Right-Handed Neutrinos and T-Violating, P-Conserving Interactions

arxiv: 1605.xxxxx[hep-ph]

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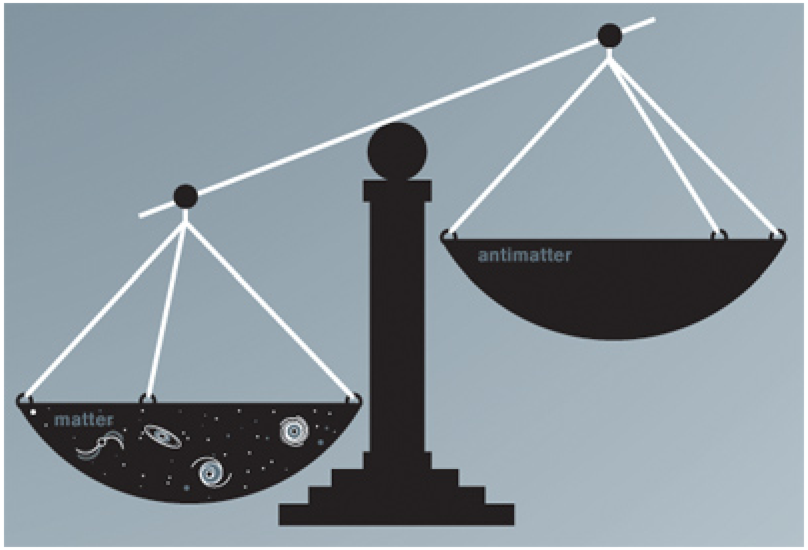
Outline

- P-even, T-odd physics in β–decay
- Direct and indirect bounds
- Effective field theory descriptions
- Analysis of dim-6 operators with/without right-handed neutrinos
- Summary

Why Study T-violation?

- Sakharov criteria for baryon-antibaryon asymmetry: *A.D.Sakharov, Pisma Zh. Eksp. Teor. Fiz 5 (1967) 32*
  - B-violation
  - C and CP-violation
  - Interaction out of thermal equilibrium

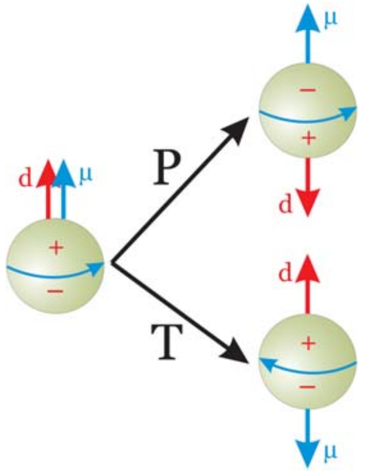
CP-violation → T-violation by CPT theorem



	P-even	P-odd
T-even	**Big** SM background.	**Big** SM background.
T-odd	**Small** SM background. **Less** constrained.	**Small** SM background. **Tightly** constrained.

Tight Constraints on P-odd, T-odd Physics: Electric Dipole Moments (EDMs)

$$V_{EDM} = -d_n \vec{J} \cdot \vec{E}$$



System	Present Limit (e cm)	SM Prediction (CKM) (e cm)
e	8.7×10^{-29}	10^{-38}
Hg	7.4×10^{-30}	10^{-33}
p	7.9×10^{-25}	10^{-31}
n	3.0×10^{-26}	10^{-31}

	P-even	P-odd
T-even	**Big** SM background.	**Big** SM background.
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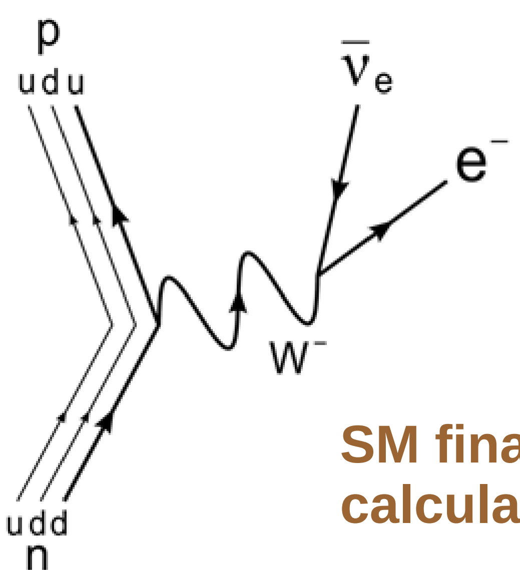
P-even, T-odd observable in polarized neutron β–decay

$$n \to p e^- \overline{\nu}_e$$

$$\frac{d\Gamma}{d\Omega_e d\Omega_\nu dE_e} = \frac{(G_F V_{ud})^2}{(2\pi)^5}(1+3g_A^2)\,|\,\vec{p}_e\,|\,E_e E_\nu^2\{1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \hat{s}\cdot(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu})\}$$



T-odd, P-even

Experimental value:

$$D = (-0.96 \pm 1.89 \pm 1.01) \times 10^{-4}$$

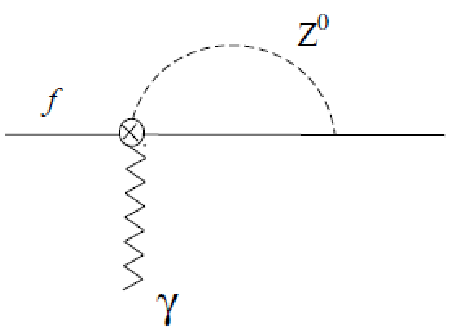
Mumm et al, Phys.Rev.Lett., 107 (2011) 102301

SM final-state interaction: $D_f \sim 10^{-5}$
calculated to 1% accuracy.

Ando, McGovern and Sato, Phys. Lett B677 (2009) 109

Direct and Indirect Bound

- **General argument**: a P-even, T-odd operator may also induce P, T-odd interaction via electroweak loop corrections that violate P. *Conti and Khriplovich, PRL 68(1992)3262*
- **Example**: A dim-7 gauge-invariant P-even, T-odd operator may induce fermion EDM at one loop:



$$\mathcal{O}_7^{\gamma Z} = C_7^{\gamma Z}\, \bar{\psi}\sigma_{\mu\nu}\psi F^{\mu\lambda} Z_\lambda^\nu$$

Ramsey-Musolf, PRL 83 (1999) 3997

- **Question**: are the "indirect bounds" set by limits on P, T-odd observables always more stringent than the direct experimental bounds on P-even, T-odd observables?

Effective Field Theory Description

- P-even, T-odd interaction **CANNOT** arise at tree-level in a renormalizable gauge theory (Herczeg, Hyperfine Interact, 75, (1992)127)
- This motivates us to adopt **EFT**: a **bottom-up approach** to the study of BSM physics
- Assumption: new DOFs are heavy and can be integrated out

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \ldots$$

- Flavor-conserving P-even, T-odd operators occur at d≥7 (Conti and Khriplovich, PRL 68(1992)3262)
- d≥6 for flavor non-conserving P-even, T-odd operators

We shall focus on d=6.

Dim-6 Semi-Leptonic Operators With Right-Handed Neutrino

$$\hat{O}_1 = \frac{c_1}{\Lambda^2}\bar{L}^i \nu_R \bar{u}_R Q^i + h.c.$$
$$\hat{O}_2 = \frac{c_2}{\Lambda^2}\varepsilon^{ij}\bar{L}^i \nu_R \bar{Q}^j d_R + h.c.$$
$$\hat{O}_3 = \frac{c_3}{\Lambda^2}\varepsilon^{ij}\bar{L}^i \sigma^{\mu\nu} \nu_R \bar{Q}^j \sigma_{\mu\nu} d_R + h.c.$$

Induced D-coefficient: $$D \approx -\frac{g_S g_T}{\Lambda^4}\frac{1}{G_F^2 V_{ud}^2 (g_V^2 + 3g_A^2)}\mathrm{Im}[(c_1 - c_2)c_3^*]$$

(**Quadratic** in BSM Wilson Coefficients)

Implications from experimental bound:

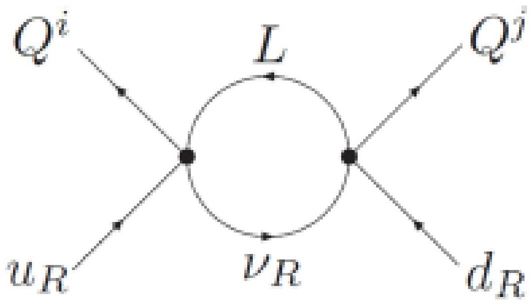
$$\left|\frac{\mathrm{Im}[(c_1 - c_2)c_3^*]}{\Lambda^4}\right| < 3 \times 10^{-13}\mathrm{GeV}^{-4}$$

Implied scale of new physics assuming c_i~1:

$$\Lambda > 1\,\mathrm{TeV}$$

Dim-6 Semi-Leptonic Operators With Right-Handed Neutrino

Implications from neutron EDM:



Semi-leptonic operator
↓
Four-quark operator
↓
Neutron EDM

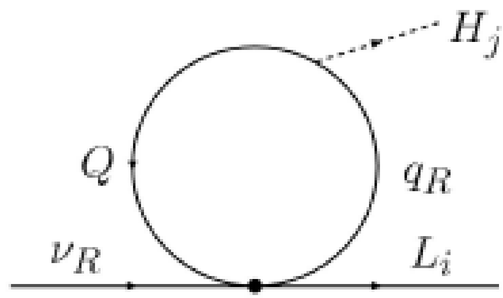
Naïve dimensional analysis (NDA) leads to $(v/\Lambda)^2 \,\mathrm{Im}\{c_1^* c_2\} \sim 10^{-5}$

Two points for the save:

1. Large uncertainty expected in the NDA estimation.
2. EDMs only constrain Im$c_1^*c_2$ but do not touch c_3. It cannot place any strict bound on D-coefficient.

Dim-6 Semi-Leptonic Operators With Right-Handed Neutrino

Naturalness bound from neutrino mass:



$$m_\nu \sim \frac{c_i}{\Lambda^2}\frac{\Lambda^2}{16\pi^2} m_q = \frac{c_i m_q}{16\pi^2} \qquad i=1,2$$

Naïve Dimensional Analysis (NDA) involved

$m_\nu < 1\,\mathrm{eV}$ leads to: $c_i < 3\times 10^{-5}$

But the result **may vary a lot** depending on details of the underlying BSM scenario!

*Also, the coefficient of **tensor operator c_3** is unconstrained.*

Contrast: Dim-6 Operators WITHOUT Right-Handed Neutrinos

φud:

$$\hat{O}_{\varphi ud} = \frac{\mathrm{Im}C_{\varphi ud}}{\Lambda^2}(\tilde{\varphi}^+ D_\mu \varphi)(\bar{u}_R \gamma^\mu d_R) + h.c.$$

Four-fermion:

$$\hat{O}_{ledq} = i\frac{\mathrm{Im}C_{ledq}}{\Lambda^2} \bar{L}^i e_R \bar{d}_R Q^i + h.c.$$

$$\hat{O}^{(1)}_{lequ} = i\frac{\mathrm{Im}C^{(1)}_{lequ}}{\Lambda^2} \varepsilon^{ij} \bar{L}^i e_R \bar{Q}^j u_R + h.c.$$

$$\hat{O}^{(3)}_{lequ} = i\frac{\mathrm{Im}C^{(3)}_{lequ}}{\Lambda^2} \varepsilon^{ij} \bar{L}^i \sigma^{\mu\nu} e_R \bar{Q}^j \sigma_{\mu\nu} u_R + h.c.$$

Dipole operators:

$$\hat{O}_{eB} = i\frac{g' \mathrm{Im}C_{eB}}{\Lambda^2} \bar{L}\sigma^{\mu\nu} H e_R B_{\mu\nu} + h.c.$$

$$\hat{O}_{eW} = i\frac{g \mathrm{Im}C_{eW}}{\Lambda^2} \bar{L}\sigma^{\mu\nu} \frac{\tau^i}{2} H e_R W^i_{\mu\nu} + h.c.$$

Grzadkowski et al, JHEP 1010 (2010) 085

Contrast: Dim-6 Operators WITHOUT Right-Handed Neutrinos

φud:

$$\hat{O}_{\varphi ud} \sim \frac{C_{\varphi ud}}{\Lambda^2}(\tilde{\varphi}^+ D_\mu \varphi)(\bar{u}_R \gamma^\mu d_R) + h.c.$$

$$\rightarrow \frac{C'}{\Lambda^2}\bar{u}_R \gamma^\mu d_R(\bar{e}_L \gamma_\mu \nu_L + \bar{d}_L \gamma_\mu u_L) + h.c.$$

Semi-leptonic:
β-decay

Non-leptonic:
hadron EDMs

Indirect bound on D-coefficient by neutron EDM: $D < 10^{-6}$

Two orders-of-magnitude more stringent than the direct bound and there is ***NO ESCAPE***!

Ng and Tulin, PRD 85, 033001 (2012)

Seng, de Vries, Mereghetti, Patel and Ramsey-Musolf, Phys. Lett B736 (2014) 147

Contrast: Dim-6 Operators WITHOUT Right-Handed Neutrinos

Four-fermion:

$$\hat{O}_{ledq} = i\frac{\mathrm{Im}C_{ledq}}{\Lambda^2}\bar{L}^i e_R \bar{d}_R Q^i + h.c.$$

$$\hat{O}^{(1)}_{lequ} = i\frac{\mathrm{Im}C^{(1)}_{lequ}}{\Lambda^2}\varepsilon^{ij}\bar{L}^i e_R \bar{Q}^j u_R + h.c.$$

$$\hat{O}^{(3)}_{lequ} = i\frac{\mathrm{Im}C^{(3)}_{lequ}}{\Lambda^2}\varepsilon^{ij}\bar{L}^i \sigma^{\mu\nu} e_R \bar{Q}^j \sigma_{\mu\nu} u_R + h.c.$$

Contribute ***quadratically*** to ***D-coefficient*** but ***linearly*** to ***EDMs***.

Hopeless to escape from stringent indirect bounds without fine-tuning.

Contrast: Dim-6 Operators WITHOUT Right-Handed Neutrinos

Dipole operators:

$$\hat{O}_{eB} = i\frac{g'\mathrm{Im}C_{eB}}{\Lambda^2}\bar{L}\sigma^{\mu\nu}He_R B_{\mu\nu} + h.c.$$

$$\hat{O}_{eW} = i\frac{g\mathrm{Im}C_{eW}}{\Lambda^2}\bar{L}\sigma^{\mu\nu}\frac{\tau^i}{2}He_R W^i_{\mu\nu} + h.c.$$

Induced D-coefficient:

$$D = -\frac{4\sqrt{2}g_A^2}{g_V^2 + 3g_A^2}\left(\frac{m_e}{v}\right)\left(\frac{v}{\Lambda}\right)^2 \mathrm{Im}C_{eW}$$

Induced electron EDM:

$$d_e = -\frac{\sqrt{2}e}{v}\left(\frac{v}{\Lambda}\right)^2(\mathrm{Im}C_{eB} - \mathrm{Im}C_{eW})$$

Setting $\mathrm{Im}\,C_{eB} \approx \mathrm{Im}\,C_{eW}$ at μ=m_W may avoid EDM but it is **highly unnatural** due to **electroweak loop correction**; requires 13 orders of magnitude fine-tuning at μ=10 TeV!

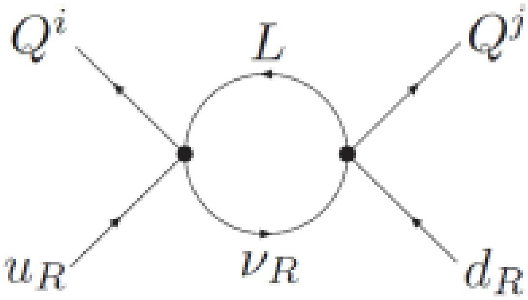
Conclusions

- The triple-correlation (D-coefficient) in neutron/nuclear β–decay serves as a probe of P-conserving, T-violating interactions
- If neutrinos are Dirac particles, current bound on neutron D-coefficient points towards a new scale of PCTV physics: Λ/c>1TeV
- The chance of observing a non-zero D-coefficient in a next-generation experiment is not precluded by constraints of EDM search null results.
- Operators without right-handed neutrinos cannot avoid stringent bounds from EDMs without fine-tuning.
- Resolving the tension between a non-zero PCTV correlation and neutrino mass naturalness consideration would provide interesting challenge for model building.

Thank You!

Backup Slides

EDM induced by O_1-O_3



Matching to the four-quark operator:

$$\frac{C^{(1)}_{quqd}}{\Lambda^2}\varepsilon^{ij}\bar{Q}^i u_R \bar{Q}^j d_R + h.c.$$

$$\frac{C^{(1)}_{quqd}}{\Lambda^2} \sim \frac{c_1^* c_2}{\Lambda^4}\frac{\Lambda^2}{16\pi^2} = \frac{c_1^* c_2}{16\pi^2\Lambda^2}$$

Matching between the four-quark operator and neutron EDM:

$$d_n = \beta_n^{quqd}(\frac{v}{\Lambda})^2 \mathrm{Im} C^{(1)}_{quqd}$$

Estimated range of hadronic matrix element:

$$\beta_n^{quqd} = (10-80)\times 10^{-7}\, e\,\mathrm{fm}$$

Engel, Ramsey-Musolf and van Kolck, Prog. Part. Nucl. Phys. 71(2013) 21

Running of Dipole Operators

Closed set of T-odd operators:

$$\hat{O}_{eB} \;=\; i\frac{g'\mathrm{Im}C_{eB}}{\Lambda^2}\bar{L}\sigma^{\mu\nu}He_R B_{\mu\nu} + h.c.$$
$$\hat{O}_{eW} \;=\; i\frac{g\mathrm{Im}C_{eW}}{\Lambda^2}\bar{L}\sigma^{\mu\nu}\frac{\tau^i}{2}He_R W^i_{\mu\nu} + h.c.$$
$$\hat{O}_{eH^3} \;=\; i\frac{\mathrm{Im}C_{eH^3}}{\Lambda^2}\bar{L}He_R H^\dagger H + h.c.$$

Constraints from neutron D-coefficient and electron EDM:

$$(v/\Lambda)^2|\mathrm{Im}C_{eW}| < 1\times 10^2.$$

$$(v/\Lambda)^2|\mathrm{Im}C_{eB} - \mathrm{Im}C_{eW}| < 7.7\times 10^{-13}$$

Electroweak running:

$$\frac{d\Theta}{d\ln\mu} = \begin{pmatrix} \frac{151g'^2-27g^2}{192\pi^2} & -\frac{3gg'}{64\pi^2} & 0 \\ -\frac{gg'}{16\pi^2} & \frac{-11g^2+3g'^2}{192\pi^2} & 0 \\ -\frac{3g'(g^2-3g'^2)}{16\pi^2} & -\frac{9g(g^2-g'^2)}{32\pi^2} & -\frac{3(9g^2+7g'^2)}{64\pi^2} \end{pmatrix} \Theta$$

$$\Theta = \left(g'\mathrm{Im}C_{eB} \;\; g\mathrm{Im}C_{eW} \;\; \mathrm{Im}C_{eH^3} \right)^T$$

If $\mathrm{Im}C_{eW}$ and $\mathrm{Im}C_{eB}$ are set to marginally satisfy the two bounds at $\mu=m_W$, then at μ=10TeV, we have:

$$|\,\mathrm{Im}C_{eW} - \mathrm{Im}C_{eB}\,| \approx 4$$

but has to be fine-tuned to $2*10^{-11}$% of its magnitude!