The Neutrino Magnetic Moment

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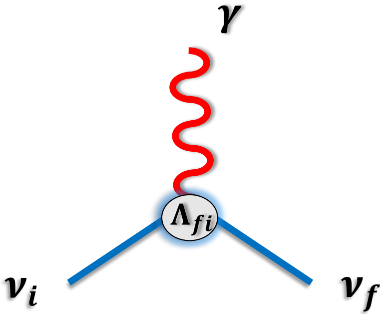
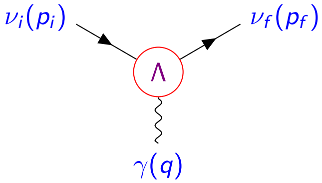


Neutrino Electromagnetic Interactions

- Effective Hamiltonian: $\mathcal{H}_{\text{em}}^{(\nu)}(x) = j_\mu^{(\nu)}(x) A^\mu(x) = \sum_{k,j=1} \overline{\nu_k}(x) \Lambda_\mu^{kj} \nu_j(x) A^\mu(x)$

- Effective electromagnetic vertex:



$$\langle \nu_f(p_f) | j_\mu^{(\nu)}(0) | \nu_i(p_i) \rangle = \overline{u_f}(p_f) \Lambda_\mu^{fi}(q) u_i(p_i)$$

$$q = p_i - p_f$$

- Vertex function:

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right) \left[F_Q(q^2) + F_A(q^2) q^2 \gamma_5\right] - i\sigma_{\mu\nu} q^\nu \left[F_M(q^2) + i F_E(q^2) \gamma_5\right]$$

Lorentz-invariant form factors: charge (F_Q), anapole (F_A), magnetic (F_M), electric (F_E)

$q^2 = 0 \implies$ q, a, μ, ε

chirality-conserving (q, a) — chirality-flipping (μ, ε)

Electromagnetic Vertex Function

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right)\left[F_Q(q^2) + F_A(q^2) q^2 \gamma_5\right] - i\sigma_{\mu\nu} q^\nu \left[F_M(q^2) + iF_E(q^2)\gamma_5\right]$$

Lorentz-invariant form factors: charge (F_Q), anapole (F_A), magnetic (F_M), electric (F_E)

$q^2 = 0 \implies$ charge → q, anapole → a, magnetic → μ, electric → ε

- Hermitian form factors: $F_Q = F_Q^\dagger$, $F_A = F_A^\dagger$, $F_M = F_M^\dagger$, $F_E = F_E^\dagger$
- Majorana neutrinos: $F_Q = -F_Q^T$, $F_A = F_A^T$, $F_M = -F_M^T$, $F_E = -F_E^T$

no diagonal charges and electric and magnetic moments in the mass basis!

- Left-handed ultrarelativistic neutrinos: $\gamma_5 \to -1$:
  - charge and anapole have similar phenomenology
  - magnetic and electric moments have similar phenomenology:

    dipole moments $d = \mu - i\varepsilon$

- Ultrarelativistic neutrinos: chirality $\simeq$ helicity:
  - the charge and anapole terms conserve helicity
  - the magnetic and electric terms invert helicity

Neutrino Electric Charges

- Neutrinos can be millicharged particles in BSM theories.
- There are strong experimental limits:

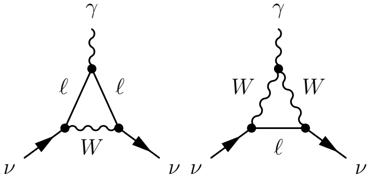
Limit	Method	Reference
$\lvert q_{\nu_e} \rvert \lesssim 3 \times 10^{-21}\, e$	Neutrality of matter	Raffelt (1999)
$\lvert q_{\nu_e} \rvert \lesssim 3.7 \times 10^{-12}\, e$	Nuclear reactor	Gninenko et al (2006)
$\lvert q_{\nu_e} \rvert \lesssim 1.5 \times 10^{-12}\, e$	Nuclear reactor	Studenikin (2013)
$\lvert q_{\nu_\mu} \rvert \lesssim 3 \times 10^{-8}\, e$	COHERENT CEνNS	Cadeddu et al (2020)
$\lvert q_{\nu_{\mu\tau}} \rvert \lesssim 2 \times 10^{-8}\, e$	COHERENT CEνNS	Cadeddu et al (2020)
$\lvert q_{\nu_\mu} \rvert \lesssim 3 \times 10^{-9}\, e$	LSND	Das et al (2020)
$\lvert q_{\nu_\tau} \rvert \lesssim 4 \times 10^{-6}\, e$	DONUT	Das et al (2020)
$\lvert q_{\nu_\tau} \rvert \lesssim 3 \times 10^{-4}\, e$	SLAC e^- beam dump	Davidson et al (1991)
$\lvert q_{\nu_\tau} \rvert \lesssim 4 \times 10^{-4}\, e$	BEBC beam dump	Babu et al (1993)
$\lvert q_{\nu} \rvert \lesssim 6 \times 10^{-14}\, e$	Solar cooling (plasmon decay)	Raffelt (1999)
$\lvert q_{\nu} \rvert \lesssim 2 \times 10^{-14}\, e$	Red giant cooling (plasmon decay)	Raffelt (1999)

