Magnetic Moments of Dirac Neutrinos

Nicole Bell
Vincenzo Cirigliano, Michael Ramsey-Musolf, Mark Wise and Petr Vogel
Caltech

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Size of neutrino magnetic moments

❖ Very small in the standard model:

$$\mu_\nu < 0.3\times 10^{-18}\,\mu_B\left(m_\nu / 1\,\mathrm{eV}\right)$$

→ A sizeable value would indicate new physics.

❖ Present limits much larger. A magnetic moment near the present limit would make a significant contribution to neutrino-nucleus cross-sections at MeV energies.

→neutrino-electron scattering. Weak and EM comparable if:

$$\frac{\mu_\nu}{\mu_B} \sim \frac{G_F m_e}{\sqrt{2}\pi\alpha}\sqrt{m_e T} \sim 10^{-10}\sqrt{\frac{T}{m_e}}$$

where T=kinetic energy of recoiling electron

Present Limits

- Reactor neutrinos: $0.9\times10^{-10}\,\mu_B$
- Solar neutrinos: $1.5\times10^{-10}\,\mu_B$

→ These both involve electrons → "μ_e"

- Red giant stars: $3\times10^{-12}\,\mu_B$

(energy loss mechanism, cannot exceed energy loss via weak processes.)

→ All flavors

Connection between Magnetic Moment and Neutrino Mass?

- In general, magnetic moment and mass are connected in a model *dependent* way.

- Large μ implies large m.

- We shall calculate a *model-independent* bound.

In the absence of fine-tuning:

$$m < 1\,\mathrm{eV} \quad \Rightarrow \quad |\mu_\nu| \leq 10^{-14}\,\mu_B$$

❖Leading contribution of μ to the neutrino mass is:

$$\delta m_\nu \sim \frac{\alpha}{32\pi} \frac{\Lambda^2}{m_e} \frac{\mu_\nu}{\mu_B}$$

where Λ is the scale of the new physics.

❖This is a contribution to the 4D neutrino mass operator:

$$\hat{O}_M^{(4)} = \left(\overline{L}\,\tilde{\phi}\right)\nu_R$$

❖The precise value of this 4D term cannot be cannot be calculated in a model-independent way, but for

$$\Lambda \geq 1\,\mathrm{TeV},\ \ m < 1\,\mathrm{eV} \quad \Rightarrow \quad |\mu_\nu| \leq 10^{-14}\,\mu_B$$

For Λ not significantly larger than the EW scale, higher dimension operators are important, and their contribution to m_ν can be calculated in a model-independent way.

What is the most general operator that could give rise to a neutrino magnetic moment term?

$$\overline{\nu}_L \sigma^{\mu\nu} F_{\mu\nu} \nu_R$$

Should be invariant under the SM gauge group SU(2)xU(1)

→

$$\hat{O}_B = \frac{g_1}{\Lambda^2} \left(\overline{L} \tilde{\phi} \right) \sigma^{\mu\nu} B_{\mu\nu} \nu_R$$

$$\hat{O}_W = \frac{g_2}{\Lambda^2} \left(\overline{L} \tau^a W^a_{\mu\nu} \tilde{\phi} \right) \sigma^{\mu\nu} \nu_R$$

O_B and O_W will mix under renormalization with the 6D mass operator O_M

$$\hat{O}_M = \frac{1}{\Lambda^2} \left(\overline{L} \tilde{\phi} \right) \left(\phi^\dagger \phi \right) \nu_R$$

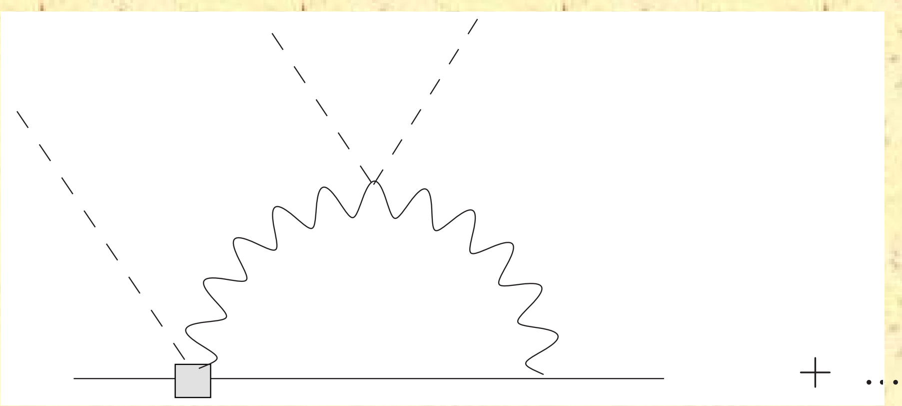
$$L_{eff} = C_B(\mu)\hat{O}_B + C_W(\mu)\hat{O}_W + C_M(\mu)\hat{O}_M + h.c.$$

