Time-Reversal Violation in Radiative β Decay

— with a Broader View —

Susan Gardner

Department of Physics and Astronomy
University of Kentucky
Lexington, KY 40506

gardner@pa.uky.edu

Based, in part, on SG & Daheng He, arXiv:1302.1862 [PRD], 1202.5239 [PRD] (and in preparation)

UNIVERSITY OF KENTUCKY

Context

The LHC has discovered a Higgs (like) boson but no other new particles.

Observational cosmology tells us, however, that only some 4% of the energy density of the Universe is in known stuff (baryons)...

Dark matter is a **tangible** unknown, but it may not couple to SM particles with more than gravitational strength. Its existence speaks to possible **hidden sector** particles, interactions, symmetries.

How can we discover such new dynamics?

Answering questions that the SM does not may require new theoretical paradigms – perhaps a "bottom up" construction will emerge as *quantum mechanics* **itself was.**

Emerging experimental anomalies may well lead the way....

Two Paths to Discovery

of **new physics** via low-energy, precision measurements

Make "null" tests of the breaking of SM symmetries

Enter tests of ...

- **B-L** (such as n-$\bar{n}$ oscillations, $0\nu\beta\beta$ decay),
- **CP** (such as EDMs, A_{CP} in charm (Dalitz plot), (pseudo) T-odd correlations in β decay [here])

– or –

Confront nonzero quantities which can be computed precisely (or assessed) within the SM

Enter PVES, muon $g-2$, β decay correlations, ...

All probe new degrees of freedom, both visible and "hidden."

Analysis Framework for BSM Effects

Suppose new physics enters at energies beyond a scale Λ. Then for $E < \Lambda$ we can extend the SM as per

$$\mathcal{L}_{\rm SM} \Longrightarrow \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^{D-4}} \mathcal{O}_i^D \,,$$

where the new operators have mass dimensions $D > 4$, and we impose $SU(2)_L \times U(1)$ gauge invariance on the operator basis (because of flavor physics constraints)

New physics can enter in distinct ways:

(i) through the appearance of new operators

(ii) through the modification of c_i for operators in the SM

Null results are also crucial: they constrain the energy scale Λ.
e.g., on dimensional grounds, the EDM of a fermion f with mass m_f is $d_f \sim e \sin\phi_{\rm CP} m_f/\Lambda^2$ [de Rujula et al., 1991]
With $\sin\phi_{\rm CP} \sim 1$, $m_f \sim 10$ MeV, and $|d_n^{\rm expt}| < 2.9 \times 10^{-26}$ e-cm [Baker et al., 2006]
$\log_{10}[\Lambda({\rm GeV})] \sim 5$. With a loop factor of $\alpha/4\pi \sim 10^{-3}$, $\Lambda \sim 3\,{\rm TeV}$.

BSM Analysis Framework for β Decay

$$\mathcal{L}^{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{1}{\Lambda_i^2} O_i \Longrightarrow \mathcal{L}_{\rm SM} + \frac{1}{v^2} \sum_i \hat{\alpha}_i O_i \,,$$

with $\hat{\alpha}_i = v^2/\Lambda_i{}^2$. [Buchmuller & Wyler, 1986; Grzadkowski et al., 2010; Cirigliano, Jenkins, González-Alonso, 2010; Cirigliano, González-Alonso, Graesser, 2013]

$$\begin{aligned}
\mathcal{L}^{\rm eff} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \Big[& \left(1+\delta_\beta\right) \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
+ \quad & \epsilon_L \; \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d + \tilde{\epsilon}_L \; \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
+ \quad & \epsilon_R \; \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \; + \; \tilde{\epsilon}_R \; \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\
+ \quad & \epsilon_S \; \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}d \; + \; \tilde{\epsilon}_S \; \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}d \\
- \quad & \epsilon_P \; \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d \; - \; \tilde{\epsilon}_P \; \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d \\
+ \quad & \epsilon_T \; \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \; + \; \tilde{\epsilon}_T \; \bar{e}\sigma_{\mu\nu}(1+\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1+\gamma_5)d \\
+ \quad & \text{h.c.} \, .
\end{aligned}$$

There is a one-to-one map between these operators and Lee & Yang, 1956.

