$ and keeping only terms proportional to B_x^2 or B_y^2 when doing the averaging, we obtain

$$\begin{aligned} \langle \dot{\rho}_1 \rangle &= (\dots) + \iint [-h_7(t'') \dot{\rho}_4(t') + h_6(t'') \dot{\rho}_5(t') - h_5(t'') \dot{\rho}_6(t') + h_4(t'') \dot{\rho}_7(t')] dt'' dt' \\ &= (\dots) + k[(-c_{12}^2 \rho_1 - s_{12} c_{12} \rho_3 - \sqrt{3} s_{12} c_{12} \rho_8) + (-c_{12}^2 \rho_1 - s_{12} c_{12} \rho_3 - \sqrt{3} s_{12} c_{12} \rho_8) \\ &\quad + (-s_{12}^2 \rho_1 + s_{12} c_{12} \rho_3 - \sqrt{3} s_{12} c_{12} \rho_8) + (-s_{12}^2 \rho_1 + s_{12} c_{12} \rho_3 - \sqrt{3} s_{12} c_{12} \rho_8)] \\ &= (\dots) + k[-2\rho_1 - 2\sqrt{3} \sin 2\theta_{12} \rho_8], \end{aligned}$$

$$\begin{aligned} \langle \dot{\rho}_2 \rangle &= (\dots) + \iint [-h_6(t'') \dot{\rho}_4(t') - h_7(t'') \dot{\rho}_5(t') + h_4(t'') \dot{\rho}_6(t') + h_5(t'') \dot{\rho}_7(t')] dt'' dt' \\ &= (\dots) + k[(-c_{12}^2 \rho_2) + (-c_{12}^2 \rho_2) + (-s_{12}^2 \rho_2) + (-s_{12}^2 \rho_2)] \\ &= (\dots) - 2k\rho_1, \end{aligned}$$

$$\begin{aligned} \langle \dot{\rho}_3 \rangle &= (\dots) + \iint [-h_5(t'') \dot{\rho}_4(t') + h_4(t'') \dot{\rho}_5(t') + h_7(t'') \dot{\rho}_6(t') - h_6(t'') \dot{\rho}_7(t')] dt'' dt' \\ &= (\dots) + k[(-s_{12} c_{12} \rho_1 - s_{12}^2 \rho_3 - \sqrt{3} s_{12}^2 \rho_8) + (-s_{12} c_{12} \rho_1 - s_{12}^2 \rho_3 - \sqrt{3} s_{12}^2 \rho_8) \\ &\quad + (+s_{12} c_{12} \rho_1 - c_{12}^2 \rho_3 + \sqrt{3} c_{12}^2 \rho_8) + (+s_{12} c_{12} \rho_1 - c_{12}^2 \rho_3 + \sqrt{3} c_{12}^2 \rho_8)] \\ &= (\dots) + k[-2\rho_3 + 2\sqrt{3} \cos 2\theta_{12} \rho_8], \end{aligned}$$

$$\begin{aligned} \langle \dot{\rho}_8 \rangle &= (\dots) + \iint [-\sqrt{3} h_5(t'') \dot{\rho}_4(t') + \sqrt{3} h_4(t'') \dot{\rho}_5(t') - \sqrt{3} h_7(t'') \dot{\rho}_6(t') + \sqrt{3} h_6(t'') \dot{\rho}_7(t')] dt'' dt' \\ &= (\dots) + k\sqrt{3}[(-s_{12} c_{12} \rho_1 - s_{12}^2 \rho_3 - \sqrt{3} s_{12}^2 \rho_8) + (-s_{12} c_{12} \rho_1 - s_{12}^2 \rho_3 - \sqrt{3} s_{12}^2 \rho_8) \\ &\quad + (-s_{12} c_{12} \rho_1 + c_{12}^2 \rho_3 - \sqrt{3} c_{12}^2 \rho_8) + (-s_{12} c_{12} \rho_1 + c_{12}^2 \rho_3 - \sqrt{3} c_{12}^2 \rho_8)] \\ &= (\dots) + k[-2\sqrt{3} \sin 2\theta_{12} \rho_1 + 2\sqrt{3} \cos 2\theta_{12} \rho_3 - 6\rho_8]. \end{aligned}$$

