Introduction to neutrino magnetic and electric dipole moments

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Cinvestav

September 17, 2020

Outline

Pauli's letter of the 4th of December 1930

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, ... I have hit upon a deseperate remedy ... Namely, the possibility that there could exist in the nuclei electrically neutral particles, that **I wish to call neutrons,** *which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses...*

Now it is also a question of which forces act upon neutrons. For me, the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), **that the neutron at rest is a magnetic dipole with a certain moment μ.** *...*

...Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back. Your humble servant, W. Pauli

The text above is an abridged version of the original.

The solar neutrino problem

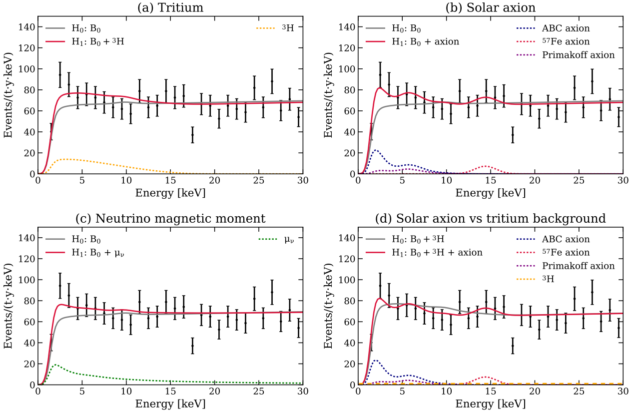
One of the first proposals to solve the solar neutrino problem

$$P(\nu_{e_L} \to \nu_{e_R}; r) = \sin^2\left(\int_0^r \mu_\nu B_\perp(r')dr'\right).$$

$$\mu_\nu B_\perp r \approx \frac{\pi}{2}$$

A. Cisneros, Effect of neutrino magnetic moment on solar neutrino observations, Astrophys. Space Sci. **10**, 87 (1971).

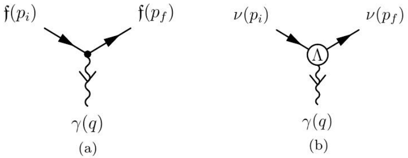
Xenon1T



E. Aprile et. al. Observation of Excess Electronic Recoil Events in XENON1T, 2006.09721

Electromagnetic interactions

$$\mathcal{H}_{em}^{f}(x) = j_{\mu}^{f}(x)A^{\mu}(x) = \mathfrak{q}_f \bar{f}(x)\gamma_{\mu} f(x)A^{\mu}(x),$$



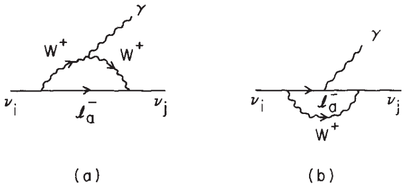
* For neutrinos: $q_{\nu} = 0 \to$ there are no electromagnetic interactions at tree level.

* However, such interactions can arise from loop diagrams at higher order in the perturbative expansion.

$$\mathcal{H}_{eff}(x) = j_{\mu}^{eff}(x)A^{\mu}(x) = \sum_{k,j=1}^{3} \overline{\nu_k}(x)\Lambda_{\mu}^{kj}\nu_j(x)A^{\mu}(x)$$

C. Giunti, A. Studenikin RMP **87** (2015) 531

Neutrino magnetic moment



Robert E. Shrock NPB **206** (1982) 359

Dirac neutrinos

$$\mathcal{H}_{em}^{D} = \frac{1}{2}\overline{\nu}\,(\mu + i d\gamma_5)\,\sigma^{\alpha\beta}\nu F_{\alpha\beta} = \frac{1}{2}\overline{\nu_R}\,\lambda\,\sigma^{\alpha\beta}\nu_L F_{\alpha\beta} + h.c.,$$

with $\nu = \nu_L + \nu_R$.

$$\mu^\dagger = \mu \quad \text{(MM matrix)}, \qquad d^\dagger = d \quad \text{(EDM matrix)}.$$

The MM and EDM matrices are condensed in $\lambda = \mu - id$ (NMM matrix).

Dirac Case:

The MM and EDM matrices are hermitian.

Majorana neutrinos

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

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

Majorana case:

The MM and EDM matrices are antisymmetric and hermitian, and, therefore, imaginary. λ is an antisymmetric matrix.

