A T-odd Momentum Correlation in Radiative β-Decay

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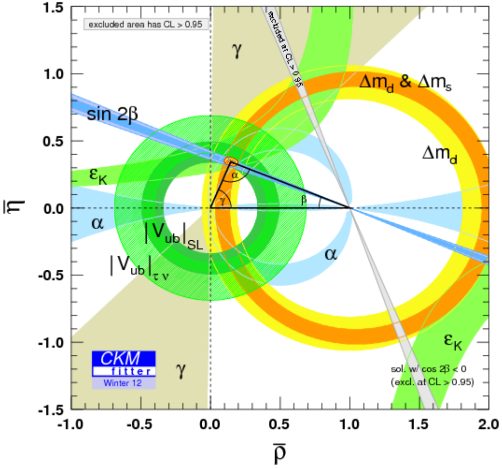
Context: CP violation in 2012



Flavor and CP violation in flavor-changing processes is dominated by the CKM mechanism.

[CKMfitter: hep-ph/0104062, hep-ph/0406184 ; http://ckmfitter.in2p3.fr – Winter, 2012 update]

But the CKM mechanism cannot explain the Baryon asymmetry of the Universe....

What's Next?

We can

i) continue to test the **relationships** that a single CP-violating parameter entails to higher precision

– as well as –

ii) continue to make "null" tests.
Enter EDMs, as they are inaccessibly small in the (C)KM model.

Limits on permanent EDMs of nondegenerate systems and T-odd correlations in β-decays probe new sources of CP violation — these observables necessarily involve spin.

In some models the severity of EDM limits make the appreciable appearance of new physics in T-odd β-decay correlations [D term] impossible.

[Herczeg (2004), Ng and Tulin (2012)]

In radiative β-decay we can form a T-odd correlation from momenta alone, $\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\nu)$: we probe new spin-independent sources of CP violation.

Anomalous interactions at low energies

What sort of interaction gives rise to a $\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\nu)$ correlation at low energy?

Harvey, Hill, and Hill: Gauging the axial anomaly of QCD under $SU(2)_L \times U(1)_Y$ makes the baryon vector current anomalous and gives rise to "Chern-Simons" contact interactions (containing $\varepsilon^{\mu\nu\rho\sigma}$) at low energy.

[Harvey, Hill, and Hill (2007, 2008)]

In a chiral Lagrangian with nucleons, pions, and a complete set of electroweak gauge fields, the requisite terms appear at N^2LO in the chiral expansion. Namely, [Hill (2010)]

$$\mathcal{L}^{(3)} = ... + \frac{c_5}{M^2} \bar{N} i \varepsilon^{\mu\nu\rho\sigma} \gamma_\sigma \tau^a \mathrm{Tr}(\{A_\mu, [iD_\nu, iD_\rho]\}) N + ...$$

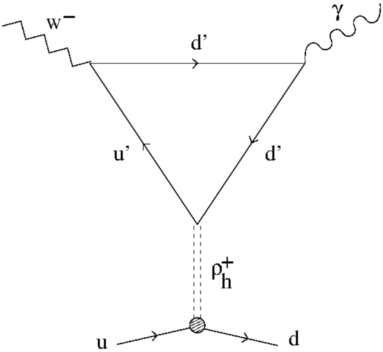
Thus the weak vector current can mediate parity violation on its own.

Our correlation probes the Im part of the interference with the leading vector amplitude. Existing constraints are poor.

What new physics can enter?

The LEC c_5 need not be real in theories beyond the SM.

Hidden-sector fermionic matter can appear via



and interfere with SM contributions to yield $\mathrm{Im}(c_5\, g_v)$.

The notion of new matter with QCD-like interactions is not new. Note, e.g., "quirks" [Okun (1980); Kang and Luty (2008)] "dark quarks" [Blennow et al. (2011)].

Here we imagine the matter to be light and weakly coupled. We probe CP phases associated with hidden-sector interactions.

"Dark" Baryogenesis

Perhaps a hidden sector helps mediate baryogenesis.

In **asymmetric dark matter** models dark matter and the BAU are tied...

Usually

i) **A baryon asymmetry is formed and transferred to dark matter.** [DB Kaplan, PRL 1992; ... DE Kaplan, Luty, Zurek, PRD 2009]

A B-L asymmetry generated at high T is transferred to DM which carries a B-L charge.

The relic density is set by the BAU and **not** by thermal freeze-out.