Note Bhattacharya et al., 2011 for the one-nucleon scalar & tensor matrix elements in lattice QCD.

Connecting to Lee and Yang

$$\mathcal{H}_{int} = (\bar{\psi}_p\psi_n)(C_S\bar{\psi}_e\psi_\nu - C'_S\bar{\psi}_e\gamma_5\psi_\nu) + (\bar{\psi}_p\gamma_\mu\psi_n)(C_V\bar{\psi}_e\gamma^\mu\psi_\nu - C'_V\bar{\psi}_e\gamma^\mu\gamma_5\psi_\nu)$$
$$-(\bar{\psi}_p\gamma_\mu\gamma_5\psi_n)(C_A\bar{\psi}_e\gamma^\mu\gamma_5\psi_\nu - C'_A\bar{\psi}_e\gamma^\mu\psi_\nu) + (\bar{\psi}_p\gamma_5\gamma_\mu\psi_n)(C_P\bar{\psi}_e\gamma_5\psi_\nu - C'_P\bar{\psi}_e\psi_\nu)$$
$$+\frac{1}{2}(\bar{\psi}_p\sigma_{\lambda\mu}\psi_n)(C_T\bar{\psi}_e\sigma^{\lambda\mu}\psi_\nu - C'_T\bar{\psi}_e\sigma^{\lambda\mu}\gamma_5\psi_\nu) + h.c.$$

[Lee and Yang, 1956; note also Gamow and Teller, 1936]

confronts the β-decay of oriented nuclei (here neutron), namely,

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \xi S(p_e, E_e)[1 + a\frac{\boldsymbol{p}_e\cdot\boldsymbol{p}_\nu}{E_eE_\nu} + b\frac{m}{E_e} + \boldsymbol{\sigma_n}\cdot(A\frac{\boldsymbol{p}_e}{E_e} + B\frac{\boldsymbol{p}_\nu}{E_\nu} + D\frac{\boldsymbol{p}_e\times\boldsymbol{p}_\nu}{E_eE_\nu})]$$

[Jackson, Treiman, and Wyld, 1957]

to yield the V-A Law: $C'_A = C_A$, $C'_V = C_V$, with all others zero.

[Feynman and Gell-Mann, 1958; Sudarshan and Marshak, 1958]

Searches continue. Note, e.g.,

$$\begin{aligned} b\xi &= \pm 2\mathrm{Re}[C_S C_V^* + C'_S C'^*_V + 3(C_T C_A^* + C'_T C'^*_A)] \\ D\xi &= -2\frac{\mathrm{Im}(C_V C_A^* + C'_V C'^*_A)}{|C_V|^2} + \frac{\mathrm{Im}(C_S C_T^* + C'_S C'^*_T)}{|C_V|^2} + \mathcal{O}(\alpha) \end{aligned}$$

T-odd Observables at Low Energies....

For the neutron: [Jackson, Treiman, and Wyld, 1957]

$$d^3\Gamma \propto E_e|\boldsymbol{p}_e|(E_e^{\max} - E_e)^2 \times \left[1 + a\frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + \boldsymbol{\sigma}_N \cdot \left(A\frac{\boldsymbol{p}_e}{E_e} + B\frac{\boldsymbol{p}_\nu}{E_\nu} + D\frac{\boldsymbol{p}_e \times \boldsymbol{p}_\nu}{E_e E_\nu}\right)\right] dE_e d\Omega_e d\Omega_\nu$$

A and B are P odd, T even, whereas D is (pseudo)T odd, P even.

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

In *radiative* β-decay we can form a T-odd correlation from momenta alone: $\mathbf{p}_\gamma \cdot (\mathbf{p}_e \times \mathbf{p}_\nu)$, so that we probe new physics sources which are not constrained by EDM limits. [SG and Daheng He, 2012]

N.B. decay correlations can only be motion-reversal odd.
Thus they are not – and cannot be – true tests of T.

In β decay, the mimicking FSI are **electromagnetic** and can be computed.