Neutrino Charge Radius

- In the Standard Model neutrinos are neutral and there are no electromagnetic interactions at the tree-level.

- Radiative corrections generate an effective electromagnetic interaction vertex

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right) F(q^2)$$



- $F(q^2) = \cancel{F(0)} + q^2 \left. \dfrac{dF(q^2)}{dq^2} \right|_{q^2=0} + \ldots = q^2 \dfrac{\langle r^2 \rangle}{6} + \ldots$

- In the Standard Model: [Bernabeu et al, PRD 62 (2000) 113012, NPB 680 (2004) 450]

$$\langle r^2_{\nu_\ell} \rangle_{\text{SM}} = -\frac{G_F}{2\sqrt{2}\pi^2}\left[3 - 2\log\left(\frac{m_\ell^2}{m_W^2}\right)\right]$$

$$\langle r^2_{\nu_e} \rangle_{\text{SM}} = -8.2 \times 10^{-33}\,\text{cm}^2$$
$$\langle r^2_{\nu_\mu} \rangle_{\text{SM}} = -4.8 \times 10^{-33}\,\text{cm}^2$$
$$\langle r^2_{\nu_\tau} \rangle_{\text{SM}} = -3.0 \times 10^{-33}\,\text{cm}^2$$

Experimental Bounds

Method	Experiment	Limit [cm^2]	CL	Year
Reactor $\bar{\nu}_e\, e^-$	Krasnoyarsk	$\lvert\langle r^2_{\nu_e}\rangle\rvert < 7.3 \times 10^{-32}$	90%	1992
	TEXONO	$-4.2 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 6.6 \times 10^{-32}$	90%	2009
Accelerator $\nu_e\, e^-$	LAMPF	$-7.12 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 10.88 \times 10^{-32}$	90%	1992
	LSND	$-5.94 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 8.28 \times 10^{-32}$	90%	2001
Accelerator $\nu_\mu\, e^-$	BNL-E734	$-5.7 \times 10^{-32} < \langle r^2_{\nu_\mu}\rangle < 1.1 \times 10^{-32}$	90%	1990
	CHARM-II	$\lvert\langle r^2_{\nu_\mu}\rangle\rvert < 1.2 \times 10^{-32}$	90%	1994

[see the review CG, Studenikin, arXiv:1403.6344

and the update in Cadeddu, CG, Kouzakov, Y.F. Li, Studenikin, Y.Y. Zhang, arXiv:1810.05606]

Neutrino Magnetic and Electric Moments

- Effective dimension-5 Lagrangian:

$$\mathcal{L}_{\text{mag}} = \frac{1}{2} \sum_{k,j=1}^{\mathcal{N}} \overline{\nu_{Lk}} \, \sigma^{\alpha\beta} \left(\mu_{kj} + \varepsilon_{kj} \, \gamma_5 \right) N_{Rj} \, F_{\alpha\beta} + \text{H.c.}$$

- Note that the magnetic and electric moments (as the charge and anapole) are well-defined in the mass basis.

- $\mathcal{N} = 3$, $N_{Rj} = \nu_{Rj}$, and $\Delta L = 0 \implies$ Dirac neutrinos with diagonal and off-diagonal (transition) magnetic and electric moments

- $\mathcal{N} = 3$ and $N_{Rj} = \nu_{Lj}^{c} \implies$ Majorana neutrinos with transition magnetic and electric moments only

- $\mathcal{N} > 3 \implies$ active + sterile Dirac ($\Delta L = 0$) or Majorana neutrinos

  "neutrino dipole portal" or "neutrino magnetic moment portal"

Dirac Neutrinos

[Fujikawa, Shrock, PRL 45 (1980) 963; Pal, Wolfenstein, PRD 25 (1982) 766; Shrock, NPB 206 (1982) 359; Dvornikov, Studenikin, PRD 69 (2004) 073001, JETP 99 (2004) 254]

