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New limits on neutrino magnetic moments from low energy neutrino data

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Abstract.

Here we give a brief review on the current bounds on the general Majorana transition neutrino magnetic moments (TNMM) which cover also the conventional neutrino magnetic moments (NMM). Leptonic CP phases play a key role in constraining TNMMs. While the Borexino experiment is the most sensitive to the TNMM magnitudes, one needs complementary information from reactor and accelerator experiments in order to probe the complex CP phases.

1. Introduction

The study of neutrino electromagnetic properties is of great importance, since it could open a new window to investigate physics beyond the Standard Model. Though there are various types of electromagnetic properties [1, 2], such as a neutrino charge radius [3, 4, 5, 6] or a neutrino milli-charge [7, 8], here we concentrate on the case of TNMM [9, 10, 11]. These are appealing for several reasons. For instance, like neutrinoless double beta decay [12], TNMMs can shed light on the fundamental issue of the Dirac or Majorana nature of neutrinos [9, 10, 11]. They are also expected to be calculable in a gauge theory, their finite values given in terms of fundamental neutrino properties, such as masses and mixing parameters, in addition to other genuine new physics parameters such as new messenger particle masses. The main constraints on neutrino electromagnetic properties come from reactor neutrino studies [13, 14] as well as from solar neutrino data [15, 16]. There are, moreover, many proposals aiming to improve the current bounds, one of them using a megacurie ⁵¹Cr neutrino source and a large liquid Xenon detector [17]. Based on the analysis reported in [18], we summarize some of the most relevant constraints on TNMM and discuss their dependence on the CP phases.

We include different types of neutrino data samples, such as the most recent data from the TEXONO reactor experiment [14], as well as the latest results from the Borexino experiment [19]. Data from the reactor experiments Krasnoyarsk [20], Rovno [21] and MUNU [22] along with the accelerator experiments LAMPF [23] and LSND [24] are also included. In addition, we take into account the updated values of the neutrino mixing parameters as determined in global oscillation fits [25], including the value of θ_{13} implied by Daya-Bay [26] and RENO [27] reactor data, as



well as accelerator data [28]. Besides, we stress on the role played by the, yet unknown, leptonic CP violating phases.

2. Neutrino magnetic moments

The interaction between Majorana neutrinos and the electromagnetic field is described by the general effective Hamiltonian [9]

$$H_{em}^M = -\frac{1}{4}\nu_L^T C^{-1} \lambda \sigma^{\alpha\beta} \nu_L F_{\alpha\beta} + h.c., \quad (1)$$

with $\lambda = \mu - id$ a complex antisymmetric matrix in generation space, implying that $\mu^T = -\mu$ and $d^T = -d$ are pure imaginary. Therefore, we need six real parameters to describe the Majorana NMM. The Majorana NMM matrix can be written in the flavor (mass) basis, λ ($\tilde{\lambda}$), as follows

$$\lambda = \begin{pmatrix} 0 & \Lambda_\tau & -\Lambda_\mu \\ -\Lambda_\tau & 0 & \Lambda_e \\ \Lambda_\mu & -\Lambda_e & 0 \end{pmatrix}, \quad \tilde{\lambda} = \begin{pmatrix} 0 & \Lambda_3 & -\Lambda_2 \\ -\Lambda_3 & 0 & \Lambda_1 \\ \Lambda_2 & -\Lambda_1 & 0 \end{pmatrix}. \quad (2)$$

Here we have defined $\lambda_{\alpha\beta} = \varepsilon_{\alpha\beta\gamma} \Lambda_\gamma$, through the complex parameters: $\Lambda_\alpha = |\Lambda_\alpha| e^{i\zeta_\alpha}$, $\Lambda_i = |\Lambda_i| e^{i\zeta_i}$. Having described our theoretical framework, we now discuss the relation of these observables with the parameters measured in current neutrino experiments. For neutrino-electron scattering, the differential cross section for the NMM contribution will be given by

$$\left(\frac{d\sigma}{dT}\right)_{em} = \frac{\pi\alpha^2}{m_e^2 \mu_B^2} \left(\frac{1}{T} - \frac{1}{E_\nu}\right) \mu_\nu^2, \quad (3)$$

