New limits on neutrino magnetic moments

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Outline

1. Motivation
2. Formalism
3. Limits
4. Future proposals
5. Conclusions

Based on B.C. Cañas, OGM, A. Parada, M. Tortola, J.W.F. Valle
PLB **753** 191 (2016) and Add. PLB **757** 568 (2016).

Electromagnetic interactions

In a minimal extension of the Standard Model the neutrino magnetic moment is expected to be very small:

$$\mu_\nu = 3.2 \times 10^{-19} \left(\frac{m_\nu}{1eV} \right) \mu_B$$

B.W. Lee, R.E. Shrock, PRD **16** 1444 (1977)
W. Marciano, A. I. Sanda PLB **67** 303 (1977)

Electromagnetic interactions

- Charged scalar singlet

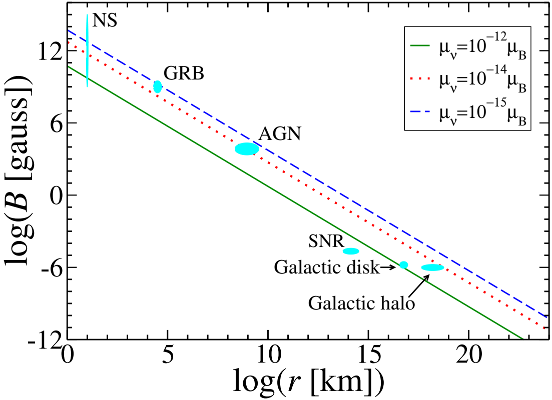
$$\mu_{ij} = e \sum_k \frac{f_{ki} g^\dagger_{kj} + g_{ik} f^\dagger_{kj}}{32\pi^2} \frac{m_{l\,k}}{m^2{}_\eta} \left(\ln \frac{m_\eta^2}{m_{l\,k}^2} - 1 \right) .$$

M. Fukugita, T. Yanagida PRL **58** (1987) 1807

- Charged scalars plus additional simmetries

$$\mu_{\alpha\beta} = e \frac{ff'}{8\pi^2} \frac{m_\tau}{m_\eta^2} \ln \frac{m_\eta^2}{m_\tau^2}$$

R. Barbieri, R. N. Mohapatra PLB **218** 225 (1989) K.S. Babu, R.N. Mohapatra PRL **63** (1989) 228



J. Barranco, OGM, Moura, Parada, PLB **718** 26 (2012)

S. Hummer, M. Maltoni, W. Winter, C. Yaguna, Astropart. Phys. **34** 205 (2010)

A.M. Hillas, Ann. Rev. Astron. Astrophys. **22** 425 (1984)

Electromagnetic interactions

- SN 1987A

$$\mu_\nu \leq 1 \times 10^{-12} \mu_B$$

R. Barbieri, R.N. Mohapatra, PRL **61** (1988) 27 A. Ayala, J.C. D'Olivo, M. Torres, PRD **59** (1999)111901

- Red giant luminosity

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

G.G. Raffelt PRL **64** (1990) 2856

See also the review: C. Giunti, A. Studenikin RMP **87** (2015) 531

Majorana neutrinos

$$\mathcal{H}^{M}_{em} = -\frac{1}{4}\nu_L^T C^{-1}\,(\mu - i d\gamma_5)\,\sigma^{\alpha\beta}\nu_L F_{\alpha\beta} = -\frac{1}{4}\nu_L^T C^{-1}\,\lambda\,\sigma^{\alpha\beta}\nu_L F_{\alpha\beta} + h.c.,$$

$$\mu^T = -\mu, \qquad d^T = -d$$

J. Schechter and J. W. F. Valle, PRD **24** 1883 (1981)

P. B. Pal and L. Wolfenstein, Phys. Rev. D25, 766 (1982)

B. Kayser, Phys.Rev. D26, 1662 (1982)

J. F. Nieves, Phys. Rev. D26, 3152 (1982)

The above discussion could be translated into a more phenomenological approach in which the NMM is described by a complex matrix $\lambda = \mu - id$ ($\tilde{\lambda}$) in the flavor (mass) basis, that for the Majorana case takes the form