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)

Neutrino magnetic in the "Standard Model"

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

$$\mu_{ij} = \frac{3eG_F}{16\pi^2\sqrt{2}}(m_{\nu\,i} + m_{\nu\,j}) \sum_{\alpha=e}^{\tau} i\,\mathcal{I}m\left[U^*_{\alpha i}U_{\alpha j}\left(\frac{m_{l\alpha}}{M_{\mathrm{W}}}\right)^2\right].$$

Robert E. Shrock NPB **206** (1982) 359
P. B. Pal and L. Wolfenstein, Phys. Rev. D25, 766 (1982)

Neutrino magnetic in the "Standard Model"

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

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

Robert E. Shrock NPB **206** (1982) 359

W. Marciano, A. I. Sanda PLB **67** 303 (1977)

Models beyond the Standard Model

- Charged scalar singlet

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

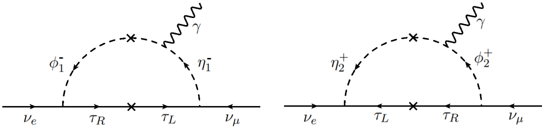
M. Fukugita, T. Yanagida PRL **58** (1987) 1807

- Charged scalars plus additional simmetries

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

R. Barbieri, R. N. Mohapatra PLB **218** (1989) 225

K.S. Babu, R.N. Mohapatra PRL **63** (1989) 228



$$\mu_{\nu_e \nu_\mu} = \frac{ff'}{8\pi^2} m_\tau \sin 2\alpha \left[\frac{1}{m_{h^+}^2} \left\{ \ln \frac{m_{h^+}^2}{m_\tau^2} - 1 \right\} - \frac{1}{m_{H^+}^2} \left\{ \ln \frac{m_{H^+}^2}{m_\tau^2} - 1 \right\} \right] . \quad (1)$$

Here (m_{h^+}, m_{H^+}) denote the common masses of the two charged scalars (h_i^+, H_i^+).

K .S. Babu, Sudip Jana, Manfred Lindner, 2007.04291

The effective neutrino magnetic moment

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)

Phase counting.

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

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

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)

Experimental searches

Reactor experiments

Neutrino-electron scattering

The electromagnetic contribution is given by

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

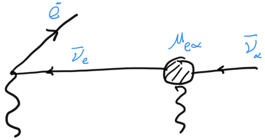
where μ_ν is an effective magnetic moment.

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

Neutrino electron scattering

$$\lambda\lambda^\dagger = \begin{pmatrix} |\Lambda_\mu|^2 + |\Lambda_\tau|^2 & -\Lambda_\mu\Lambda_e^* & -\Lambda_\tau\Lambda_3^* \\ -\Lambda_e\Lambda_\mu^* & |\Lambda_e|^2 + |\Lambda_\tau|^2 & -\Lambda_\tau\Lambda_\mu^* \\ -\Lambda_e\Lambda_\tau^* & -\Lambda_\mu\Lambda_\tau^* & |\Lambda_e|^2 + |\Lambda_\mu|^2 \end{pmatrix}$$

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



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

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

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

Canas, OGM, Parada, Tortola, Valle PLB **753** 191 (2016).

Effective NMM at reactor experiments.

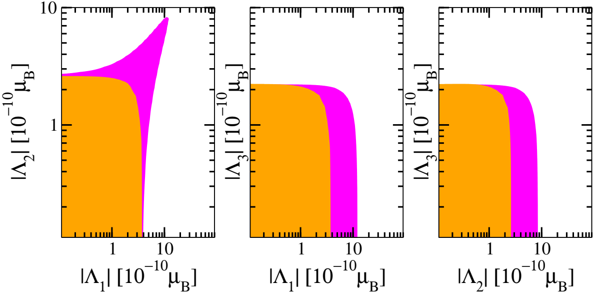


Figure: 90% C.L. allowed regions for the TNMMs in the mass basis from the reactor experiment TEXONO. The two-dimensional projections in the plane ($|\Lambda_i|$, $|\Lambda_j|$) have been calculated marginalizing over the third component. The magenta (outer) region is obtained for $\delta = 3\pi/2$ and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

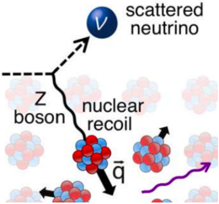
Canas, OGM, Parada, Tortola, Valle PLB **753** 191 (2016).