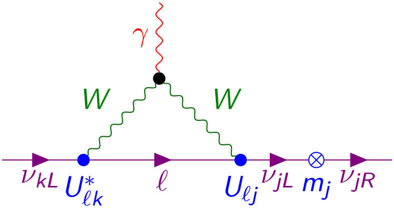
Simplest extension of the Standard Model with
three right-handed neutrinos and $\Delta L = 0$

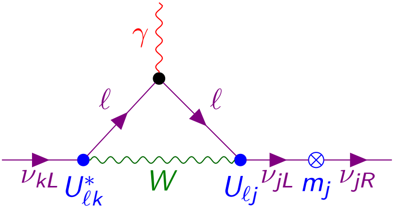
$$\mathcal{L}_{\text{mag}} = \frac{1}{2} \sum_{k,j=1}^{3} \overline{\nu_{Lk}}\, \sigma^{\alpha\beta} \left(\mu_{kj} + \varepsilon_{kj}\, \gamma_5 \right) \nu_{Rj}\, F_{\alpha\beta} + \text{H.c.}$$

$$\left.\begin{matrix} \mu_{kj}^{\text{D}} \\ i\varepsilon_{kj}^{\text{D}} \end{matrix}\right\} \simeq \frac{3eG_{\text{F}}}{16\sqrt{2}\pi^2} \left(m_k \pm m_j \right) \left(\delta_{kj} - \frac{1}{2} \sum_{\ell=e,\mu,\tau} U_{\ell k}^{*}\, U_{\ell j} \frac{m_\ell^2}{m_W^2} \right)$$

- The constraint $\Delta L = 0$ is necessary to forbid a Majorana mass term for the three right-handed neutrinos ν_{1R}, ν_{2R}, ν_{3R}.
- The magnetic and electric moments are proportional to the neutrino masses!
- This is because Standard Model interactions involve only ν_{1L}, ν_{2L}, ν_{3L}.

- A mass insertion is needed to flip chirality:





- Diagonal magnetic and electric moments:

$$\mu^{\mathrm{D}}_{kk} \simeq \frac{3eG_{\mathrm{F}}m_k}{8\sqrt{2}\pi^2}$$

$$\varepsilon^{\mathrm{D}}_{kk} = 0 \quad \leftarrow \quad \text{No diagonal electric moments!}$$

- Diagonal magnetic moments: $\mu^{\mathrm{D}}_{kk} \simeq 3.2 \times 10^{-19} \mu_{\mathrm{B}} \left(\frac{m_k}{\mathrm{eV}}\right)$

Strongly suppressed by small neutrino masses!

$$\mu_{\mathrm{B}} \equiv \frac{e}{2\,m_e} \simeq 6 \times 10^{-15}\,\frac{\mathrm{MeV}}{\mathrm{Gauss}}$$

- The transition magnetic and electric moments $(k \neq j)$ are GIM-suppressed:

$$\left.\begin{matrix} \mu_{kj}^{\mathrm{D}} \\ i\varepsilon_{kj}^{\mathrm{D}} \end{matrix}\right\} \simeq -3.9 \times 10^{-23} \mu_{\mathrm{B}} \left(\frac{m_k \pm m_j}{\mathrm{eV}} \right) \sum_{\ell=e,\mu,\tau} U_{\ell k}^{*} U_{\ell j} \left(\frac{m_\ell}{m_\tau} \right)^2$$

At least four orders of magnitude smaller than the diagonal ones!

Majorana Neutrinos

- Only GIM-suppressed transition magnetic and electric moments $(k \neq j)$:

$$\mu_{kj}^{\mathrm{M}} \simeq -7.8 \times 10^{-23} \mu_{\mathrm{B}} \, i \, (m_k + m_j) \sum_{\ell=e,\mu,\tau} \mathrm{Im} \left[U_{\ell k}^{*} U_{\ell j} \right] \frac{m_\ell^2}{m_W^2}$$

$$\varepsilon_{kj}^{\mathrm{M}} \simeq 7.8 \times 10^{-23} \mu_{\mathrm{B}} \, i \, (m_k - m_j) \sum_{\ell=e,\mu,\tau} \mathrm{Re} \left[U_{\ell k}^{*} U_{\ell j} \right] \frac{m_\ell^2}{m_W^2}$$

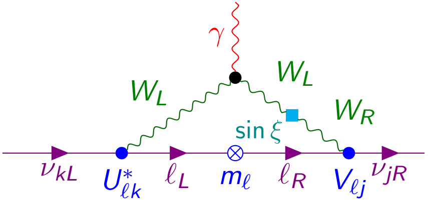
[Shrock, NPB 206 (1982) 359]

