

Neutrino Magnetic Moments from Inverse Seesaw with Novel Horizontal Symmetry

based on arXiv:2611.XXXXX

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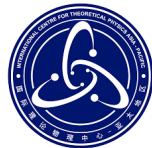
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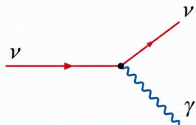
1. Motivation
2. Mechanisms to decouple mass and magnetic moment
3. Neutrino Magnetic Moments from Inverse Seesaw with $SU(2)_N$ symmetry
4. Summary



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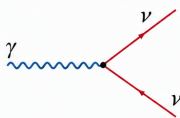
- ▶ Neutrinos are electrically neutral in the Standard Model and don't possess direct coupling with photons.
- ▶ Quantum loop corrections can induce electromagnetic properties, including neutrino magnetic moment.
- ▶ Consequences of neutrino magnetic moments

Neutrino decay



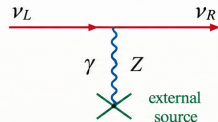
$$\Gamma_{\nu_i \rightarrow \nu_j + \gamma} = \frac{1}{8\pi} \left(\frac{m_i^2 - m_j^2}{m_i} \right)^3 |\mu_{ij}|^2$$

Plasmon decay



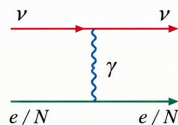
$$\Gamma_{\gamma^* \rightarrow \nu \bar{\nu}}(\mu_\nu) = \frac{\mu_\nu^2}{24\pi} Z \frac{\omega_p^4}{\omega_\gamma}$$

Spin-flavor precession



$$i \frac{d}{dr} \begin{pmatrix} \nu \\ \bar{\nu} \end{pmatrix} = \begin{pmatrix} 0 & B_L M \\ -B_L M & 0 \end{pmatrix} \begin{pmatrix} \nu \\ \bar{\nu} \end{pmatrix}$$

Scattering



$$\left(\frac{d\sigma}{dT_e} \right)_{\text{Tot}} = \left(\frac{d\sigma}{dT} \right)_{\text{SM}} + \left(\frac{d\sigma}{dT} \right)_{\text{mag}}$$

Experimental limits on Neutrino Magnetic Moments



Method	Experiment	Limit [μ_B]	CL	Year
Reactor $\bar{\nu}_e$ E ν ES	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
	CONUS	$\mu_{\nu_e} < 7.5 \times 10^{-11}$	90%	2022
Solar E ν ES	XENONnT (71)	$\mu_{\nu_e} < 9.0 \times 10^{-12}$	90%	2022
		$\mu_{\nu_\mu} < 1.5 \times 10^{-11}$		
		$\mu_{\nu_\tau} < 1.3 \times 10^{-11}$		
	LUX-ZEPLIN (74) + PandaX-4T (78) + XENONnT (71)	$\mu_S^{\text{LE}} < 7.5 \times 10^{-12}$	90%	2023
		$\mu_{\nu_e} < 1.0 \times 10^{-11}$ $\mu_{\nu_\mu}, \mu_{\nu_\tau} < 1.6 \times 10^{-11}$		

list is not exhaustive

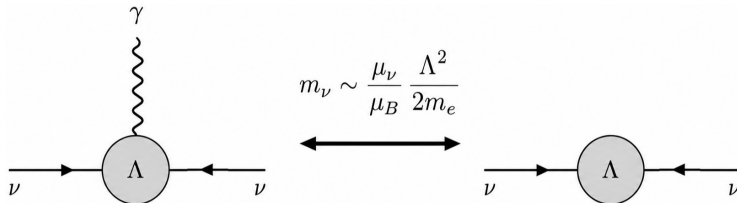
(Giunti, Kouzakov, Li, Studenikin 2024)

- ▶ Current experiments reach sensitivity of order $\mu_\nu \sim 10^{-11} \mu_B$.
- ▶ Generally any extension of SM: $\mu_\nu < 10^{-19} \mu_B$.

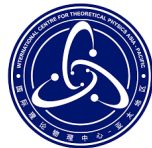
μ_ν - m_ν conundrum: general argument



- ▶ Neutrino magnetic moment and mass are both chirality flipping operators.
- ▶ By removing the photon line from the loop diagram that induces μ_ν one would generate a neutrino mass term. (Λ is the scale of new physics)



- ▶ $m_\nu = \frac{\mu_\nu}{\mu_B} \frac{\Lambda^2}{em_e} \sim 0.1 \text{ MeV}$ for $\Lambda \sim 100 \text{ GeV}$ and $\mu_\nu \sim 10^{-11} \mu_B$,
- ▶ To generate large μ_ν we need to decouple μ_ν and m_ν .