Limits on the effective NMM from reactor and accelerator data

Experiment	Bounds	
Reactors		
KRASNOYARSK	$\mu_{\bar{\nu}_e} \leq 2.4 \times 10^{-10} \mu_B$	JETP Lett. 55 (1992) 206
ROVNO	$\mu_{\bar{\nu}_e} \leq 1.9 \times 10^{-10} \mu_B$	JETP Lett. 57 (1993) 768
MUNU	$\mu_{\bar{\nu}_e} \leq 9 \times 10^{-11} \mu_B$	Phys.Lett.B 615 (2005) 153
TEXONO	$\mu_{\bar{\nu}_e} \leq 2.2 \times 10^{-10} \mu_B$	Phys.Rev.D 81 (2010) 072001
TEXONO	$\mu_{\bar{\nu}_e} \leq 7.4 \times 10^{-11} \mu_B$	Phys Rev. D75 012001 (2007)
GEMMA	$\mu_{\bar{\nu}_e} \leq 2.9 \times 10^{-11} \mu_B$	Adv.High Energy Phys. 2012 (2012) 350150

Future reactor experiments

Coherent elastic neutrino nucleus scattering (Cevns)



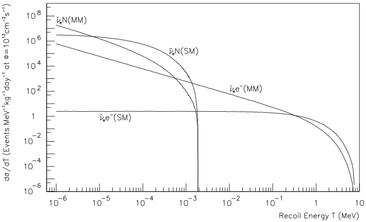


Figure 1. Differential cross section showing the recoil energy spectrum in $\bar{\nu}_e$-e and coherent $\bar{\nu}_e$-N scatterings, at a reactor neutrino flux of 10^{13} cm^{-2}s^{-1}, for the Standard Model (SM) processes and due to a neutrino magnetic moment (MM) of 10^{-10} μ_B.

$E_\nu \leq 50$ MeV

$QR << 1$

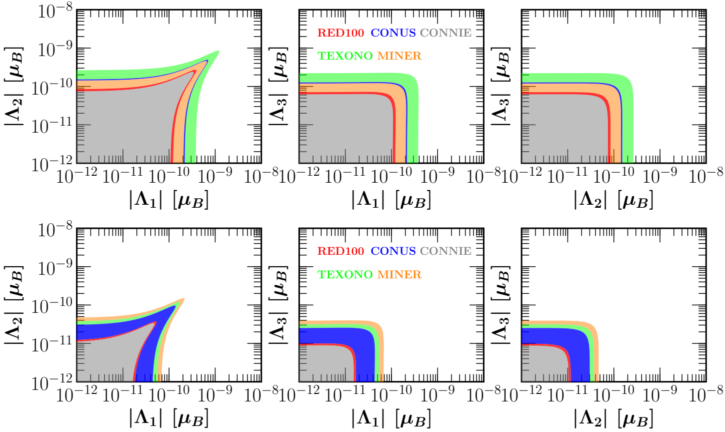
D. Freedman Phys. Rev. **D9** (1974) 1389

COHERENT Coll. Science 357 (2017) 1123

COHERENT Coll. 2003.10630

TEXONO NPB Proc. Supp. **138** 333 (2005)

Future Reactor constraints



[OGM, Papoulias, Tórtola, Valle, JHEP 1907 (2019) 103]

Solar neutrino detection

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

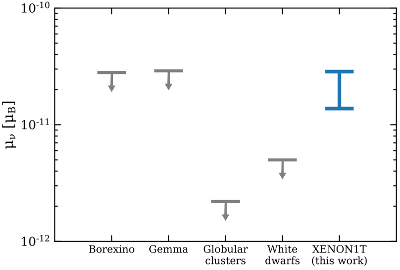
Grimus, Maltoni, Schwetz, Tórtola, Valle, Nucl. Phys. **B648** (2003) 376

Effective neutrino magnetic moment in Borexino

	$\mu_{eff} \leq 2.8 \times 10^{-11} \mu_B$	
$\lvert\mu_{11}\rvert \leq 3.4 \times 10^{-11} \mu_B$	$\lvert\mu_{22}\rvert \leq 5.1 \times 10^{-11} \mu_B$	$\lvert\mu_{33}\rvert \leq 18.7 \times 10^{-11} \mu_B$
$\lvert\mu_{12}\rvert \leq 2.8 \times 10^{-11} \mu_B$	$\lvert\mu_{13}\rvert \leq 3.4 \times 10^{-11} \mu_B$	$\lvert\mu_{23}\rvert \leq 5.0 \times 10^{-11} \mu_B$

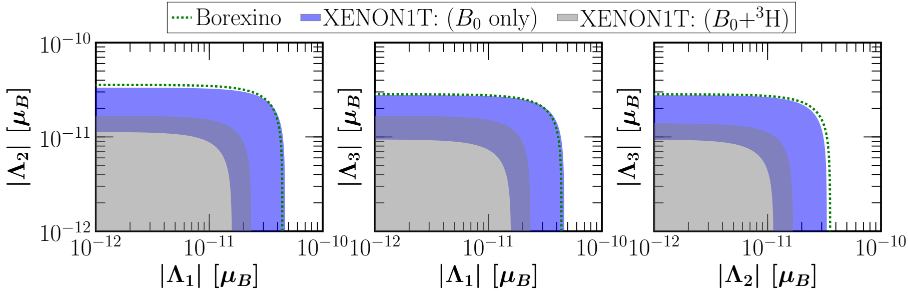
Borexino coll. Phys.Rev.D 96 (2017) 091103

Effective neutrino magnetic moment in Xenon1T.