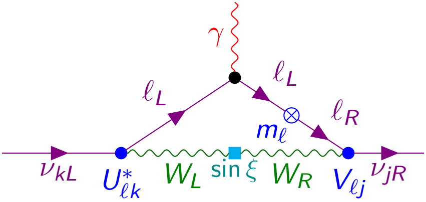
However, additional model-dependent contributions of the scalar sector can enhance the Majorana transition magnetic and electric moments

[Pal, Wolfenstein, PRD 25 (1982) 766; Barr, Freire, Zee, PRL 65 (1990) 2626; Pal, PRD 44 (1991) 2261]

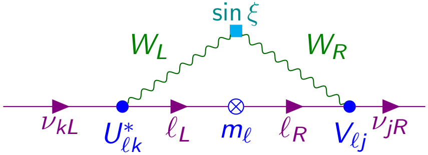
Left-Right Simmetric Models

- Right-handed interactions mediated by W_R avoid the necessity of the mass insertion to flip chirality:





- Problem: The same diagrams without the photon line contribute to the neutrino masses:



- General Problem: difficult to get large magnetic moments and small masses.
- Common Solution: ad-hoc symmetries.

General argument:

- Contribution of a BSM diagram to the magnetic moment:

$$\mu_\nu \sim \frac{eG}{\Lambda}$$

G: coupling constants and loop factors

Λ: BSM energy scale

- The same diagram without photon line gives $\delta m_\nu \sim G\Lambda$

- Therefore: $\mu_\nu \sim 10^{-18}\,\mu_{\text{B}} \left(\frac{\delta m_\nu}{\text{eV}}\right) \left(\frac{\Lambda}{\text{TeV}}\right)^{-2}$

- A more quantitative analysis gives:

$$\mu_\nu^{\text{D}} \lesssim 3 \times 10^{-15}\,\mu_{\text{B}} \left(\frac{m_\nu}{\text{eV}}\right) \left(\frac{\Lambda}{\text{TeV}}\right)^{-2}$$

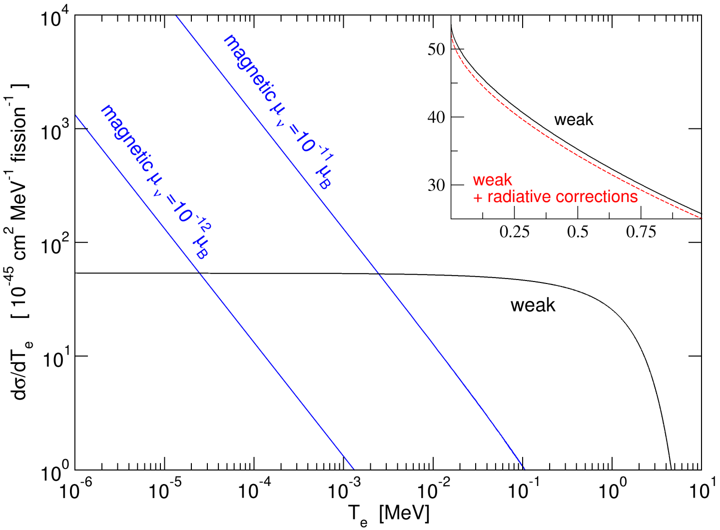
[Bell et al, hep-ph/0504134]

$$\mu_{\ell\ell'}^{\text{M}} \lesssim 4 \times 10^{-9}\,\mu_{\text{B}} \left(\frac{M_{\ell\ell'}^{\text{M}}}{\text{eV}}\right) \left(\frac{\Lambda}{\text{TeV}}\right)^{-2} \left|\frac{m_\tau^2}{m_\ell^2 - m_{\ell'}^2}\right|$$

[Bell et al, hep-ph/0606248]

- Majorana magnetic moments are less constrained by the smallness of the neutrino masses because the diagram contribution to the mass is Yukawa suppressed (additional Yukawa couplings are needed to convert the antisymmetric magnetic moment operator into a symmetric mass operator).

$$\left(\frac{d\sigma_{\nu e^-}}{dT_e}\right)_{\text{mag}} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)\left(\frac{\mu_\nu}{\mu_B}\right)^2$$



[Balantekin, Vassh, arXiv:1312.6858]