where μ_ν is an effective magnetic moment accounting for the NMM contribution to the scattering process. It is defined in terms of the components of the NMM matrix in Eq. (2). In the flavor basis, this parameter can be written as [16]

$$(\mu_\nu^F)^2 = a_-^\dagger \lambda^\dagger \lambda a_- + a_+^\dagger \tilde{\lambda} \tilde{\lambda}^\dagger a_+, \quad (4)$$

where we have denoted the negative and positive helicity neutrino amplitudes by a_- and a_+ , respectively. The flavour and mass neutrino basis are connected through the neutrino mixing matrix U

$$\tilde{a}_- = U^\dagger a_-, \quad \tilde{a}_+ = U^T a_+, \quad \tilde{\lambda} = U^T \lambda U, \quad (5)$$

such that the effective NMM in the mass basis is given by

$$(\mu_\nu^M)^2 = \tilde{a}_-^\dagger \tilde{\lambda}^\dagger \tilde{\lambda} \tilde{a}_- + \tilde{a}_+^\dagger \tilde{\lambda} \tilde{\lambda}^\dagger \tilde{a}_+. \quad (6)$$

Notice that there are six complex phases in the effective NMM parameter: ζ_1 , ζ_2 and ζ_3 from the NMM matrix; δ and two-Majorana phases from the leptonic mixing matrix. However, as noticed in Ref. [29], it is clear that only three of these six complex phases are independent. To carry out our analysis [18], we choose the Dirac CP phase δ , and the two relative phases, $\xi_2 = \zeta_3 - \zeta_1$ and $\xi_3 = \zeta_2 - \zeta_1$.

In reactor experiments, we initially have only an electron antineutrino flux and, therefore, $a_+^1 = 1$ will be the only nonzero entry. With this initial condition, we get from Eq. (4) the following expression for the effective Majorana NMM for reactor antineutrino experiments in the flavor basis:

$$(\mu_R^F)^2 = |\Lambda_\mu|^2 + |\Lambda_\tau|^2. \quad (7)$$

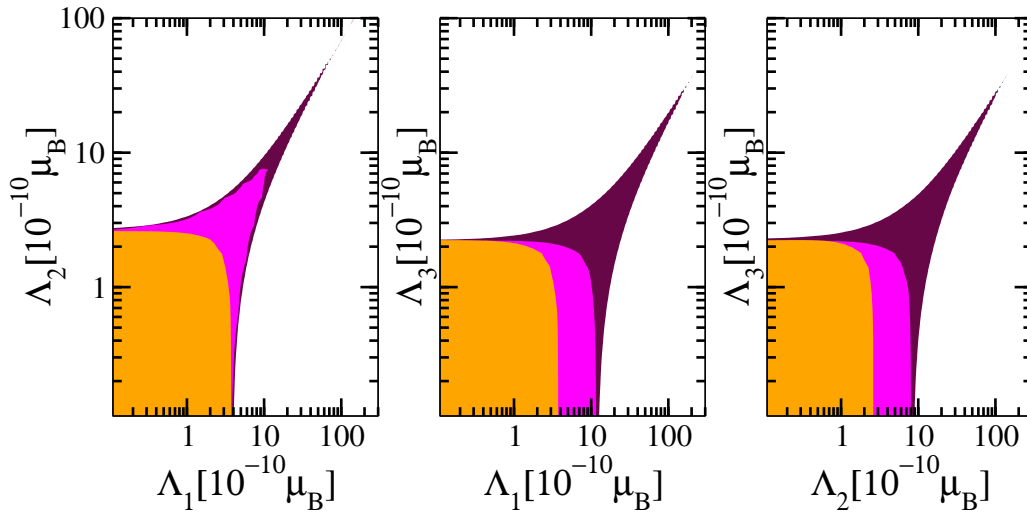


Figure 1. Allowed regions for the TNMM, at 90 % CL, obtained from TEXONO data. The two-dimensional regions ($|\Lambda_i|$, $|\Lambda_j|$) have been computed by marginalizing over the third component, $|\Lambda_k|$. For the purple (outer) region we have fixed the phases to be $\delta = 0$ and $\xi_2 = \xi_3 = 0$ (see Eq. (9)), while in the magenta (middle) region we have set $\delta = 3\pi/2$ and $\xi_2 = \xi_3 = 0$. The orange (inner) region corresponds to $\delta = 3\pi/2$, $\xi_2 = 0$ and $\xi_3 = \pi/2$.