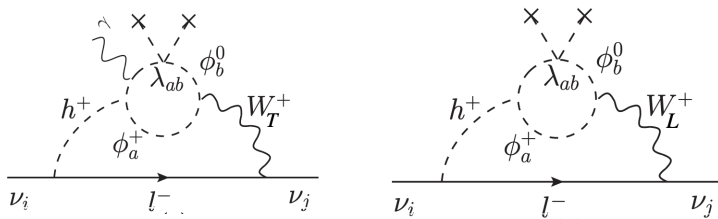


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Spin-symmetry mechanism



- μ_ν arises from an effective $\gamma h^- W^+$ vertex at two loops.

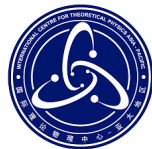


- Removing the photon leg forbids the spin-0 $\rightarrow$ spin-1 transition.
- Only the longitudinal gauge-boson component contributes
- Leading to a suppression of m_ℓ^2/m_W^2 in neutrino mass.
- Achieve neutrino transition magnetic moment as big as $3 \times 10^{-12} \mu_B$

(Barr, Freire, Zee 1990)

(Babu, Chang, Keung, Philips 1992)

$SU(2)_H$ Horizontal symmetry



- ▶ Mass operator is a Lorentz scalar and symmetric, whereas the magnetic moment is a Lorentz tensor and antisymmetric in the fermion fields.
- ▶ Voloshin proposed $SU(2)_\nu$ symmetry under which $(\nu_R^c, \nu_L)^T$ transform as a doublet. Under this transformation $\nu_L \rightarrow \nu_R^c$ and $\nu_R \rightarrow -\nu_L^c$

$$\bar{\nu}_L \nu_R \rightarrow -\bar{\nu}_L \nu_R, \quad \bar{\nu}_L \sigma_{\mu\nu} \nu_R F^{\mu\nu} \rightarrow +\bar{\nu}_L \sigma_{\mu\nu} \nu_R F^{\mu\nu}$$

(Voloshin 1988)

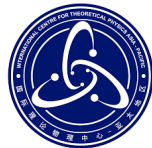
- ▶ Implementing Voloshin symmetry is challenging, as it doesn't commute with SM.

(Barbari, Mohapatra 1989)

- ▶ A horizontal $SU(2)_H$ symmetry acting on the electron and muon families can serve the same purpose, as it commutes with the weak interactions.

(Babu, Mohapatra 1990)

- ▶ $SU(2)_H$ need to be broken to explain mass difference between e^- and μ^-



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Inverse Seesaw mechanism with $SU(2)_N$



- ▶ Extend SM neutrino sector by two SM gauge singlets: ν^c and N .
- ▶ Mass matrix in basis $\{\nu, \nu^c, N\}$,

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & M'_R & M_R \\ 0 & M_R^T & m_N \end{pmatrix}.$$

- ▶ N is doublet under $SU(2)_N$. In the $SU(2)_N$ limit $m_N = 0$.
- ▶ $M_{\text{diag}} = U^T M_\nu U$

$$U \equiv \begin{pmatrix} 1 & 0 & \rho \\ 0 & 1 & 0 \\ -\rho^T & 0 & 1 \end{pmatrix}, \quad \rho = m_D M_R^{T-1}$$

- ▶ We considered the limit, $m_N \ll m_D \ll M_R$ and $M'_R \ll M_R$
- ▶ $m_\nu^{\text{light}} = m_D M_R^{T-1} m_N M_R^{-1} m_D^T$
- ▶ Consider $\mu_N \neq 0$,

$$\mathcal{L}_{\text{mag}}^N = \frac{1}{2} \mu_{N_{ij}} \bar{N}_i \sigma^{\mu\nu} N_j F_{\mu\nu}$$

- ▶ SM neutrinos acquire a magnetic moment through mixing with N .

$$\begin{aligned} \mu_\nu^{\text{light}} &= \rho \mu_N \rho^T \\ &= m_D M_R^{T-1} \mu_N M_R^{-1} m_D^T. \end{aligned}$$

- ▶ We need large μ_N with suppressed mass m for N .