Method	Experiment	Limit [μ_B]	CL	Year
Reactor $\bar{\nu}_e\, e^-$	Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}$	90%	1992
	Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}$	95%	1993
	MUNU	$\mu_{\nu_e} < 9 \times 10^{-11}$	90%	2005
	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}$	90%	2006
	GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}$	90%	2012
Accelerator $\nu_e\, e^-$	LAMPF	$\mu_{\nu_e} < 1.1 \times 10^{-9}$	90%	1992
Accelerator $(\nu_\mu, \bar{\nu}_\mu)\, e^-$	BNL-E734	$\mu_{\nu_\mu} < 8.5 \times 10^{-10}$	90%	1990
	LAMPF	$\mu_{\nu_\mu} < 7.4 \times 10^{-10}$	90%	1992
	LSND	$\mu_{\nu_\mu} < 6.8 \times 10^{-10}$	90%	2001
Accelerator $(\nu_\tau, \bar{\nu}_\tau)\, e^-$	DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}$	90%	2001
Solar $\nu_e\, e^-$	Super-Kamiokande	$\mu_S(E_\nu \gtrsim 5\,\text{MeV}) < 1.1 \times 10^{-10}$	90%	2004
	Borexino	$\mu_S(E_\nu \lesssim 1\,\text{MeV}) < 2.8 \times 10^{-11}$	90%	2017

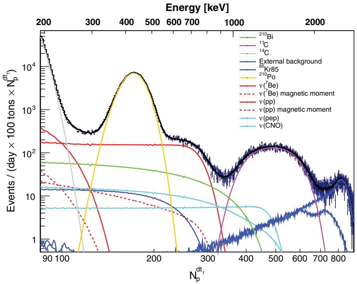
[see the review CG, Studenikin, arXiv:1403.6344]

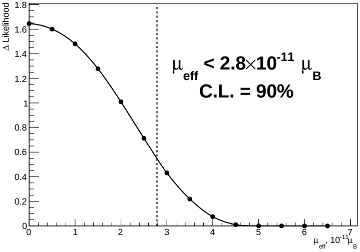
- Gap of about 8 orders of magnitude between the experimental limits and the $\lesssim 10^{-19}\,\mu_B$ prediction of the minimal Standard Model extensions.
- $\mu_\nu \gg 10^{-19}\,\mu_B$ discovery $\Rightarrow$ non-minimal new physics beyond the SM.
- Neutrino spin-flavor precession in a magnetic field

[Lim, Marciano, PRD 37 (1988) 1368; Akhmedov, PLB 213 (1988) 64]

Borexino

[arXiv:1707.09355]





- $$\left(\frac{d\sigma_{\nu e^-}}{dT_e}\right) = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)\left(\frac{\mu_{\text{eff}}}{\mu_B}\right)^2$$
- Taking into account neutrino oscillations:

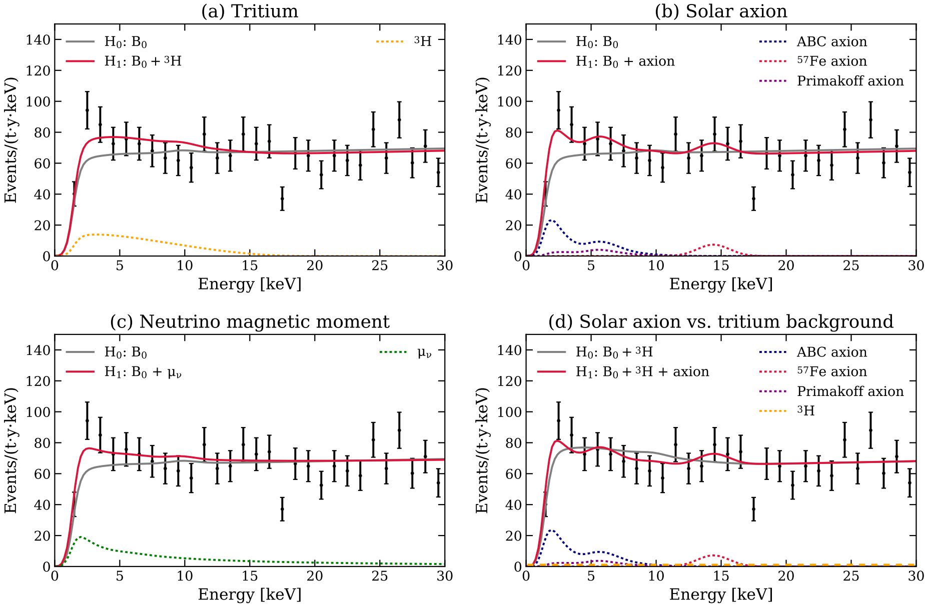
$$\mu_{\text{eff}}^2 = \sum_{k,j=1}^{3} P_{\nu_e\to\nu_k}|\mu_{kj}|^2$$