Anomalous interactions at low energies

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

Harvey, Hill, and Hill: Gauging the axial anomaly of QCD under $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ 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^{2}LO in the chiral expansion. [Hill (2010); note also Fettes, Meißner, Steininger (1998) (isovector)]

Integrating out the $W^\pm$ yields

$$-\frac{4c_5}{M^2}\frac{eG_F V_{ud}}{\sqrt{2}}\varepsilon^{\sigma\mu\nu\rho}\bar{p}\gamma_\sigma n\bar{\psi}_{eL}\gamma_\mu\psi_{\nu_e L}F_{\nu\rho}\,,$$

which can infere with (dressed by a bremsstrahlung photon)

$$\frac{G_F V_{ud}}{\sqrt{2}}g_V\bar{p}\gamma^\mu n\bar{\psi}_e\gamma_\mu(1-\gamma_5)\psi_{\nu_e}\,,$$

Thus the weak vector current can mediate parity violation, too.

Radiative β-Decay

In $n(p_n) \to p(p_p) + e^-(l_e) + \overline{\nu}_e(l_\nu) + \gamma(k)$ decay the interference of the c_5 term with the leading $V - A$ terms yields

$$|\mathcal{M}|^2_{c_5} = 256 e^2 G_F^2 |V_{ud}|^2 \mathrm{Im}\,(c_5\, g_V) \frac{E_e}{l_e \cdot k} (\mathbf{l}_e \times \mathbf{k}) \cdot \mathbf{l}_\nu + \dots\,,$$

neglecting corrections of radiative and recoil order.
Note EMIT II limits $\mathrm{Im}\, g_V < 7 \cdot 10^{-4}$ (68%CL). [Mumm et al., 2011; Chupp et al., 2012]
First row CKM unitarity yields $\mathrm{Im}\, g_V < 2 \cdot 10^{-2}$ (68%CL).
Defining $\xi \equiv (\mathbf{l}_e \times \mathbf{k}) \cdot \mathbf{l}_\nu$, we form an asymmetry:

$$\mathcal{A}(\omega_{\min}) \equiv \frac{\Gamma_+(\omega_{\min}) - \Gamma_-(\omega_{\min})}{\Gamma_+(\omega_{\min}) + \Gamma_-(\omega_{\min})}\,,$$

where $\Gamma_\pm$ contains an integral of the spin-averaged $|\mathcal{M}|^2$ over the region of phase space with $\xi \gtrless 0$, respectively, neglecting corrections of recoil order.

Results

Table: T-odd asymmetries in units of $\mathrm{Im}\,[g_V(c_5/M^2)]\,[\mathrm{MeV}^{-2}]$ for neutron, $^{19}\mathrm{Ne}$, and $^{35}\mathrm{Ar}$ radiative β decay.

$\omega_{\min}(\mathrm{MeV})$	$\mathcal{A}^{\mathrm{HHH}}(n)$	$\mathrm{BR}(n)$	$\mathcal{A}^{\mathrm{HHH}}(^{19}\mathrm{Ne})$	$\mathrm{BR}(^{19}\mathrm{Ne})$
0.01	-5.61×10^{-3}	3.45×10^{-3}	-3.60×10^{-2}	4.82×10^{-2}
0.05	-1.30×10^{-2}	1.41×10^{-3}	-6.13×10^{-2}	2.82×10^{-2}
0.1	-2.20×10^{-2}	7.19×10^{-4}	-8.46×10^{-2}	2.01×10^{-2}
0.3	-5.34×10^{-2}	8.60×10^{-5}	-0.165	8.86×10^{-3}

Limits on $\mathrm{Im}(c_5)$ come only from the empirical radiative β decay BR:
$|\mathrm{Im}(c_5/M^2)| < 12\,\mathrm{MeV}^{-2}$ **at 68% C.L.**
In constrast the Lee-Yang Hamiltonian yields ($C_i^{(\prime)} \equiv G_F V_{ud} \tilde{C}_i^{(\prime)}/\sqrt{2}$)

$$|\mathcal{M}|^2_{\mathrm{T-odd,LY}} = 16 e^2 G_F^2 |V_{ud}|^2 M \mathbf{l}_\nu \cdot (\mathbf{l}_e \times \mathbf{k}) \frac{1}{l_e \cdot k} \mathrm{Im}[\tilde{C}_T(\tilde{C}_S'^* + \tilde{C}_P'^*) + \tilde{C}_T'(\tilde{C}_S^* + \tilde{C}_P^*)]$$