$$\lambda = \begin{pmatrix} 0 & \Lambda_\tau & -\Lambda_\mu \\ -\Lambda_\tau & 0 & \Lambda_e \\ \Lambda_\mu & -\Lambda_e & 0 \end{pmatrix}, \qquad \tilde{\lambda} = \begin{pmatrix} 0 & \Lambda_3 & -\Lambda_2 \\ -\Lambda_3 & 0 & \Lambda_1 \\ \Lambda_2 & -\Lambda_1 & 0 \end{pmatrix},$$

where $\lambda_{\alpha\beta} = \varepsilon_{\alpha\beta\gamma}\Lambda_\gamma$.

The transition magnetic moments Λ_α and Λ_i are complex parameters:

$$\Lambda_\alpha = |\Lambda_\alpha| e^{i\zeta_\alpha}, \qquad \Lambda_i = |\Lambda_i| e^{i\zeta_i}.$$

W. Grimus, T. Schwetz, NPB **587** 45 (2000)

Neutrino-electron scattering

The electromagnetic contribution is given by

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

where μ_ν is an effective magnetic moment.

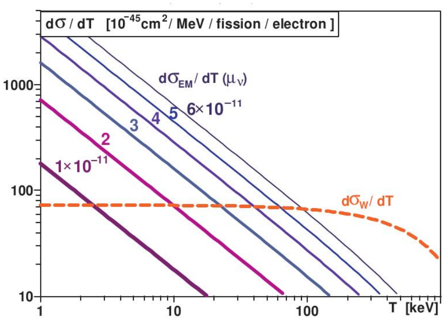


Figure : Weak and electromagnetic cross-sections calculated for several neutrino magnetic moment values.

$$\mu_{\bar{\nu}_e} \lesssim 7.4 \times 10^{-11} \mu_B$$

H. Wong et al. Phys Rev. D75 012001 (2007)

$$\mu_{\bar{\nu}_e} \lesssim 2.9 \times 10^{-11} \mu_B$$

A.G. Beda et al. Adv High Energy Phys. 2012 350150 (2012)

Effective NMM at reactor experiments.

In the flavor basis

$$(\mu_\nu^F)^2 = a_-^\dagger \lambda^\dagger \lambda a_- + a_+^\dagger \lambda \lambda^\dagger a_+ .$$

In this case ($\overline{\nu_e}$): $$a_+ = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \qquad a_- = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}.$$

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

Effective NMM at reactor experiments.

In the mass basis

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

where $\tilde{a}_- = U^\dagger a_- \to \tilde{a}_-^\dagger = a_-^\dagger U, \qquad \tilde{a}_+ = U^T a_+ \to \tilde{a}_+^\dagger = a_+^\dagger U^*.$

$$\begin{aligned}(\mu_R^M)^2 &= |\boldsymbol{\Lambda}|^2 - s_{12}^2 c_{13}^2 |\Lambda_2|^2 - c_{12}^2 c_{13}^2 |\Lambda_1|^2 - s_{13}^2 |\Lambda_3|^2 \\ &- 2 s_{12} c_{12} c_{13}^2 |\Lambda_1||\Lambda_2| \cos\delta_{12} - 2 c_{12} c_{13} s_{13} |\Lambda_1||\Lambda_3| \cos\delta_{13} \\ &- 2 s_{12} c_{13} s_{13} |\Lambda_2||\Lambda_3| \cos\delta_{23}, \qquad \theta_{13} \neq 0\end{aligned}$$

$\delta_{12} = \xi_3$, $\delta_{23} = \xi_2 - \delta$, and $\delta_{13} = \delta_{12} - \delta_{23}$.