- All the positive magnetic moment contributions can be constrained.
- At 90% CL, in units of $10^{-11}\,\mu_B$:

$$|\mu_{11}| < 3.4 \qquad |\mu_{12}| < 2.8$$
$$|\mu_{22}| < 5.1 \qquad |\mu_{13}| < 3.4$$
$$|\mu_{33}| < 18.7 \qquad |\mu_{23}| < 5.0$$

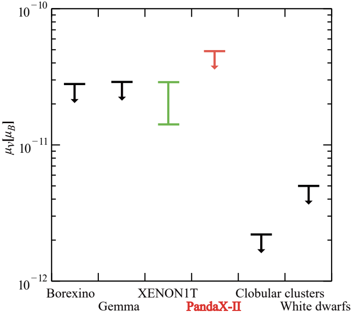
XENON1T

[arXiv:2006.09721]



- $\mu_\nu \in (1.4,\ 2.9) \times 10^{-11}\,\mu_{\rm B} \quad (90\%\ {\rm CL})$

  [arXiv:2006.09721]



[PandaX-II, arXiv:2008.06485]

- μ_ν is the same of Borexino $\mu_{\rm eff}$:

$$\mu_\nu^2 = \sum_{k,j=1}^{3} P_{\nu_e \to \nu_k} |\mu_{kj}|^2$$

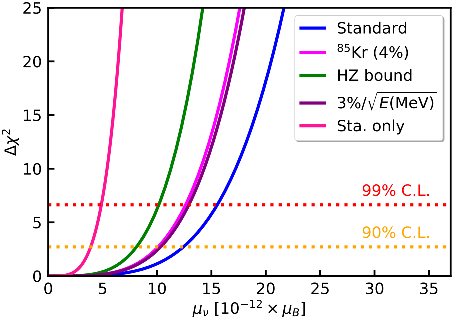
- μ_ν is not directly comparable to GEMMA μ_{ν_e}

$$\mu_{\nu_e}^2 = \sum_j \left| \sum_k U_{ek}^* \left(\mu_{jk} - i\varepsilon_{jk} \right) \right|^2$$

[see CG, Studenikin, arXiv:1403.6344]

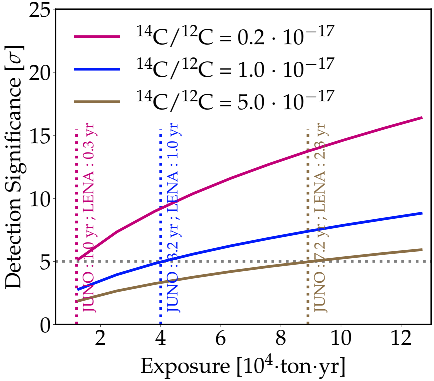
- Neglecting the electric moments, we have

$$\mu_{\nu_e}^2 = \sum_{i,j} U_{ei}\, \mu_{ij}^2\, U_{ej}^*$$



[Baobiao Yue, Jiajun Liao, Jiajie Ling, arXiv:2102.12259]

Jinping neutrino experiment
2400 m underground
water-based liquid scintillator
4 kton fiducial target mass
5 kton total mass
10-year exposure



[Z. Ye, F. Zhang, D. Xu, J. Liu, arXiv:2103.11771]

JUNO: 10 years, 12.7 kton f.m.

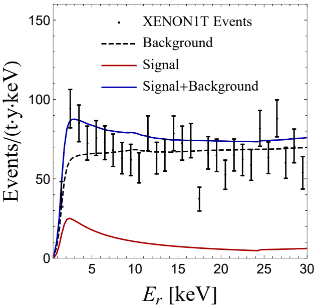
LENA: 3.3 years, 39 kton f.m.

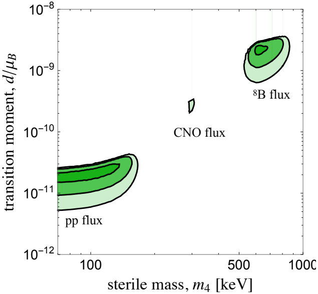
$$\left.\begin{matrix} 0.7 \\ 0.9 \\ 1.1 \end{matrix}\right\} \times 10^{-11}\,\mu_B \text{ for } \left\{\begin{matrix} 0.2 \\ 1.0 \\ 5.0 \end{matrix}\right\} \times 10^{-17}\,\frac{^{14}C}{^{12}C}$$

Borexino: $^{14}C/^{12}C = 0.27 \times 10^{-17}$

Active-to-Sterile ν Transition Dipole Moment

[Shoemaker, Tsai, Wyenberg, arXiv:2007.05513]





$\leftarrow \begin{cases} m_4 = 640\,\text{keV} \\ d = 2.2 \times 10^{-9}\,\mu_B \end{cases}$ Best Fit

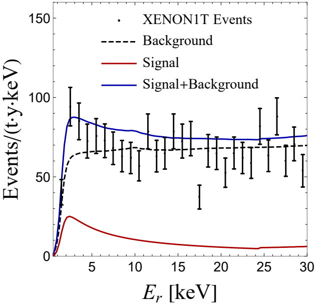
"neutrino dipole portal"

- Dipole moment: $d = \mu - i\,\varepsilon$
- $\mathcal{L} \supset d\,\bar{\nu}_L\,\sigma^{\mu\nu}\,N_R\,F_{\mu\nu} + \text{H.c.}$
- Upscattering $\nu_{\text{solar}} + e \to e + N$

$$\frac{d\sigma}{dE_R} = d^2\alpha\left[\frac{1}{E_R} - \frac{m_4^2}{2E_\nu E_R m_e}\left(1 - \frac{E_R}{2E_\nu} + \frac{m_e}{2E_\nu}\right) - \frac{1}{E_\nu} + \frac{m_4^4(E_R - m_e)}{8E_\nu^2 E_R^2 m_e^2}\right]$$

Active-to-Sterile ν Transition Dipole Moment

[Shoemaker, Tsai, Wyenberg, arXiv:2007.05513]



$\leftarrow \begin{cases} m_4 = 640\,\text{keV} \\ d = 2.2 \times 10^{-9}\,\mu_B \end{cases}$ Best Fit

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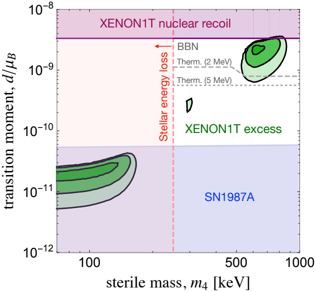
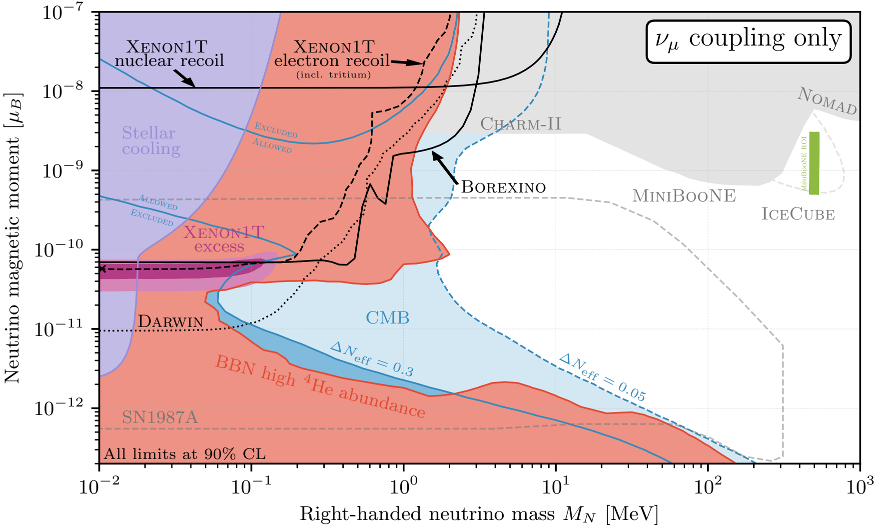


- Dipole moment: $d = \mu - i\,\varepsilon$
- $\mathcal{L} \supset d\,\bar{\nu}_L\,\sigma^{\mu\nu}\,N_R\,F_{\mu\nu} + \text{H.c.}$
- Upscattering $\nu_{\text{solar}} + e \to e + N$

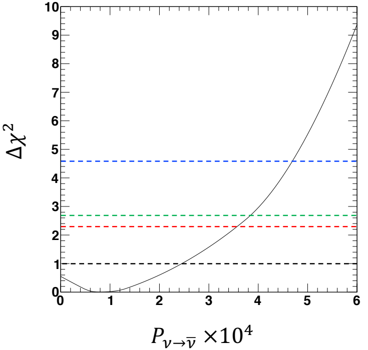
$$\frac{d\sigma}{dE_R} = d^2\alpha\left[\frac{1}{E_R} - \frac{m_4^2}{2E_\nu E_R m_e}\left(1 - \frac{E_R}{2E_\nu} + \frac{m_e}{2E_\nu}\right) - \frac{1}{E_\nu} + \frac{m_4^4(E_R - m_e)}{8E_\nu^2 E_R^2 m_e^2}\right]$$