With $\mathrm{Im}\,\mathcal{C}_{\mathrm{LY}} \equiv \mathrm{Im}[\tilde{C}_T(\tilde{C}_S'^* + \tilde{C}_P'^*) + \tilde{C}_T'(\tilde{C}_S^* + \tilde{C}_P^*)]$, we have for $\omega^{\min} = 0.3\,\mathrm{MeV}$, in units of $\mathrm{Im}\,\mathcal{C}_{\mathrm{LY}}$

$$\mathcal{A}^{\mathrm{LY}}(n) = 5.21\times10^{-6} \quad ; \quad \mathcal{A}^{\mathrm{LY}}(^{19}\mathrm{Ne}) = 4.53\times10^{-7} \quad ; \quad \mathcal{A}^{\mathrm{LY}}(^{35}\mathrm{Ar}) = 8.63\times10^{-7}$$

These asymmetries are negligible cf. to $\mathrm{Im}(c_5)$.

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**.

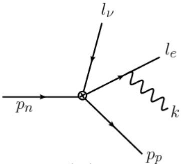
$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{tree}}|^2 + \mathcal{M}_{\mathrm{tree}} \cdot \mathcal{M}^*_{\mathrm{loop}} + \mathcal{M}_{\mathrm{loop}} \cdot \mathcal{M}^*_{\mathrm{tree}} + \mathcal{O}(\alpha^2)$$

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

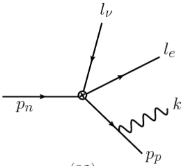
Note "Cutkosky cuts" [Cutkosky, 1960]

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

There are many cancellations. At tree level

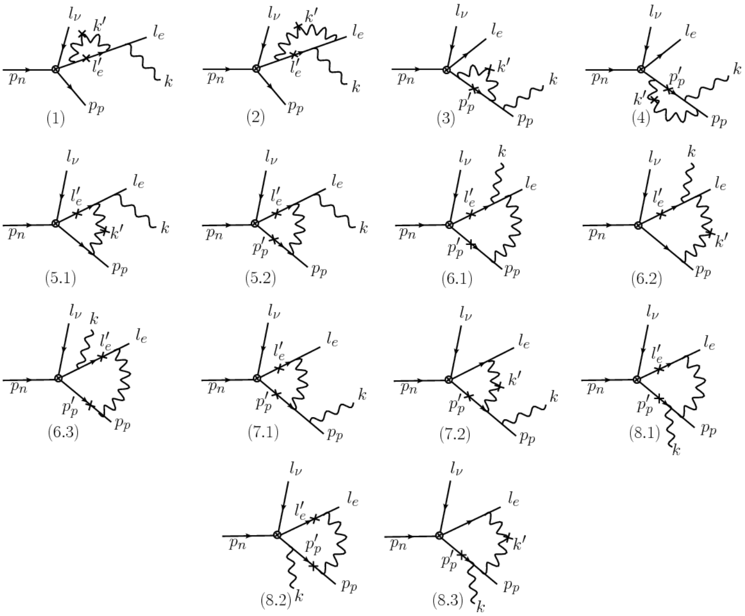


(01)



(02)

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



Results

Table: Asymmetries from SM FSI in various weak decays. The range of the opening angle between the outgoing electron and photon is chosen to be $-0.9 < \cos(\theta_{e\gamma}) < 0.9$.

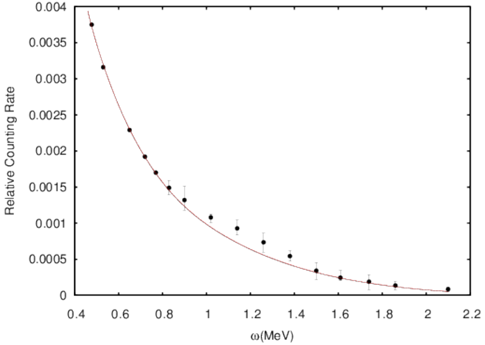
$\omega_{\rm min}$(MeV)	$\mathcal{A}^{\rm FSI}(n)$	$\mathcal{A}^{\rm FSI}(^{19}\mathrm{Ne})$	$\mathcal{A}^{\rm FSI}(^{35}\mathrm{Ar})$
0.01	1.76×10^{-5}	-2.86×10^{-5}	-8.35×10^{-4}
0.05	3.86×10^{-5}	-4.76×10^{-5}	-1.26×10^{-3}
0.1	6.07×10^{-5}	-6.40×10^{-5}	-1.60×10^{-3}
0.3	1.31×10^{-4}	-1.14×10^{-4}	-2.55×10^{-3}

The computation of the nuclear FSI proceeds similarly; the final results depend on the Z of the daughter.