On the other hand, for the mass basis, we have the expression

$$\begin{aligned}
 (\mu_R^M)^2 &= |\mathbf{\Lambda}|^2 - s_{12}^2 c_{13}^2 |\Lambda_2|^2 - c_{12}^2 c_{13}^2 |\Lambda_1|^2 - s_{13}^2 |\Lambda_3|^2 \\
 &\quad - 2s_{12}c_{12}c_{13}^2 |\Lambda_1||\Lambda_2| \cos \delta_{12} - 2c_{12}c_{13}s_{13} |\Lambda_1||\Lambda_3| \cos \delta_{13} \\
 &\quad - 2s_{12}c_{13}s_{13} |\Lambda_2||\Lambda_3| \cos \delta_{23},
 \end{aligned} \tag{8}$$

with $c_{ij} = \cos \theta_{ij}$, $s_{ij} = \sin \theta_{ij}$. The phases in this equation depend on the three independent CP phases already mentioned: $\delta_{12} = \xi_3$, $\delta_{23} = \xi_2 - \delta$, and $\delta_{13} = \delta_{12} - \delta_{23}$. The dependence on these CP phases is very interesting and adds an extra complexity to the interpretation of the experimental constraints. For instance, in the particular case where all the independent phases vanish, i.e. $\delta_{12} = \delta_{23} = \delta_{13} = 0$, the effective Majorana NMM in Eq. (8) is given by

$$(\mu_R^M)^2 = |\mathbf{\Lambda}|^2 - (c_{12}c_{13}|\Lambda_1| + s_{12}c_{12}c_{13}|\Lambda_2| + s_{13}|\Lambda_3|)^2. \tag{9}$$

It is easy to notice that if we also impose the conditions

$$|\Lambda_1| = c_{12}c_{13}|\mathbf{\Lambda}|, \quad |\Lambda_2| = s_{12}c_{13}|\mathbf{\Lambda}|, \quad |\Lambda_3| = s_{13}|\mathbf{\Lambda}|, \tag{10}$$

$(\mu_R^M)^2$ cancels exactly and, hence, in this case reactor experiments would not be sensitive to this parameter. This is illustrated in Fig. 1.

A similar situation will appear in accelerator experiments such as the LAMPF [23] and LSND [24], where a dependence on the CP phases will appear [18].

On the other hand, in solar neutrino experiments like Borexino [19], the effective NMM parameter in the mass basis is given by

$$(\mu_{\text{sol}}^M)^2 = |\mathbf{\Lambda}|^2 - c_{13}^2 |\Lambda_2|^2 + (c_{13}^2 - 1) |\Lambda_3|^2 + c_{13}^2 P_{e1}^{2\nu} (|\Lambda_2|^2 - |\Lambda_1|^2), \tag{11}$$

where we have defined the effective two-neutrino oscillation probabilities as $P_{e1,e2}^{2\nu}$. Due to the loss of coherence, the effective NMM measured from the solar neutrino flux is independent of any phase, a fact already noticed in [16]. Notice also that the analysis presented here takes into account the non-zero value of the reactor angle θ_{13} [18].