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

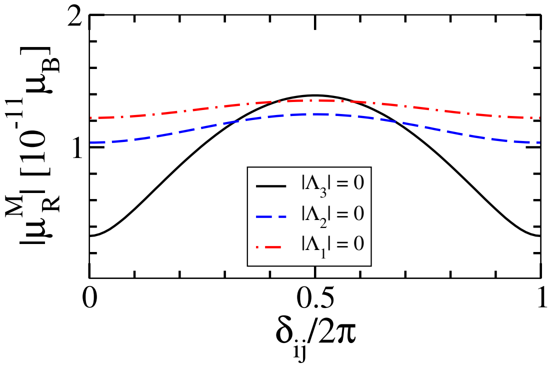


Figure : Effective Majorana TMM probed in reactor neutrino experiments, versus the relative phases δ_{ij} for three limiting cases where one of the absolute values $|\Lambda_k|$ vanishes.

Effective NMM at acelerator experiments.

$$(\mu_\nu^F)^2 = a_-^\dagger \lambda^\dagger \lambda a_- + a_+^\dagger \lambda \lambda^\dagger a_+ .$$

In this case $(\overline{\nu_\mu}, \nu_e, \nu_\mu)$: $a_+ = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$, $a_- = \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix}$.

$$(\mu_A^F)^2 = |\mathbf{\Lambda}|^2 + |\Lambda_e|^2 + 2\,|\Lambda_\tau|^2 - 2\,|\Lambda_\mu||\Lambda_e| \cos\eta ,$$

where $|\mathbf{\Lambda}|^2 = |\Lambda_e|^2 + |\Lambda_\mu|^2 + |\Lambda_\tau|^2$ and $\eta = \zeta_e - \zeta_\mu$.

Effective neutrino magnetic moment in Borexino.

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

In this case

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

This expression is independent of any phase and we take into account the non-zero value of θ_{13}.

Results

Limits on the effective NMM from reactor and accelerator data

Experiment	Bounds
Reactors	
KRASNOYARSK	$\mu_{\bar{\nu}_e} \leq 2.7 \times 10^{-10} \mu_B$
ROVNO	$\mu_{\bar{\nu}_e} \leq 1.9 \times 10^{-10} \mu_B$
MUNU	$\mu_{\bar{\nu}_e} \leq 1.2 \times 10^{-10} \mu_B$
TEXONO	$\mu_{\bar{\nu}_e} \leq 2.0 \times 10^{-10} \mu_B$
GEMMA	$\mu_{\bar{\nu}_e} \leq 2.9 \times 10^{-11} \mu_B$
Accelerators	
LAMPF	$\mu_{\nu_e} \leq 7.3 \times 10^{-10} \mu_B$
LAMPF	$\mu_{\nu_\mu} \leq 5.1 \times 10^{-10} \mu_B$
LSND	$\mu_{\nu_e} \leq 1.0 \times 10^{-9} \mu_B$
LSND	$\mu_{\nu_\mu} \leq 6.5 \times 10^{-10} \mu_B$
Solar	
Borexino	$\mu \leq 5.4 \times 10^{-11} \mu_B$

Experiment.	$\lvert\Lambda_1\rvert$	$\lvert\Lambda_2\rvert$	$\lvert\Lambda_3\rvert$
KRASN.	$4.7 \times 10^{-10}\mu_B$	$3.3 \times 10^{-10}\mu_B$	$2.8 \times 10^{-10}\mu_B$
ROVNO	$3.0 \times 10^{-10}\mu_B$	$2.1 \times 10^{-10}\mu_B$	$1.8 \times 10^{-10}\mu_B$
MUNU	$2.1 \times 10^{-10}\mu_B$	$1.5 \times 10^{-10}\mu_B$	$1.3 \times 10^{-10}\mu_B$
TEXONO	$3.4 \times 10^{-10}\mu_B$	$2.4 \times 10^{-10}\mu_B$	$2.0 \times 10^{-10}\mu_B$
GEMMA	$5.0 \times 10^{-11}\mu_B$	$3.5 \times 10^{-11}\mu_B$	$2.9 \times 10^{-11}\mu_B$
LSND	$6.0 \times 10^{-10}\mu_B$	$8.1 \times 10^{-10}\mu_B$	$7.0 \times 10^{-10}\mu_B$
LAMPF	$4.5 \times 10^{-10}\mu_B$	$6.2 \times 10^{-10}\mu_B$	$5.3 \times 10^{-10}\mu_B$
Borexino	$8.7 \times 10^{-11}\mu_B$	$6.8 \times 10^{-11}\mu_B$	$5.4 \times 10^{-11}\mu_B$

Table : 90% C.L. limits on the NMM components in the mass basis, Λ_i, from reactor, accelerator, and solar data from Borexino. In this particular analysis we constrain one parameter at a time, setting all other magnetic moment parameters and phases to zero.