$\mathcal{A}_\xi^{\rm SM}$ 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 also suppress $\mathcal{A}_\xi^{\rm SM}$. One can use the lifetime or the β asymmetry to infer $\lambda^{\rm eff}$. **The SM asymmetries are sufficiently small as to be negligible for present purposes.**

Nuclear Radiative β-Decay

Very little data exist. $^6\mathrm{He}$ decay offers a proof-of-principle experiment?



Data from the 1960's.

For $^6\mathrm{He}$ β-decay (GT!):

$\omega_{\mathrm{min}}(\mathrm{MeV})$	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}

Now we turn to models which can generate $\mathrm{Im}\, c_5$.

Hidden Sector Models

Many variants exist....

Hermetic

Dark matter which is neutral under all SM gauge interactions. Suppose it possesses an exact hidden U(1). DM (here a hidden sector stau) is self-interacting and thus subject to observational constraints... e.g., $\alpha_\chi < 10^{-7}$ for $M_\chi \sim 1$ GeV.

[Feng, Kaplinghat, Tu, Yu, arXiv:0905.3039; Feng, Tu, Yu, arXiv:0808.2328]

Models with Abelian Connectors

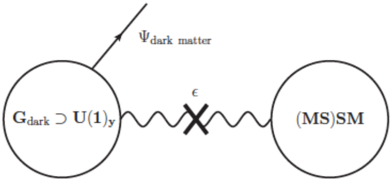
Astrophysical anomalies prompts models which mix with $\mathrm{U}(1)_Y$.

[Essig, Schuster, Toro, 2009; Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2009; Baumgart, Cheung, Ruderman, Wang, Yavin, 2009]

Models with non-Abelian Connectors

[Baumgart, Cheung, Ruderman, Wang, Yavin, 2009; SG and He, arXiv:1302.1862]

U(1) Kinetic Mixing with a Hidden Sector



[Baumgart et al., 2009]

Let A' be the gauge field of a massive dark U(1)$'$ gauge group

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} - \frac{1}{4} F^{\prime,\mu\nu} F'_{\mu\nu} + m_{A'}^2 A'^{\mu} A'_{\mu}$$

With $A_\mu \to \tilde{A}_\mu = A_\mu - \epsilon A'_\mu$, the A' gains a tiny electric charge ϵe.

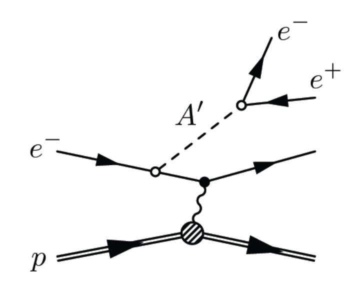
[Holdom, 1986]

The A' can be discovered in fixed-target experiments....

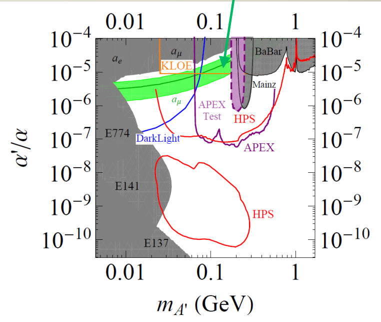
[Bjorken, Essig, Schuester, Toro, arXiv:0906.0580]

New Opportunity: Search for A' at JLab

Search for new forces mediated by ~100 MeV vector boson A' with weak coupling to electrons:



g – 2 preferred!



Irrespective of astrophysical anomalies:

- New ~GeV–scale force carriers are important category of physics beyond the SM
- Fixed-target experiments @JLab (FEL + CEBAF) have unique capability to explore this!