$$\frac{\mu_\nu}{\mu_B} = -4\sqrt{2}\left(\frac{m_e v}{\Lambda^2}\right)C_+(\mu) \qquad C_\pm = C_B \pm C_W$$

$$\delta m_\nu = -C_M(\mu)\frac{v^3}{2\sqrt{2}\Lambda^2}$$

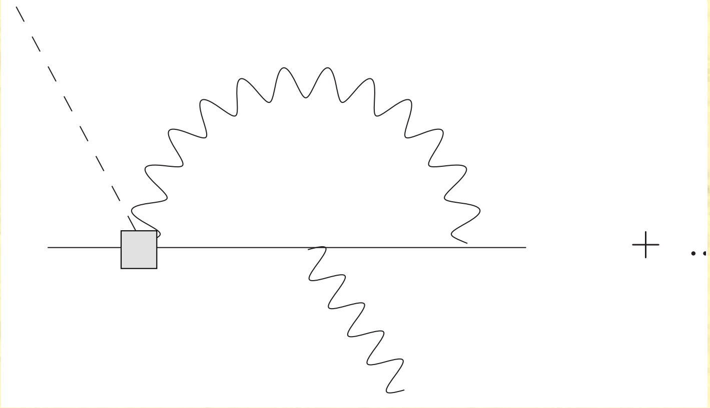
In order to relate μ and m, need connection between the coefficients $C_j(\mu)$ at the weak scale, μ=v.

→ Renormalization group eqns. relate $C_j(\Lambda)$ to $C_k(v)$.

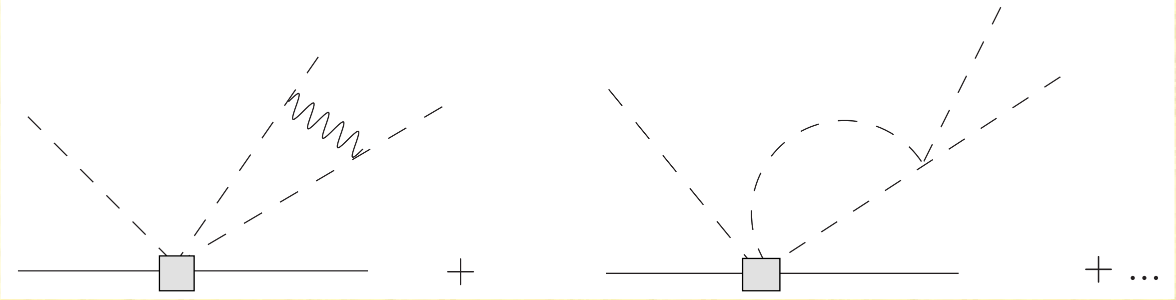


Renormalization of O_M by O_B, O_W

→Generates nu mass



Self-renormalization of O_B ,O_W



Self-renormalization of O_M

$$\frac{|\mu_\nu|}{\mu_B} = \frac{G_F m_e}{\sqrt{2}\pi\alpha}\left[\frac{\delta m_\nu}{\alpha \ln(\Lambda/v)}\right]\frac{32\pi \sin^4\theta_W}{9f}$$

$$f = (1-r) - \frac{2}{3} r \tan^2\theta_W - \frac{1}{3}(1+r)\tan^4\theta_W$$

where: $$r = \frac{C_-(\Lambda)}{C_+(\Lambda)} \equiv \frac{C_B(\Lambda) - C_W(\Lambda)}{C_B(\Lambda) + C_W(\Lambda)}$$

$$\boxed{\Lambda \geq 1\,\mathrm{TeV} \quad \Rightarrow \quad \frac{|\mu_\nu|}{\mu_B} \leq 0.8\times 10^{-14}\left(\frac{\delta m_\nu}{1\,\mathrm{eV}}\right)\frac{1}{|f|}}$$

What about Majorana neutrinos?

❖Differences: Only transition moments allowed.

Magnetic moment → μ_{ij} antisymmetric in i,j

Mass matrix → m_{ij} symmetric in i,j

→δm higher order in μ or involve insertions of Yukawa couplings/charged lepton masses → weaker limit

S.Davidson, M.Gorbahn and A.Santamaria, hep-ph/0506085.

Flavor dependent:

→ $\mu_{e\tau}, \mu_{\mu\tau}$ constrained to $\mu / \mu_B \approx 10^{-11} \left(\delta m_\nu / 1\text{eV} \right)$

→ Bound on $\mu_{e\mu}$ is weaker again.

Summary

❖In the absence of fine-tuning, the natural size of a Dirac neutrino magnetic moment is: $\mu < 10^{-14}\,\mu_B$

❖This applies to *any* element of μ_{ij}

➢Reactor/solar neutrino limits: $\mu < 10^{-10}\,\mu_B$
➢Astrophysical limits: $\mu < 10^{-12}\,\mu_B$

Bell, Cirigliano, Ramsey-Musolf, Wise & Vogel, Phys. Rev. Lett. 95, 151802, 2005.