Thus $n_{\rm DM} \sim n_{\rm B}$ and $\Omega_{\rm DM} \sim (M_{\rm DM}/M_{\rm B})\Omega_{\rm B}$. Note $M_{\rm DM} \sim 5 - 15$ GeV.

But alternatives are possible:

ii) **A dark matter asymmetry is formed and transferred to the baryon sector.** [Shelton and Zurek, arXiv:1008.1997; Davoudiasl et al., arXiv:1008.2399; Haba and Matsumoto, arXiv:1008.2487; Buckley and Randall, arXiv:1009.0270.]

iii) **Dark matter and baryon asymmetries are formed simultaneously.** [Blennow et al, arXiv:1009.3159; Hall, March-Russell, and West, arXiv:1010.0245]

E.g., a lepton asymmetry is induced and converted to baryons and DM via new sphaleron processes from an extra non-abelian symmetry common ($SU(2)_H$) to both visible and dark sectors....

New fermions with QCD-like interactions do not mix with neutrinos.

A T-odd Correlation in Radiative β-Decay

In $n(p_n) \to p(p_p) + e^-(l_e) + \overline{\nu}_e(l_\nu) + \gamma(k)$ decay interference with the $V - A$ terms yields to leading recoil and radiative order

$$|\mathcal{M}|^2 = 512 M^2 \frac{e^2 G_F^2}{2} \mathrm{Im}\,(c_5\, g_v) \frac{E_e}{l_e \cdot k} (\mathbf{l}_e \times \mathbf{k}) \cdot \mathbf{l}_\nu + \ldots$$

The pseudo-T-odd interference term is finite as $\omega \to 0$.

Defining $\xi \equiv (\mathbf{l}_e \times \mathbf{k}) \cdot \mathbf{l}_\nu$ we partition phase space into regions of definite sign:

$$\mathcal{A} \equiv \frac{(\Gamma_{\xi>0} - \Gamma_{\xi<0})}{(\Gamma_{\xi>0} + \Gamma_{\xi<0})}$$

To leading recoil order, where $\omega^{\min}$ is lowest detectable photon energy,

$$\mathcal{A}(\omega^{\min} = 0.01\,\mathrm{MeV}) = -1.2 \cdot 10^{-2} \mathrm{Im}\, \frac{c_5 g_v}{M^2} (\mathrm{MeV}^{-2})\,,$$

$$\mathrm{Br}(\omega^{\min} = 0.01\,\mathrm{MeV}) = 3.5 \cdot 10^{-3} \text{ and}$$

$$\mathcal{A}(\omega^{\min} = 0.3\,\mathrm{MeV}) = -1.0 \cdot 10^{-1} \mathrm{Im}\, \frac{c_5 g_v}{M^2} (\mathrm{MeV}^{-2})\,, \mathrm{Br}(\omega^{\min} = 0.3\,\mathrm{MeV}) = 8.6 \cdot 10^{-5}$$

Induced Correlations from Known Final-State Interactions

Decay correlations can be motion-reversal-odd only. This means that final-state interactions can mimic T-odd effects.

[Callan and Treiman (1967); Khriplovich and Okun (1967)]

A triple momentum correlation has been previously studied in $K^+ \to \pi^0 l^+ \nu_l \gamma$ decay. There both electromagnetic and strong (π mediated) radiative corrections can mimic the T-odd effect, but the em-induced effects are orders of magnitude larger.

[Braguta, Likhoded, and Chalov (2002); Khriplovich and Rudenko, arXiv:1012.0147 (2010); Müller, Kubis, and Meißner (2006)]

The small energy release associated with neutron and nuclear radiative β-decay imply that only electromagnetic radiative corrections can mimic the T-odd effect. The induced T-odd effects in this case have never been studied before.

Let's look at the radiative corrections which appear in $\mathcal{O}(\alpha)$ in neutron radiative β-decay.

Electromagnetic Simulation of T-Odd Effects

We first compute $\overline{|\mathcal{M}|^2}_{\mathrm{T-odd}}$ and then the asymmetry. We work in $\mathcal{O}(\alpha)$ and in **leading recoil order**.