[R. McKeown, GHP 2011, April APS] [Note M. Pospelov for $g-2$ connection.]

Non-Abelian Kinetic Mixing with a Hidden Sector

Consider an operator Φ which transforms under the adjoint rep of a non-Abelian dark group. Then $\mathrm{tr}(\Phi F_{\mu\nu})\mathrm{tr}(\tilde{\Phi}\tilde{F}_{\mu\nu})$ can connect the sectors.

[Baumgart et al., 2009]

This operator should become more important at low energies.

We model this as (noting the hidden local symmetry model of QCD)

[Bando, Kugo, Uehara, Yamawaki, Yanagida, 1985]

$$\begin{aligned}\mathcal{L}^{\pm}_{mix} &= -\frac{1}{4}\rho^{+\,\mu\nu}\rho^{-}_{\mu\nu} - \frac{1}{4}\rho'^{+\,\mu\nu}\rho'^{-}_{\mu\nu} + \frac{\epsilon}{2}\left(\rho^{+\,\mu\nu}\rho'^{-}_{\mu\nu} + \rho^{-\,\mu\nu}\rho'^{+}_{\mu\nu}\right) \\ &+ \frac{g_\rho}{\sqrt{2}}(\rho^{+}_{\mu}J^{+\,\mu} + \rho^{-}_{\mu}J^{-\,\mu})\,.\end{aligned}$$

Under $\tilde{\rho}^{\pm}_{\mu} = \rho^{\pm}_{\mu} - \epsilon\rho'^{\pm}_{\mu}$, the baryon vector current couples to $\rho'^{\pm}$....

One can hope to detect the ρ' through its possible CP-violating effects.

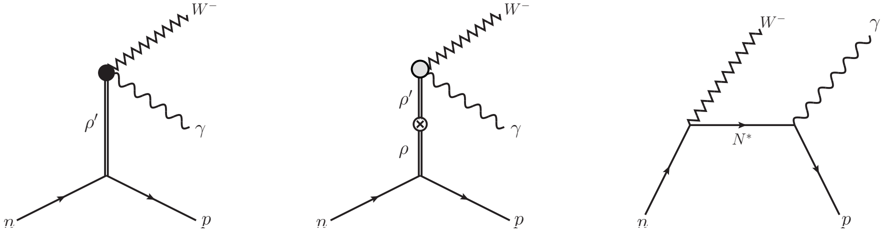
A Tale of Two Models

The notion of new physics in QCD is vintage. [Okun, 1980; Bjorken, 1979; Gupta, Quinn, 1982]
Note much more recent "quirk" models:
quirks are charged under "infracolor" and are supposed to have mass $M_Q \sim 100 - 1000$ GeV, with $M_Q > \Lambda \Longrightarrow$ macroscopic strings!
The two sectors connect via

$$\mathcal{L}_{\rm eff} \sim \frac{g^2 g'^2}{16\pi^2 M_Q^4} F_{\mu\nu}^2 F'^2_{\mu\nu}$$

[Kang and Luty, arXiv:0805.4642]
For $M_Q \gtrsim 100$ GeV, weaker than the weak interactions!
Expect collider signatures only!
In our model we suppose hidden quarks crudely comparable to m_q in mass but with $\Lambda' < \Lambda$ and thus $m_{\rho'} < m_\rho$
Expect collider effects to be hidden under hadronization uncertainties!
Expect low-energy signatures only!
New physics can be an emergent low-energy feature... to be discovered at the Intensity Frontier!

The low-energy constant c_5 can be generated in different ways....



The first graph mediates radiative decay in the physical ρ basis, an experimental limit on the asymmetry translates as $\mathrm{Im}(c_5/M^2) = 2\epsilon\mathrm{Im}\epsilon g^2_{\rho^0}/(16\pi^2 m^2_{\rho'})$.

Collider studies can constrain away the colored scalars we used to build our "connector" to the hidden sector, i.e., they can kill **specific** models that generate low-energy effects — but not all.

Summary and Outlook

The study of a spin-independent T-odd correlation coefficient is possible via radiative β decay and allows access to CP-violating effects associated with the baryon vector current.

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 yields constraints independent of those from EDMs.