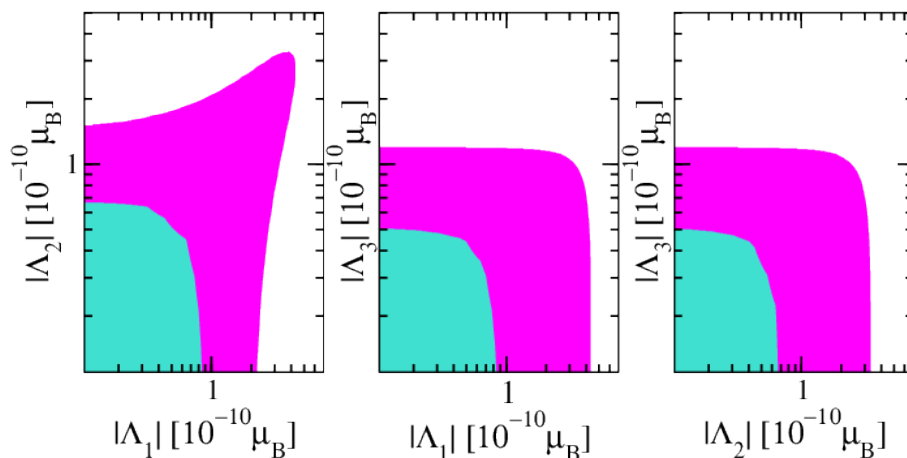


Figure 2. Allowed regions, at 90 % CL, for the TNMM [18]. The magenta region shows the constraints from reactor and accelerator data when all the phases vanish, except for $\delta = 3\pi/2$. The turquoise zone shows the corresponding bounds from the Borexino data that are phase-independent.

3. Analysis of the neutrino data

We perform a combined analysis of the experimental data in order to get constraints for the three different TNMM components Λ_i . In order to carry out the statistical analysis we use the following χ^2 function:

$$\chi^2 = \sum_{i=1}^{N_{bin}} \left(\frac{O^i - N^i(\mu)}{\Delta_i} \right)^2, \quad (12)$$

where O^i and N^i are the observed number of events and the predicted number of events in the presence of an effective NMM, μ , at the i -th bin, respectively. Here Δ_i is the statistical error for each bin. In our analysis, we have included the experimental results reported by Krasnoyarsk [20], Rovno [21], MUNU [22], and TEXONO [14] reactor experiments. We have also included the experimental data reported by the LAMPF [23] and LSND [24] collaborations, as well as the most recent measurements of the Beryllium solar neutrino flux reported in Ref. [19] by Borexino.

We perform a complete analysis taking into account the role of the CP phases in the reactor and accelerator data. For the particular case of reactor neutrinos, we have carried out a statistical analysis of TEXONO data [14] taking different values of the complex phases of Λ_i , ζ_i , and taking all nonzero TNMM amplitudes. The result of this analysis is shown in Fig. 1. Notice that the resulting restrictions on the TNMM $|\Lambda_1|$ and $|\Lambda_2|$ depend on the chosen CP phase combinations.

Finally, we carried out a combined analysis [18] of all the reactor and accelerator data for a particular choice of phases ($\delta = 3\pi/2$ and $\xi_i = 0$) and compared it with the corresponding χ^2 analysis obtained from the Borexino data. The results, shown in Fig. 2, illustrate how Borexino [19] is more sensitive in constraining the magnitude of the TNMM. We stress that the Borexino effective NMM depends only on the square magnitudes of these TNMM and hence, its constraints are almost the same as those in the one-parameter-at-a-time analysis. On the other hand, future reactor and accelerator experiments are the only ones that could give information on individual TNMMs as well as on the Majorana phases discussed here, an information inaccessible to the Borexino experiment.

4. Conclusions

In this short review, we have discussed the current status of the bounds on the transition neutrino magnetic moments. These parameters are very important, because they encode the Majorana CP phases present both in the mixing matrix and in the NMM matrix. The conventional neutrino magnetic moment emerges as a particular effective case. The Borexino solar experiment plays a key role in constraining the electromagnetic neutrino properties due to the low energies (below 1 MeV) which are probed as well as its robust statistics. Indeed, it provides the most stringent constraints on the absolute magnitude of the transition magnetic moments. However, the Borexino experiment can not probe the Majorana phases, due to the incoherent nature of the solar neutrino flux. Although less sensitive to the absolute value of the transition magnetic moment strengths, reactor and accelerator experiments provide the only chance to obtain a hint of the complex CP phases, as illustrated in Fig. 1.

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