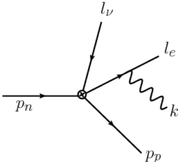
$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{tree}}|^2 + \mathcal{M}_{\mathrm{tree}} \cdot \mathcal{M}^*_{\mathrm{loop}} + \mathcal{M}_{\mathrm{loop}} \cdot \mathcal{M}^*_{\mathrm{tree}} + \mathcal{O}(\alpha^2)$$

$$\overline{|\mathcal{M}|^2}_{\mathrm{T-odd}} \equiv \frac{1}{2}\sum_{\mathrm{spins}} |\mathcal{M}|^2_{\mathrm{T-odd}} = \frac{1}{2}\sum_{\mathrm{spins}} (2\mathrm{Re}(\mathcal{M}_{\mathrm{tree}} i \mathrm{Im}\mathcal{M}^*_{\mathrm{loop}}))$$

Note "Cutkosky cuts" [Cutkosky, 1960]

$$\mathrm{Im}(\mathcal{M}_{\mathrm{loop}}) = \frac{1}{8\pi^2}\sum_n \int d\rho_n \sum_{s_n} \mathcal{M}_{fn}\mathcal{M}^*_{in} = \frac{1}{8\pi^2}\int d\rho_n \sum_{s_n} \mathcal{M}_{fn}\mathcal{M}_{ni}$$

There are many cancellations. At tree level



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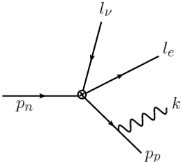

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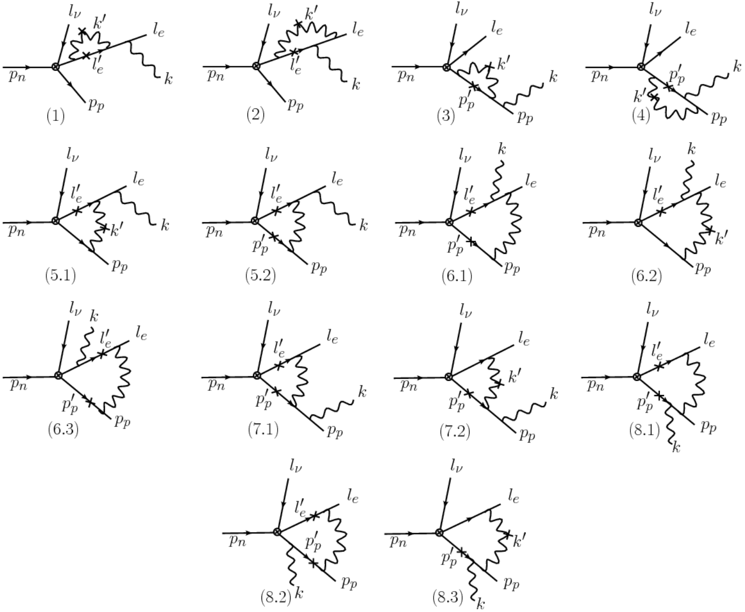
The Family of Two-Particle Cuts in $\mathcal{O}(e^3)$



Results

The interference with the tree level amplitude can yield zero. Namely, for the $\gamma - p$ family

$$\overline{|\mathcal{M}|^2}_{\mathrm{T-odd}}\,[3.01 + 3.02 + 4.01 + 4.02 + 7.2.01 + 7.2.02 + 8.3.01 + 8.3.02] = 0 + \mathcal{O}(M)\,,$$

The $e - p - \gamma$ family includes

$$\overline{|\mathcal{M}|^2}_{\mathrm{T-odd}}\,[7.1.01 + 7.1.02 + 8.1.01 + 8.1.02] = 0 + \mathcal{O}(M)\,,$$

For the $e - p$ family $a_{8.2}^{\mathrm{div}} \sim J_{8.2}^{\mathrm{div}} \sim (l_e \cdot k) J_{6.3}^{\mathrm{div}}/(M\omega)$ and $a_{6.3}^{\mathrm{div}} \sim f_{6.3}^{\mathrm{div}} \sim J_{6.3}^{\mathrm{div}}$:

$$\begin{aligned}
&\overline{|\mathcal{M}|^2}_{\mathrm{T-odd}}\,[6.3.01 + 6.3.02 + 8.2.01 + 8.2.02] \\
&= -\alpha^2 g_V^2 G_F^2 \xi 64 M^3 (1-\lambda^2)\left(\frac{2m_e^2}{l_e \cdot k} k_{6.3} - \frac{2E_e}{\omega} k_{6.3} - \frac{2E_e}{\omega} a_{6.3} - \frac{2M}{\omega} i_{6.3}\right. \\
&- \frac{M}{\omega} c_{6.3} - \frac{m_e^2}{l_e \cdot k} f_{6.3} + \frac{2m_e^2}{l_e \cdot k} a_{6.3} - \frac{m_e^2}{l_e \cdot k} J_{6.3} + \frac{2ME_e}{l_e \cdot k} a_{8.2} + \frac{2ME_e}{l_e \cdot k} i_{6.3} \\
&\left. - \frac{2ME_e}{l_e \cdot k} h_{6.3} + \frac{M^2}{l_e \cdot k} c_{8.2} - \frac{M^2}{l_e \cdot k} e_{6.3}\right).
\end{aligned}$$