Combined analysis

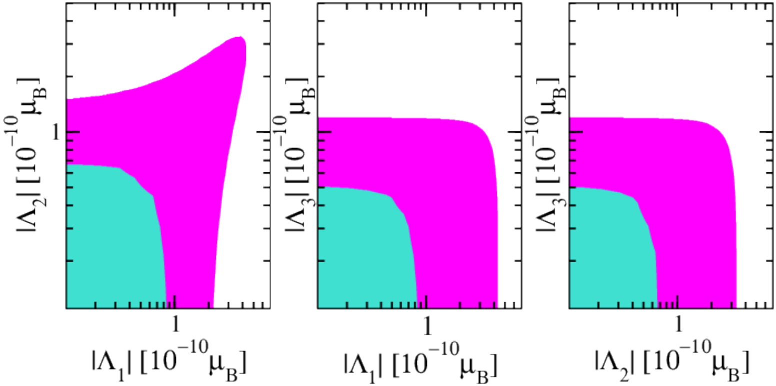
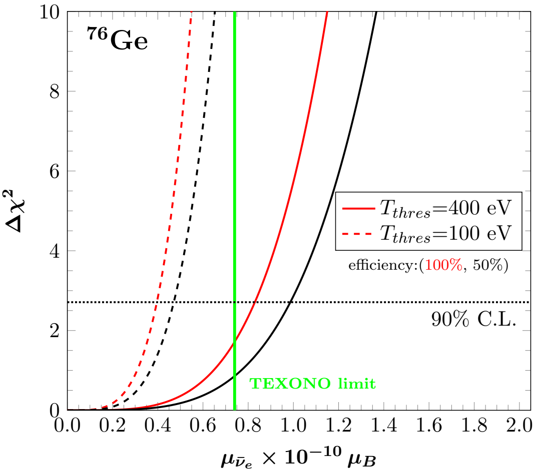


Figure : 90% C.L. allowed regions for the TNMMs in the mass basis. The result of this plot was obtained for the two parameters $|\Lambda_i|$ vs $|\Lambda_j|$ marginalizing over the third component. We show the result of a combined analysis of reactor and accelerator data with all phases set to zero except for $\delta = 3\pi/2$ (magenta region). We also show the result of the Borexino data analysis only, that is phase-independent (grey region).

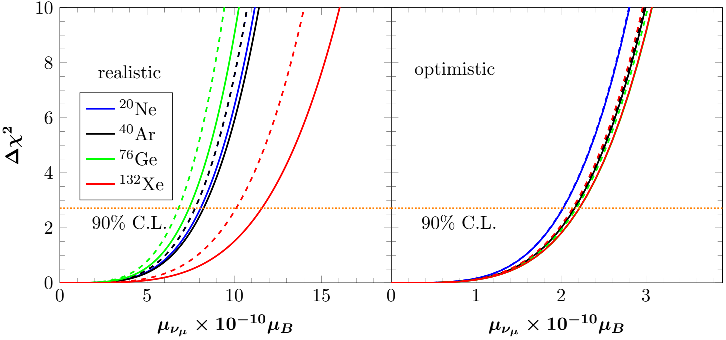
Proposals for the future

Future experiments to measure coherent ν-N scattering

- TEXONO: 1kg of germanium, reactor neutrinos Nucl.Instrum.Meth. A836 (2016) 67-82
- COHERENT: Spallation source with several rooms for one or even more detectors arXiv:1509.08702, 1211.5199
- CLEAR: stopped-π ν beam and kg-to-ton detector 0910.1989
- Connie: Reactor antineutrino experiment in Brasil JINST 11 (2016) P07024
- Kalinin: Reactor antineutrino experiment JINST 8 (2013) P10023
- MINER: Reactor antineutrino experiment Nucl.Instrum.Meth. A853 (2017) 53