Backup Slides

Evidence for New CP Phases:

We live in a known Universe of matter.

Confronting the observed ^{2}H abundance with big-bang nucleosynthesis yields a **baryon asymmetry**

$$\eta = n_{\rm baryon}/n_{\rm photon} = (5.96 \pm 0.28) \times 10^{-10}$$ [Steigman, 2012]

The particle physics of the early universe can explain this asymmetry if B, C, and CP violation exists in a non-equilibrium environment. [Sakharov, 1967]

But estimates of the baryon excess in the Standard Model are much too small, $\eta < 10^{-26}$!! [Farrar and Shaposhnikov, 1993; Gavela et al., 1994; Huet and Sather, 1995.]

Why? CP violation in the SM is special: it appears only if

$$\begin{aligned} J_{CP} &= (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_u^2)(m_s^2 - m_d^2) \\ &\times \mathrm{Im}(V_{tb} V_{td}^* V_{cd} V_{cb}^*) \neq 0 \end{aligned}$$

Now $\mathrm{Im}(V_{tb} V_{td}^* V_{cd} V_{cb}^*) \sim 3 \times 10^{-5}$ [Jarlskog, 1985] so that

$$n_{\rm baryon}/n_{\rm photon} \sim J_{CP}/T_c^{12} \sim 1 \times 10^{-19} \ (!)$$

[Nir, SSI 2012]

Ergo to explain the BAU there must be sources of CP violation beyond the CKM matrix.

T-odd Correlations

In neutron β decay, triple product correlations are spin dependent.
Major experimental efforts have recently been concluded.

D term [Mumm et al., 2011; Chupp et al., 2012]

D probes $\boldsymbol{J} \cdot (\boldsymbol{p}_e \times \boldsymbol{p}_\nu)$ and is T-odd, P-even.

$D = [-0.94 \pm 1.89(\text{stat}) \pm 0.97(\text{sys})] \times 10^{-4}$ (best ever!)

D_{FSI} is well-known (N^3LO) and some $10\times$ smaller. [Callan and Treiman, 1967; Ando et al., 2009]

D limits the phase of C_A/C_V...

R term [Kozela et al., 2009; Kozela et al., 2012]

Here the transverse components of the electron polarization are measured.

R probes $\boldsymbol{J} \cdot (\boldsymbol{p}_e \times \hat{\boldsymbol{\sigma}})$ and is T-odd, P-odd.

N probes $\boldsymbol{J} \cdot \hat{\boldsymbol{\sigma}}$ and gives a non-zero check.

$R = 0.004 \pm 0.012(\text{stat}) \pm 0.005(\text{sys})$

R limits the imaginary parts of scalar, tensor interactions...

In contrast, in radiative β-decay one can form a T-odd correlation from momenta alone, $\mathbf{p}_\gamma \cdot (\mathbf{p}_e \times \mathbf{p}_\nu)$, so that the spin does not enter.

A Common Origin for Baryonic and Dark Matter?

One can connect the origin of baryonic and dark matter in different ways.
i) Dark and ordinary matter can carry a common quantum number.
ii) Net "baryon number" is zero, with $n_B = -n_D$. [Davoudiasl and Mohapatra, arXiv:1203.1247]
Dynamically, there are also many possibilities....
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.
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]
Many models contain $\gamma - \gamma'$ mixing....

Asymmetric Dark Matter: Experimental Signatures

ADM models can give distinctive collider signatures.
E.g. long-lived metastable states, new charged states at the weak scale, and/or colored states at a TeV.
Direct detection signals can arise from the interactions which i) eliminate the symmetric DM component or ii) transfer the asymmetry.
The latter can be realized through magnetic moment or charge radius couplings.
Both interactions can give rise to anomalous nuclear recoils....

[Bagnasco, Dine, and Thomas, PLB 1994; Barger, Keung, Marfatia, arXiv:1007.4345; Banks, Fortin, and Thomas, arXiv:1007.5515]

The models we consider can generate EDM signals within the reach of planned experiments.

[Hall, March-Russell, and West, arXiv:1010.0245]

A magnetic Faraday effect can also discover dark matter if it possesses a magnetic moment... and establish asymmetric dark matter.

[SG, 2008, 2009]