E. Aprile et. al. Observation of Excess Electronic Recoil Events in XENON1T, 2006.09721

Effective neutrino magnetic moment in Xenon1T.



OGM, Papoulias, Tortola, Valle, Phys. Lett. **B808** (2020) 135685

Future sensitivity

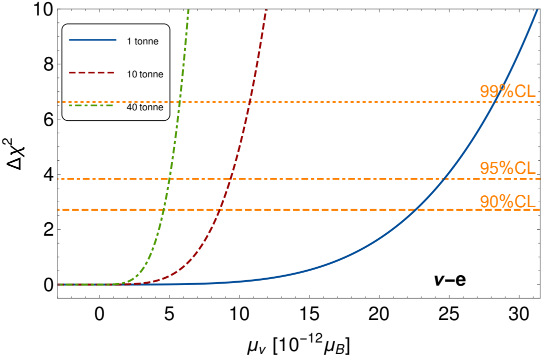
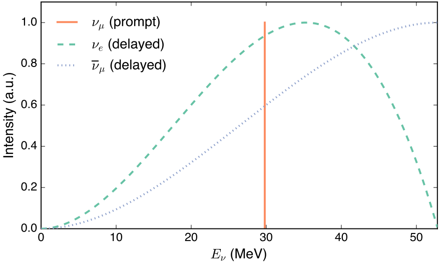


Figure: Electron recoil sensitivities to neutrino magnetic dipole moments in 1, 10 and 40 tonne active volume detectors during a one-year data taking. The result assumes a 0.3 keV threshold, 100% detector efficiency and backgrounds for XENON1T, XENONnT and DARWIN.

Aristizabal Sierra, Branada, OGM, Sanchez Garcia, 2008.05080

Neutrinos at spallation neutron source experiments

SNS facilities



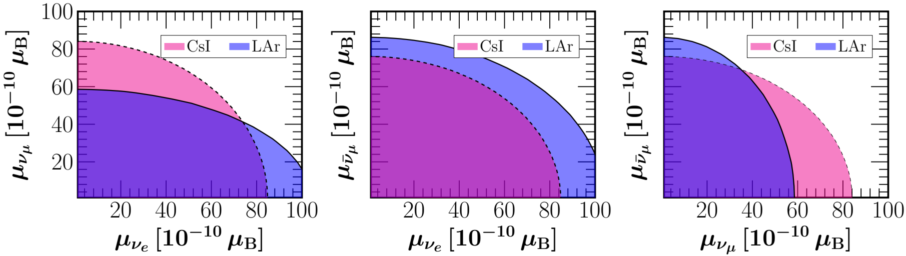
$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

Limits on the effective NMM from SNS νe data

Experiment	Bounds	
LAMPF	$\mu_{\nu_e} \leq 10.8 \times 10^{-10} \mu_B$	Phys.Rev.D 47 (1993) 11
LAMPF	$\mu_{\nu_\mu} \leq 7.4 \times 10^{-10} \mu_B$	Phys.Rev.D 47 (1993) 11
LSND	$\mu_{\nu_e} \leq 1.1 \times 10^{-9} \mu_B$	Phys.Rev.D 63 (2001) 112001
LSND	$\mu_{\nu_\mu} \leq 6.8 \times 10^{-10} \mu_B$	Phys.Rev.D 63 (2001) 112001

Effective NMM at Spallation Neutron Source experiments.



OGM, Papoulias, Sanchez Garcia, Sanders, Tórtola, Valle
JHEP 05 (2020) 130
see also Cadeddu, Dordei, Giunti, Li, Picciau, Zhang PRD **102** (2020) 015030

Conclusions

- ✓ Different experiments give a constrain on effective neutrino magnetic moment of the order of $\mu_{eff} \leq 10^{-11}\mu_B$
- ✓ Different experiments constrain a somewhat different combination of nautrino magnetic moments.
- ✓ If a possitive hint for a $\mu_{eff} \neq 0$ is confirmed, different observables could give more information on the nature of the neutrino magnetic couplings, including perhaps, their phases.

Thanks

Support from CONACyT grant 23238 is acknowledged