Again, families 4–7 decouple when we disregard the contribution of regular magnetic fields in the evolution equation, and we can write

$$\frac{d}{dt} \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \\ \rho_8 \end{pmatrix} = \begin{pmatrix} -2k & -2h_3 & 0 & -2\sqrt{3} \sin 2\theta_{12}k \\ 2h_3 & -2k & -2h_1 & 0 \\ 0 & 2h_1 & -2k & 2\sqrt{3} \cos 2\theta_{12}k \\ -2\sqrt{3} \sin 2\theta_{12}k & 0 & 2\sqrt{3} \cos 2\theta_{12}k & -6k \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \\ \rho_8 \end{pmatrix}.$$

We solved the evolution equation numerically. In Fig. 1 we present the conversion probability of antineutrinos together with the limits on this probability that can be inferred from KamLAND data and the measured values of θ_{13} , as presented in Eq. (8). The parameter region where the antineutrino production probability is larger than the KamLAND limit is excluded.

From Fig. 1 we can extract a limit on k ,

$$k < 3 \times 10^{-17} \text{ eV}, \quad (11)$$

which from Eq. (10) leads to the following limit on the magnetic field parameters:

$$\left[\frac{\mu}{10^{-11} \mu_B} \right]^2 \left[\frac{B}{100 \text{ kG}} \right] \left[\frac{L_0}{200 \text{ km}} \right] \text{ eV} < 0.9. \quad (12)$$

For a reasonable assumption on the magnetic field profile—i.e., a 100 kG regular magnetic field with random fluctuations proportional to the regular one—and a 200 km coherent length scale for such fluctuations, we translate this limit to

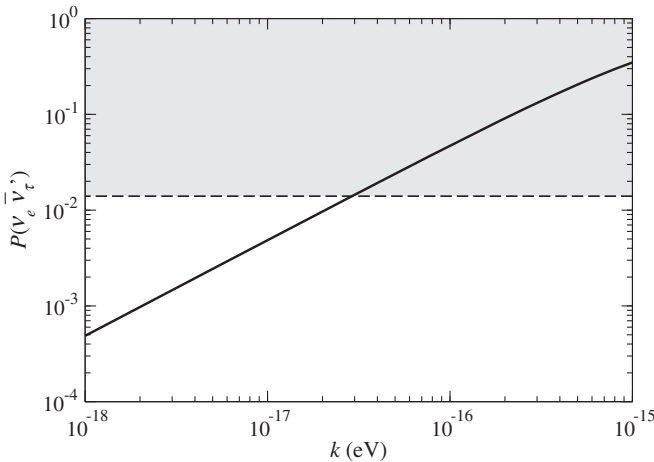


FIG. 1. Here we compare the KamLAND limits on antineutrino production with the predictions of such production in our model. The solid line corresponds to the antineutrino production probability in the Sun, with the assumption of a vanishing θ_{13} . The dashed line corresponds to the limits set by KamLAND on the solar electronic antineutrino flux, converted to a limit on the nonelectronic antineutrino probability conversion, using $\sin^2 \theta_{13} = 0.02$ (1σ) [8].

$$\mu_{23} < 9.5 \times 10^{-12} \mu_B. \quad (13)$$

Previous works obtained similar limits on the neutrino magnetic moment, based on an induced spin-flavor transition of the solar neutrino flux; see, for instance, Refs. [9–13]. A nonvanishing neutrino magnetic moment involving the electron family was always assumed, and a two-family neutrino analysis was performed. (An exception is Ref. [11], where a three-family analysis was presented in the appendix, but whose effects can be disregarded if all magnetic moments terms are of the same order. This is precisely the assumption that we do not make here.)