- ▶ Based on an approximate $SU(2)_N$ symmetry acting on the singlet fermion N analogous to the $SU(2)_H$ symmetry in the Voloshin mechanism.
- ▶ Introducing scalar fields η, ϕ and fermion fields E, E^c , with charges under $SU(2)_L \times SU(2)_N \times U(1)_Y$:

$$\eta \equiv (1, 2, 2), \quad \phi \equiv (1, 2, 0), \quad E \equiv (a, 1, -2), \quad N \equiv (1, 2, 0).$$

- ▶ The relevant Yukawa terms are given by,

$$\mathcal{L} \supset y_i \nu_i^c N^T i\tau_2 \phi + y'_i \nu_i^c \phi^\dagger N + f N^T i\tau_2 \eta^+ E + f' \eta^- N E^c.$$

- ▶ Effective potential,

$$V_{\text{scalar}} = m_\eta^2 \eta^\dagger \eta + m_\phi^2 \phi^\dagger \phi + \lambda_\phi (\phi^\dagger \phi)^2 + \lambda (\phi^\dagger \eta) (\eta^\dagger \phi) \\ + \lambda_\eta (\eta^\dagger \eta)^2 + \lambda' \{ (\eta^\dagger \phi) (\eta^T i\tau_2 \phi) + \text{h.c} \}.$$

- ▶ In the $SU(2)_N$ limit, the charged scalars η_1^+ and η_2^+ are degenerate.
- ▶ $SU(2)_N$ is broken by $\langle \phi \rangle \neq 0$, then λ, λ' breaks the degeneracy of η_1^+ and η_2^+ .

- ▶ The $SU(2)_N$ symmetry can be realised in three ways:
 1. Spontaneously broken gauged symmetry: Requires two copies of N to cancel Witten anomaly
 2. Spontaneously broken global symmetry: Three Majorons remain in thermal equilibrium until BBN via $JJ \rightarrow \bar{\nu}\nu$, leading to N_{eff} constraints. Evading them requires small ρ , suppressing μ_{ij} .
 3. Softly broken global symmetry: $m_{1,2,3,4}^2 \sim (100 \text{ MeV})^2$

$$V_{\text{soft}} = m_1^2 |\phi_2|^2 + (m_2^2 \phi_1^2 + m_3^2 \phi_2^2 + \text{h.c.}) + m_4^2 \eta_2^2$$

- ▶ The structure of V_{soft} can be understood in terms of a spurion field χ associated with $SU(2)_N$ breaking. Taking χ to be odd under the reflection symmetry, the allowed interaction terms are:

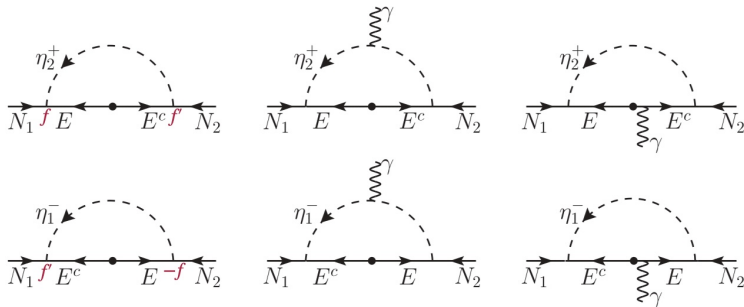
$$V_{\text{spurion}} = \kappa_1 |\phi^\dagger \chi|^2 + \left\{ \kappa_2 (\phi^T i\tau_2 \chi)^2 + \kappa_3 (\phi^\dagger i\tau_2 \chi)^2 + \text{h.c.} \right\} + \kappa_4 |\eta^\dagger \chi|^2,$$

when the spurion field χ acquires a VEV aligned with $(0, 1)^T$

Mass matrix m_N

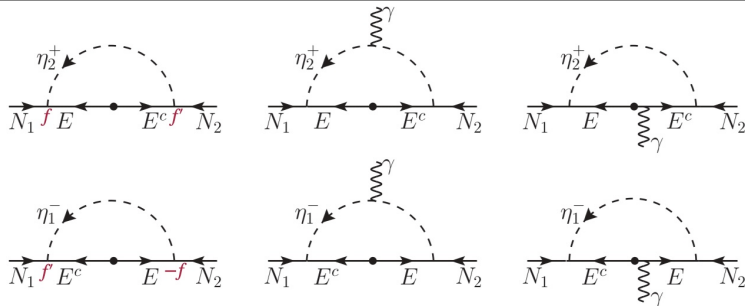


$$\mathcal{L} = f(N_1\eta_2^+ - N_2\eta_1^+)E + f' (N_1\eta_1^- + N_2\eta_2^-) E^c$$



$$m_{N_{12}} = \frac{(c_\theta^2 - s_\theta^2)ff'M_E}{16\pi^2} \left[\frac{\left(M_E^2 \log \left[\frac{\Lambda^2}{M_E^2} \right] - M_{\eta_B}^2 \log \left[\frac{\Lambda^2}{M_{\eta_B}^2} \right] \right)}{M_E^2 - M_{\eta_B}^2} - \frac{\left(M_E^2 \log \left[\frac{\Lambda^2}{M_E^2} \right] - M_{\eta_A}^2 \log \left[\frac{\Lambda^2}{M_{\eta_A}^2} \right] \right)}{M_E^2 - M_{\eta_A}^2} \right]$$

Magnetic moment μ_N



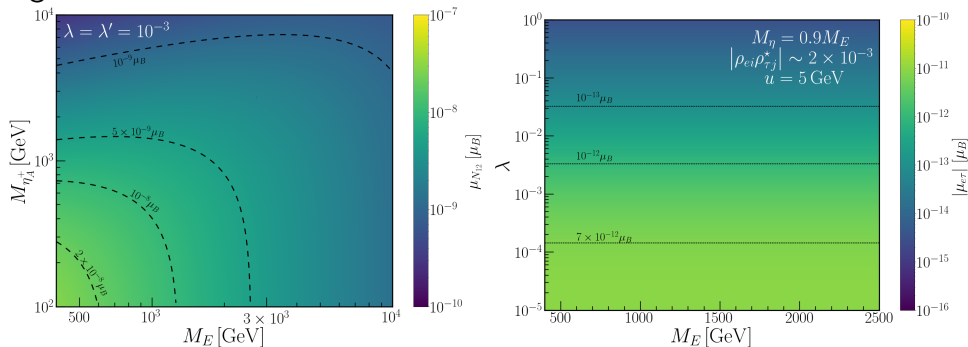
- Charge flows opposite direction for η_1^+ and η_2^+ contributions leading to constructive contributions to $\mu_{N_{12}}$.

$$\mu_{N_{12}} = \frac{e \operatorname{Re}(ff')}{32\pi^2} \left\{ \frac{M_E}{M_{\eta_B^2}} \left(Q_{\eta_B^+} F_3(x) - Q_E F_6(x) \right) - \frac{M_E}{M_{\eta_A^2}} \left(Q_{\eta_A^-} F_3(x) - Q_{E^c} F_6(x) \right) \right\},$$

$$\approx \frac{m_e}{8\pi^2} \left\{ \frac{M_E}{M_{\eta_B^2}} \operatorname{Re}(ff') \left(Q_{\eta_B^+} F_3(x) - Q_E F_6(x) \right) \right\} \mu_B.$$

$x = \frac{M_E^2}{M_{\eta_A}^2}$

- ▶ The sterile neutrino predominantly decays via $\nu^c \rightarrow \nu + J_i$, evading constraints from visible decays.
- ▶ The dominant constraints on the sterile-neutrino parameter space arise from its mixing with SM neutrinos.



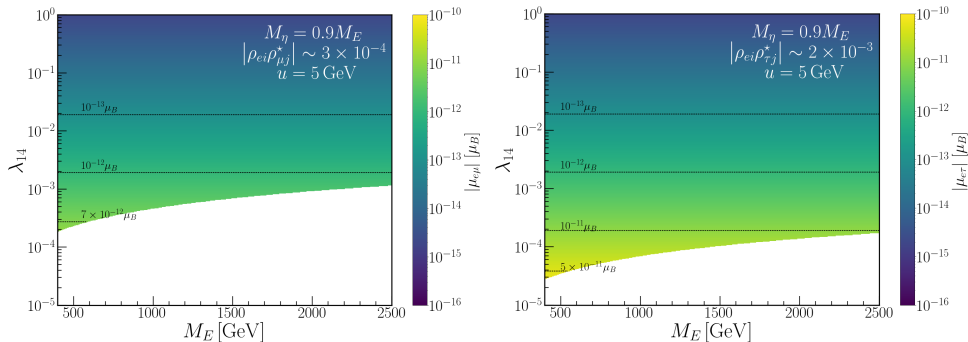
- ▶ $\mu_{e\tau}$ exhibit only a mild dependence on λ once $\lambda \lesssim m_4^2/u^2$.
- ▶ The neutrino magnetic moments can reach values as large as $10^{-11} \mu_B$



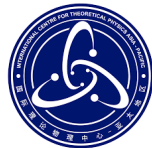
- Instead of $SU(2)$, we could employ its discrete subgroup, the quaternion group Q_4 , in our mechanism.
- Q_4 has eight elements and five irreducible representations: four singlets $\mathbf{1}^{++}, \mathbf{1}^{+-}, \mathbf{1}^{-+}, \mathbf{1}^{\sim}$ and one doublet $\mathbf{2}$.
- The scalar potential ($\phi = (\phi_1, \phi_2)^T$ and $\eta = (\eta_1, \eta_2)^T$)

$$\begin{aligned}
 V_{\text{scalar}} = & m_\phi^2 (|\phi_1|^2 + |\phi_2|^2) + m_\eta^2 (|\eta_1|^2 + |\eta_2|^2) + \lambda_1 (|\phi_1|^2 + |\phi_2|^2)^2 + \lambda_2 (|\phi_1|^2 - |\phi_2|^2)^2 \\
 & + \lambda_3 (\phi_1^* \phi_2 + \phi_2^* \phi_1)^2 + \lambda_4 [i (\phi_1^* \phi_2 - \phi_2^* \phi_1)]^2 + \frac{1}{2} [\lambda_5 (\phi_1^2 + \phi_2^2)^2 + \lambda_6 (\phi_1^2 - \phi_2^2)^2 + \lambda_7 (2\phi_1 \phi_2)^2 + \text{h.c.}] \\
 & + \lambda_8 (|\eta_1|^2 + |\eta_2|^2)^2 + \lambda_9 (|\eta_1|^2 - |\eta_2|^2)^2 + \lambda_{10} (\eta_1^* \eta_2 + \eta_2^* \eta_1)^2 + \lambda_{11} [i (\eta_1^* \eta_2 - \eta_2^* \eta_1)]^2 + \lambda_{12} \eta_1 \eta_2 \eta_1^* \eta_2^* \\
 & + \lambda_{13} (|\phi_1|^2 + |\phi_2|^2) (|\eta_1|^2 + |\eta_2|^2) + \lambda_{14} (|\phi_1|^2 - |\phi_2|^2) (|\eta_1|^2 - |\eta_2|^2) \\
 & + \lambda_{15} (\phi_1^* \phi_2 + \phi_2^* \phi_1) (\eta_1^* \eta_2 + \eta_2^* \eta_1) + \lambda_{16} [i (\phi_1^* \phi_2 - \phi_2^* \phi_1)] [i (\eta_1^* \eta_2 - \eta_2^* \eta_1)] \\
 & + \frac{1}{2} [\lambda_{17} (\phi_1^2 + \phi_2^2) [i (\eta_1^* \eta_2 - \eta_2^* \eta_1)] + \lambda_{18} (\phi_1^2 - \phi_2^2) (\eta_1^* \eta_2 + \eta_2^* \eta_1) + \lambda_{19} \phi_1 \phi_2 (|\eta_1|^2 - |\eta_2|^2) + \text{h.c.}] \\
 & + \frac{1}{2} [\lambda_{20} (\phi_1^2 + \phi_2^2) [i (\phi_1^* \phi_2 - \phi_2^* \phi_1)] + \lambda_{21} (\phi_1^2 - \phi_2^2) (\phi_1^* \phi_2 + \phi_2^* \phi_1) + \lambda_{22} \phi_1 \phi_2 (|\phi_1|^2 - |\phi_2|^2) + \text{h.c.}]
 \end{aligned}$$

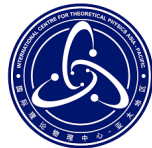
- Quartic couplings can generate masses for the Goldstone bosons.



- $\mu_{\nu_e \nu_\tau}$ can reach values as large as $5 \times 10^{-11} \mu_B$



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- ▶ We propose a novel horizontal-like symmetry to enhance the neutrino magnetic moment while keeping neutrino masses naturally small in an inverse seesaw framework.
- ▶ The sterile-neutrino mass m_N is radiatively generated, providing a natural explanation for its smallness.
- ▶ A horizontal-like $SU(2)_N$ symmetry acts on the sterile neutrinos N , while the SM sector remains unchanged.
- ▶ In the $SU(2)_N$ softly broken model, the SM neutrino magnetic moment can be as large as $\mu_{\nu_i \nu_j} \sim 10^{-11} \mu_B$.
- ▶ We could employ the global Q_4 symmetry, a discrete subgroup of $SU(2)$, where quartic couplings generate Goldstone-boson masses and SM neutrino magnetic moment can be as large as $\mu_{\nu_e \nu_\tau} \sim 5 \times 10^{-11} \mu_B$.

Thank You