The Neutrino Magnetic Moment Portal



[Brdar, Greljo, Kopp, Opferkuch, arXiv:2007.15563]

Electron Anti-Neutrinos from the Sun



- Majorana neutrinos: spin-flavor precession generate active $\bar{\nu}_{eR}$:

$$\nu_{eL} \to \nu_{eR} = \bar{\nu}_{eR}$$

- $P_{\nu_{eL}\to\bar{\nu}_{eR}} < 3.6 \times 10^{-4}$ (90% CL)

[Super-Kamiokande, arXiv:2012.03807]

- 10 years 90% CL SK-Gd sensitivity:

5.5×10^{-5} (0.02% Gd loading)
2.9×10^{-5} (0.2% Gd loading)

- The interpretation of results in terms of a magnetic moment depends on the unknown magnetic field in the Sun: [Akhmedov, Pulido, hep-ph/0209192]

$$P_{\nu_{eL}\to\bar{\nu}_{eR}} \simeq 1.8 \times 10^{-10} \sin^2 2\vartheta_{12} \left(\frac{\mu_{12}}{10^{-12}\,\mu_{\rm B}} \, \frac{B_{\perp}(0.05 R_{\odot})}{10\,\text{kG}} \right)^2$$

Neutrino Magnetic Moments in CEνNS

- Neutrino magnetic (and electric) moment contributions to CEνNS $\nu_\ell + \mathcal{N} \to \sum_{\ell'} \nu_{\ell'} + \mathcal{N}$:

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left[g_V^n N F_N(|\vec{q}|^2) + g_V^p Z F_Z(|\vec{q}|^2)\right]^2 + \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right) Z^2 F_Z^2(|\vec{q}|^2) \sum_{\ell' \neq \ell} \frac{|\mu_{\ell\ell'}|^2}{\mu_B^2}$$

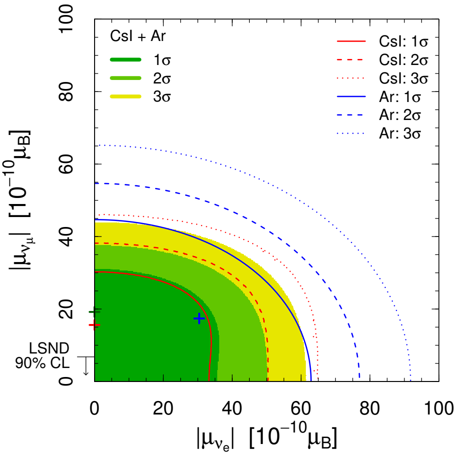
$$g_V^n = -\frac{1}{2} \qquad g_V^p = \frac{1}{2} - 2\sin^2\vartheta_W = 0.0227 \pm 0.0002$$

- The magnetic moment interaction adds incoherently to the weak interaction because it flips helicity.

- The m_e is due to the definition of the Bohr magneton: $\mu_B = e/2m_e$.

COHERENT Constraints on ν Magnetic Moments

[Cadeddu et al, arXiv:2005.01645]



- The sensitivity to $|\mu_{\nu_e}|$ is not competitive with that of reactor experiments:

$$|\mu_{\nu_e}| < 2.9 \times 10^{-11}\,\mu_B \quad (90\%\ \mathrm{CL})$$

[GEMMA, AHEP 2012 (2012) 350150]

- The constraint on $|\mu_{\nu_\mu}|$ is not too far from the best current laboratory limit:

$$|\mu_{\nu_\mu}| < 6.8 \times 10^{-10}\,\mu_B \quad (90\%\ \mathrm{CL})$$

[LSND, PRD 63 (2001) 112001]

Conclusions

- Neutrino Electromagnetic Interactions are expected in the Standard Model (charge radii) and in BSM theories: dipole magnetic and electric moments, non-standard charge radii, and millicharges
- The existence of neutrino magnetic moments is related to the existence of neutrino masses through chirality flipping BSM operators.
- Current laboratory limits are at the level of $10^{-11} - 10^{-10}\,\mu_{\rm B}$
- Conjectural theoretical expectations:
  - $\mu \lesssim 10^{-14}\,\mu_{\rm B}$ for Dirac neutrinos.
  - Maybe larger for Majorana neutrinos.
- Interesting XENON1T hint for $\mu \approx 2 \times 10^{-11}\,\mu_{\rm B}$.
- If there are BSM sterile neutrinos the active-sterile transition magnetic moments may be a dipole portal to the Dark Sector.