Also, solar neutrino experiments obtained a limit on the neutrino magnetic moment coming from modifications of the neutrino electroweak cross section. For instance, the GEMMA experiment [14]—which uses a reactor antineutrino flux and analyzes the recoil electron spectra produced from the detection of such an antineutrino flux—has established the limit $\mu_\nu < 2.9 \times 10^{-11} \mu_B$. The experiments Super-Kamiokande [15] and Borexino [16] obtained limits of $\mu_\nu < 1.1 \times 10^{-10} \mu_B$ and $\mu_\nu < 5.4 \times 10^{-11} \mu_B$, respectively, by analyzing the spectrum of the solar neutrino flux, which applies for a combination of all neutrino magnetic moment elements. Analyses of such limits in conjunction with different sets of data can be found in Refs. [17–19].

Recently, Borexino [20] expanded the analysis presented in Ref. [16] to include Phase-II solar neutrino data, and quoted distinct limits for different magnetic moments terms, which can be directly compared with ours. The limit on the effective magnetic moment is $\mu_{\text{eff}} < 2.8 \times 10^{-11} \mu_B$ which—using the best-fit points for oscillation parameters—can be translated to individual limits on μ_{ij} by the relation [21]

$$\mu_{\text{eff}}^2 = \{\mu_{12}^2 + 0.678\mu_{13}^2\} + 0.314\mu_{23}^2 < (2.8 \times 10^{-11} \mu_B)^2, \quad (14)$$

which leads to $|\mu_{23}| < 5.0 \times 10^{-11} \mu_B$.

To make it explicit that our limit has a different nature from the above, in Fig. 2 we present the combined limit obtained by Borexino superimposed onto ours. It is clear that our limit and Borexino's are complementary and exclude different regions of the parameter space.

The strongest limits on neutrino magnetic moments still come from astrophysical considerations. For instance, the authors of Ref. [22] reported

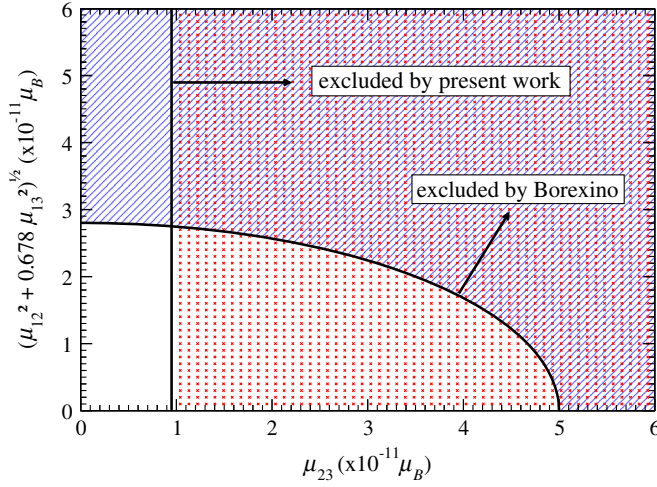


FIG. 2. Limits on μ_{eff} established by Borexino, superimposed on our limit for μ_{23} . We plot the effective transition magnetic moment involving the first family [the term in brackets in Eq. (14)] and μ_{23} on the vertical and horizontal axis, respectively.

$$\mu_\nu < 3 \times 10^{-12} \mu_B.$$

A detailed review of all of these analysis can be found in Refs. [23,24], and a complete review on the neutrino electromagnetic properties can be found in Ref. [25].

Although our limit is more stringent than the ones established from modifications of the neutrino cross section and is comparable to the astrophysical one, it is a combined limit of the neutrino magnetic moment with both the solar magnetic field profile and the characteristics of its random fluctuations. We thus present such a limit as a

complementarity approach to the previous ones, which all point to an absence of evidence for a nonvanishing neutrino magnetic moment.

IV. CONCLUSIONS

In this work, we set a limit on the neutrino transition magnetic moment involving the second and third families, μ_{23} , using solar neutrino data and assuming a specific profile for the solar magnetic field. For a vanishing mixing angle θ_{13} we could only set loose bounds on such a magnetic moment due to the electron antineutrino flavor decoupling in the neutrino evolution equation. With a reasonably high measured value for such an angle, a stringent limit was established for the first time from the direct interaction of neutrinos with magnetic fields, and under the assumption that all other neutrino magnetic moments are null. The limits we obtained are of the same order of the magnitude as the limits involving the first neutrino family and the limits coming from modifications to the electroweak cross section and astrophysics.

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