T.S. Kosmas, OGM, D.K. Papoulias, M. Tortola, J.W.F. Valle, PLB **750** 459 (2015)



T.S. Kosmas, OGM, D.K. Papoulias, M. Tortola, J.W.F. Valle, PRD **92** 013011 (2015)

Conclusions

- ✓ We have analyzed the most recent data on neutrino electron scateting and shown the current status of the constraints on NMMs.
- ✓ We have presented a detailed discussion of the constraints on the absolute value of the TMMs, as well as the role of the CP phases, stressing the complementarity of different experiments.
- ✓ Perspectives for a future improvement on the current constraints have been briefly discussed, especially for coherent neutrino-nucleus scattering

Thanks

Phase counting.

$$\tilde{\lambda} \rightarrow 3 \text{ MM phases} \quad \rightarrow \quad \zeta_1, \zeta_2, \zeta_3 \quad (\Lambda_i = |\Lambda_i| e^{i\zeta_i})$$

$$U \rightarrow 3 \text{ CPV phases} \quad \rightarrow \quad \delta, \quad 2 - \text{Majorana phases},$$

three of these six complex phases are irrelevant, as they can be reabsorbed.

We give our results in terms of: δ, $\xi_2 = \zeta_3 - \zeta_1$ and $\xi_3 = \zeta_2 - \zeta_1$.

W. Grimus, T. Schwetz, NPB **587** 45 (2000)

Borexino data.

The differential cross section is given by

$$\frac{d\sigma_\alpha}{dT_e}(E_\nu, T_e) = \overline{P}_{ee}\frac{d\sigma_e}{dT_e}(E_\nu, T_e) + (1 - \overline{P}_{ee})\frac{d\sigma_{\mu-\tau}}{dT_e}(E_\nu, T_e),$$

where the average survival electron-neutrino probability for the Beryllium line, $\overline{P}_{ee}$, determines the flavour composition of the neutrino flux detected in the experiment. According to an analysis of solar neutrino data (excluding Borexino data to avoid any correlation with the present analysis) this value is set to $\overline{P_{ee}^{\mathrm{th}}} = 0.54 \pm 0.03$.

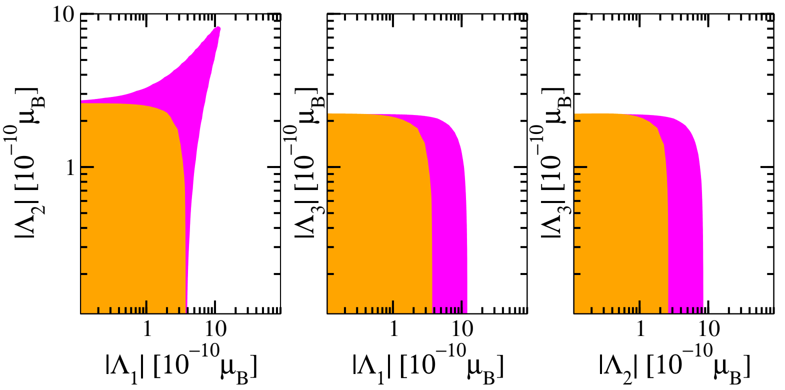


Figure : 90% C.L. allowed regions for the TNMMs in the mass basis from the reactor experiment TEXONO. The two-dimensional projections in the plane ($|\Lambda_i|$, $|\Lambda_j|$) have been calculated marginalizing over the third component. The magenta (outer) region is obtained for $\delta = 3\pi/2$ and $\xi_2 = \xi_3 = 0$, while the orange (inner) region appears for $\delta = 3\pi/2$, $\xi_2 = 0$ and $\xi_3 = \pi/2$.