The infrared divergence cancels in $\mathcal{O}(M^2)$.

Electromagnetic Simulation of T-Odd Effects

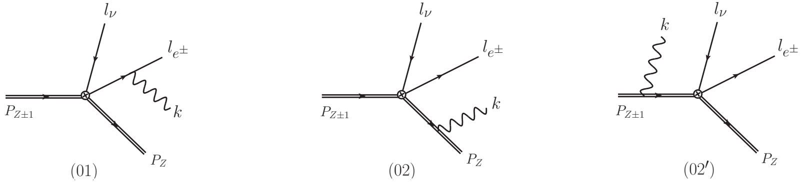
The asymmetry computed from the "$e - p$" and "$e - p - \gamma$" cuts dominate the numerical results.
For the neutron...

$\omega_{\rm min}$(MeV)	$A_\xi^{\rm SM}$
0.01	1.76×10^{-5}
0.05	3.86×10^{-5}
0.1	6.07×10^{-5}
0.2	9.94×10^{-5}
0.3	1.31×10^{-4}
0.4	1.54×10^{-4}
0.5	1.70×10^{-4}
0.6	1.81×10^{-4}
0.7	1.89×10^{-4}

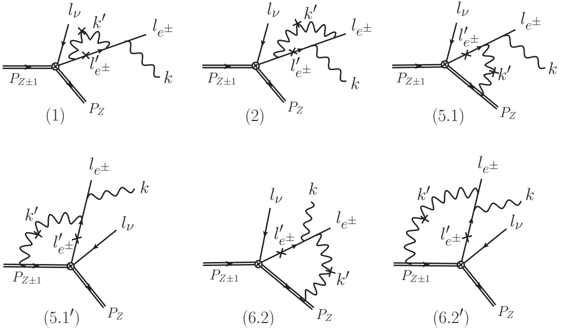
The nuclear radiative β-decay calculation can readily be reduced to "neutron" form.
Let's look at this explicitly for ^{19}Ne β-decay.
There are many more graphs, but they all cancel in leading recoil order.

The Family of Nuclear Two-Particle Cuts in $\mathcal{O}(e^3)$

At tree level...

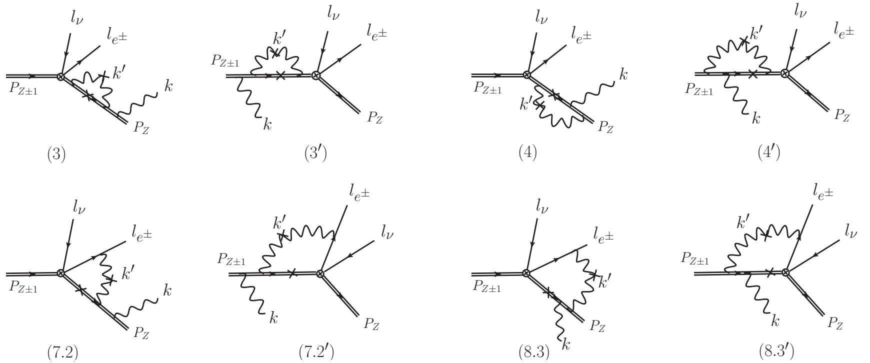


At loop level... $\gamma - e$ family:



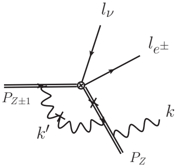
The Family of Nuclear Two-Particle Cuts in $\mathcal{O}(e^3)$

$\gamma - p$ family:



The Family of Nuclear Two-Particle Cuts in $\mathcal{O}(e^3)$

$e - p - \gamma$ family:



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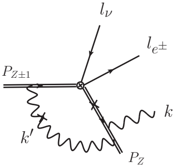

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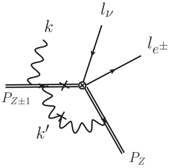

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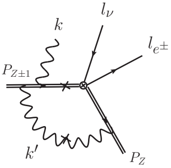

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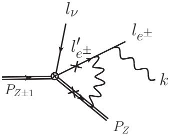
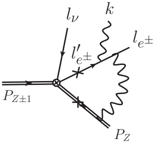
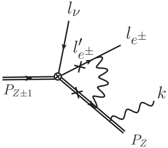


(5.2)



(6.1)



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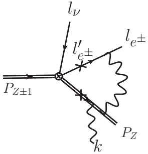
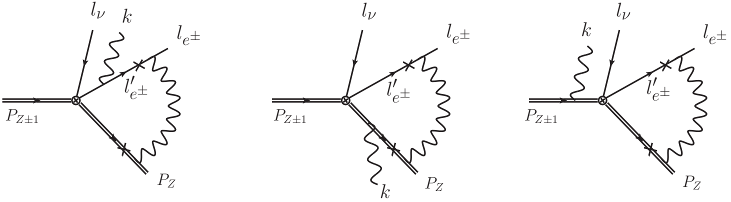


(8.1)

The Family of Nuclear Two-Particle Cuts in $\mathcal{O}(e^3)$

$e - p$ family:



(6.3) (8.2) (8.2′)

The final results depend on the Z of the daughter.

Nuclear Radiative β-Decay

Assuming decay to the ground state of the daughter...

For ^{19}Ne β-decay:

$\omega_{\min}$(MeV)	A_ξ^{SM}
0.01	-2.12×10^{-5}
0.05	-3.52×10^{-5}
0.1	-4.74×10^{-5}
0.2	-6.74×10^{-5}
0.3	-8.42×10^{-5}
0.4	-9.89×10^{-5}
0.5	-1.12×10^{-4}
0.6	-1.23×10^{-4}
0.7	-1.32×10^{-4}

For ^{6}He β-decay (GT!):

$\omega_{\min}$(MeV)	A_ξ^{SM}
0.01	7.00×10^{-5}
0.05	1.14×10^{-4}
0.1	1.52×10^{-4}
0.2	2.13×10^{-4}
0.3	2.63×10^{-4}
0.4	3.07×10^{-4}
0.5	3.45×10^{-4}
0.6	3.79×10^{-4}
0.7	4.07×10^{-4}

$\mathcal{A}_\xi^{\text{SM}}$ is proportional to $(1-\lambda^2)$, with $\lambda = g_A/g_V = 1.267$ for neutron β decay. The observed quenching of the Gamow-Teller strength in nuclear decays can suppress $\mathcal{A}_\xi^{\text{SM}}$ considerably! One can use the lifetime or the β-Asymmetry to infer λ^{eff}.

Note shell-model calculations determine $g_A^{\text{eff}} = q g_A$ where $q \approx 0.75$.

[Wildenthal, Curtin, and Brown (1983); Martínez-Pinedo et al. (1996)]

Radiative β-Decay Studies

The “HHH” asymmetry is sensitive to the energy release.
Nuclear radiative β decays with larger energy release will have larger asymmetries.

Perhaps one could study ^{19}Ne $\to$ ^{19}F radiative β-decay, e.g., in an atom trap experiment. The asymmetry is bigger because the energy release is larger, and the ^{19}Ne lifetime is 17.2 s.

The study of a Gamow-Teller decay, such as that of ^{6}He, might be a useful proof of principle experiment.

Such studies could be realized at a rare isotope accelerator such as FRIB at MSU. They favor light nuclei, so that SM FSI can be minimized.

Summary and Outlook

Harvey, Hill, and Hill suggest it is possible to study remnants of the baryon vector current anomaly in the Standard Model in low energy interactions.

Such terms also appear in theories beyond the SM with $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ electroweak symmetry at low energies – and their couplings can be complex. This possibility can be probed through a triple-product momentum correlation in neutron and/or nuclear radiative β-decay.

The triple-product momentum correlation is P-odd and pseudo-T-odd but does not involve the nucleon spin; the constraints offered through its study in neutron (and nuclear) radiative β-decay are complementary but independent from those from EDMs.

Backup Slides

Nuclear radiative β-decay

Nuclear radiative β-decay is poorly known, cf. with data (in arbitrary units) vs. photon energy for ^{6}He radiative β-decay from the 60's: