The Electric Dipole Moment of the Neutron as a Probe of New Physics

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The results shown here were achieved in collaboration with Nikolay “Kolya” Uraltsev (arXiv:1202.6270 and arXiv:1205.0233)

Kolya deceased suddenly and unexpectedly
in the morning of 13.2.2013
This talk is also in commemoration of him ...

Contents

Introduction

- Electric Dipole moments (EDMs) are CP violating
- It tests flavour-diagonal CP violation
- This is small in the Standard Model (SM):
  - CKM CP violation is flavour changing at tree level
  - Strong CP is small for yet unknown reasons
- EDMs are important as test for new physics:
  - Many models predict new sources of CP violation
  - ... some of which are flavour diagonal at tree level
  - EDMs are the killer for many new physics models
- However, we need more CP violation for the universe

Electric Dipole Moments: Generalities

- Electric dipole moments in classical physics

$$\vec{d} = \int d^3\vec{r}\ \rho(\vec{r})\vec{r} \quad \text{Energy: } U = \vec{d} \cdot \vec{E}$$

- Quantum Field theory:
  States are characterized by momentum $\vec{p}$ and Spin $\vec{J}$:
  $\vec{d}$ must be proportional to $\vec{J}$

$$U = d\,\vec{J} \cdot \vec{E}$$

- d must be parity odd:
  P Violation (and also T Violation) $\to$ CP violation

EDM's of particles

- Electromagnetic interaction with the EDM of a fermion:

$$\mathcal{L}_{\mathrm{EDM}} = \frac{d}{2} \bar{\psi} i \sigma_{\mu\nu} \gamma_5 \psi \, F^{\mu\nu}$$

- This is flavour diagonal and a static quantity
- This also holds for a composite particle such as a neutron
- Current status of measurements:
  - For the electron: $d_e < 10.5 \times 10^{-28}$ e cm
  - For the neutron: $d_N < 0.29 \times 10^{-25}$ e cm
- There are plans to improve this (in particular for the nucleon) by orders of magnitude.

Only a few words about “Strong CP”

- The QCD Vacuum generates a (CP violating) θ term:

$$\mathcal{L}_{\text{strong CP}} = \theta \frac{\alpha_s}{8\pi} G^{\mu\nu,a} \tilde{G}^a_{\mu\nu}$$

- Natural size would be $\theta \sim 1$
- θ can be rotated away by an additional symmetry
- Limit from Neutron EDM:

$$d_N \sim \theta \times 10^{-15} \mathrm{e\,cm} \quad \text{thus} \quad \theta \leq 10^{-10}$$

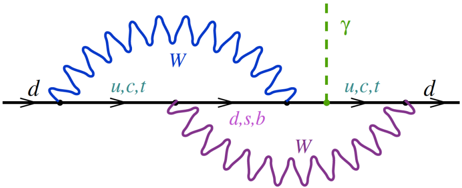
- This is one of the puzzles of the SM
- We assume in what follows that $\theta \equiv 0$.

EDMs from the CKM Sector

- Any CP violation in the SM is proportional to

$$\Delta = \mathrm{Im}\, V_{cs}^* V_{us} V_{cd} V_{ud}^*$$

- There is only a single 4^{th} order rephasing invariant
- Standard Model without Strong CP:
  d must be proportional to Δ!
- Thus we have two W exchanges.
- For an elementary fermion this is at least two loops:



- However, sum of all the two-loop diagrams vanishes for quark edm's $\to$ need another (gluon) loop Shabalin 78
- Result for d quark (similar for the up qark)

$$d_d = e\,\frac{m_d \alpha_s G_F^2 m_c^2 \Delta}{108\pi^5}\left[\ln^2\frac{m_b^2}{m_c^2}\ln\frac{M_W^2}{m_b^2}+..\right] \sim -0.3\times 10^{-34}\text{e cm}$$

Khiplovich 86, Czarnecki, Krause 97

Naive composition of the Neutron edm:

$$d_N = \frac{4}{3}d_d - \frac{1}{3}d_u \sim 10^{-34}\text{e cm}$$

This is too small, neutron is a composite object.

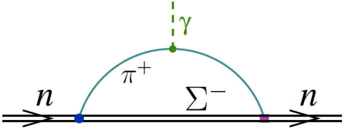
Composite Objects: Neutron EDM

Well known fact: There are long distance effects:

- Penguin Operators: $d \to s$ transitions (with CPV)

$$H_{\rm Pen} \propto \frac{G_F}{\sqrt{2}} \frac{\alpha_s}{3\pi} \sum_q (\bar{s}\Gamma_\mu T^a d)(\bar{q}\Gamma^\mu T^a q)$$

- "Long distance strangeness"t: (Gavela et al., 82, Khriplovich et al, 82)



- Estimates much larger than the EDM's of the constituents
- Still there is a loop suppression in the penguins

"Loop-less" EDM's Uraltsev, M

Systematic Study:

- Start from the effective Hamiltonian H_W for weak interactions below M_W:
- H_W is bi-linear in the CKM elements:
  CP violation will be second order in H_W

$$\mathcal{L}_2 = i\frac{G_F^2}{4}\int d^4x \, \mathrm{T}\{H_W(x)H_W(0)\}$$

- In the nucleon top and bottom are irrelevant: At tree level this means to leave them out.

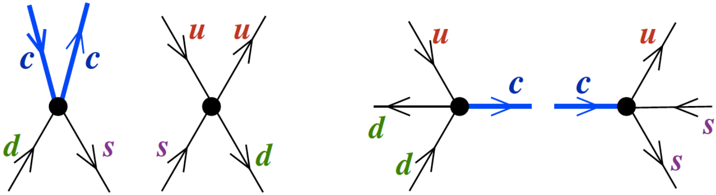
$$H_W = J_\mu^\dagger J^\mu \, , \quad J_\mu = V_{cs}\,\bar{c}\Gamma_\mu s + V_{cd}\,\bar{c}\Gamma_\mu d + V_{us}\,\bar{u}\Gamma_\mu s + V_{ud}\,\bar{u}\Gamma_\mu d$$

with $\Gamma_\mu = \gamma_\mu(1-\gamma_5)$

- This looks almost like the two-generation case, however, the remaining 2×2 matrix V_{ij} is not unitary, not all phases can be removed.
- In particular:

$$\Delta = \mathrm{Im}\, V_{cs}^* V_{cd} V_{ud}^* V_{us} \neq 0$$

- $\mathcal{L}_2$ contains 256 terms, 64 are flavour neutral. Only two combinations proportional to Δ (or its complex conjugate)
- These have q and $\bar{q}$ for each flavor.



- Left: close the charm loop, conventional penguin
- Right diagram: Integrate out highly virtual charm:

$$\frac{iG_F^2}{2} V_{cs}^* V_{cd} V_{ud}^* V_{us} \times$$
$$\int d^4x \, \mathrm{T}\{(\bar{d}\Gamma_\mu c)(\bar{u}\Gamma^\mu d)(0)\,(\bar{c}\Gamma_\nu s)(\bar{s}\Gamma^\nu u)(x)\} + h.c.$$

- Charm Propagator

$$\underbrace{c(0)\bar{c}(x)} \to \left(\frac{1}{m_c - i\not{D}}\right)_{0x}$$

- Expansion of the charm propagator: $1/m_c$ expansion

$$\left(\frac{1}{m_c - i\not{D}}\right)_{0x} = \frac{1}{m_c}\delta^4(x) + \frac{1}{m_c^2}\delta^4(x) i\not{D} + \frac{1}{m_c^3}\delta^4(x)(i\not{D})^2 + \cdots$$

- Left handed currents of the SM: only $1/m_c^2$, $1/m_c^4$ ...
- Thus in a $1/m_c$ expansion:

$$\mathcal{L}_2^{CPV} = -i\frac{G_F^2 \Delta}{2m_c^2}\mathcal{O}_{uds}$$

$$\mathcal{O}_{uds} = (\bar{u}\Gamma_\mu d)(\bar{d}\Gamma^\mu i\not{D}\Gamma^\nu s)(\bar{s}\Gamma_\nu u) - h.c.$$

- No loops, no $1/(16\pi^2)$ supressions
- However, a local dim-10 operator appears ...

- The covariant derivative contains a photon:

$$O^{\alpha}_{uds} = (\bar{u}\Gamma_{\mu} d)(\bar{d}\Gamma^{\mu} i\gamma^{\alpha}\Gamma^{\nu} s)(\bar{s}\Gamma_{\nu} u) - (s \leftrightarrow d)$$

- from this we get the overall electromagnetic current relevant for EDM's

$$\mathcal{L}^{\alpha} = -ie\Delta \frac{G_F^2}{m_c^2}\left[\frac{2}{3} O^{\alpha}_{uds} + i\int d^4x\, \mathrm{T}\{\mathcal{O}_{uds}(0) J^{\alpha}_{\mathrm{em}}(x)\}\right]$$

- The matrix element between neutron states yields

$$\langle n(p+q)|\mathcal{L}^{\alpha}|n(p)\rangle \stackrel{q\to 0}{=} d_n\, q_{\nu}\bar{u}(p+q) i\sigma^{\alpha\nu}\gamma_5 u(p)$$

How to estimate the matrix elememts

- Local piece

$$\langle n(p+q)|O^{\alpha}_{uds}|n(p)\rangle = 2i\mathcal{K}_{uds} q_{\nu} \bar{n}(p+q) i\sigma^{\alpha\nu}\gamma_5 n(p)$$

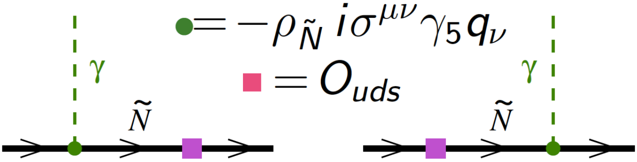
- Estimating $\mathcal{K}_{uds}$ is difficult:
  - Naive estimate by dimensions: $\mathcal{K}_{uds} \approx \kappa\mu^5_{\rm hadr}$
  - $\kappa \sim 0.3$ for the suppression of strangeness
  - $\mu \sim 0.5$ GeV, but this probably overestimates

    $$\langle\bar{q}q\rangle \approx -(250\,\mathrm{MeV})^3 \quad \text{yet} \quad \langle\bar{q}(iD)^2 q\rangle \approx -(650\,\mathrm{MeV})^2 \langle\bar{q}q\rangle$$

    hence we write a factor of $\mu_q^3 = (250\ \mathrm{MeV})^3$ for each $\bar{q}q$ pair, remaining dimensions from $\mu_{\rm hadr} \sim 500$ MeV
- Thus form the local term we get

$$|d_n| = \frac{32}{3} e \frac{G_F^2 \Delta}{m_c^2} |\mathcal{K}_{uds}| = 3.3\cdot 10^{-31}\, e\,\mathrm{cm} \times \kappa \left(\frac{\mu_q}{0.25\,\mathrm{GeV}}\right)^6 \left(\frac{0.5\,\mathrm{GeV}}{\mu_{\rm hadr}}\right)$$

- Non-local term:
  Estimate with a single intermediate $\tilde{N}$ state



- Coupling $\rho_{\tilde{N}}$ from $\tilde{N} \to n\gamma$: $\rho_{\tilde{N}} \approx 0.34\,\mathrm{GeV}^{-1}$

$$|d_n| \approx 32e\frac{G_F^2\Delta}{m_c^2}\kappa\mu_q^6\mu_{\mathrm{hadr}}\frac{\rho_{\tilde{N}}}{M_{\tilde{N}} - M_n} \approx 1.4 \cdot 10^{-31}\, e\,\mathrm{cm} \times \kappa$$

- Consistent with other (as well crude) estimates

Summary on the neutron EDM in the SM

- The loop-less estimate is (order of magnitude)

$$\boxed{|d_n| = 10^{-31}\, e\,\mathrm{cm}}$$

- Short distance loops will be parametrically small by loop factors $1/(16\pi^2)$
- The EDM's of the constituents do not play any role
- Strong CP remains a problem:

$$|d_n| \approx 2.3 \cdot 10^{-16}\, e\,\mathrm{cm} \times \theta$$

- Given the current experimental bound:

$$|d_n| \leq 2.9 \cdot 10^{-26}\, e\,\mathrm{cm} \quad (90\% CL)$$

- $1/m_c$ suppression is present in the OPE, however, this is mild $p/m_c \sim 0.5$
- Similar Effects in B decays: "Intrinsic charm"
  (Bigi et al. 2003, Zwicky et al. 2005, M. et al, 2010
- $V - A$ Structure yields an additional factor of p/m_c
- The loop-less contribution may as well be the dominant one!
- There are issues conceding the mass dependence, chiral limit, the limit $m_s \to m_d$ etc.
- "SM minimizes the EDM of the neutron"

New Physics Effects in the Neutron EDM

- Motivated by the LHCb measurements of

$$\Delta a_{\rm CP} = \mathcal{A}_{\rm CP}(D^0 \to K^+K^-) - \mathcal{A}_{\rm CP}(D^0 \to \pi^+\pi^-)$$

we consider CP violating operators for $\Delta C = \pm 1$:

$$O_1 = e m_c \bar{c}\, i\sigma_{\alpha\beta} F^{\alpha\beta}\gamma_5 u\,,\quad O_3 = [\bar{c}\Gamma_\mu u]([\bar{s}\Gamma^\mu s] + [\bar{d}\Gamma^\mu d]),$$
$$O_2 = g_s m_c \bar{c}\, i\sigma_{\alpha\beta} G^{\alpha\beta}\gamma_5 u\,,\quad O_4 = (\bar{c}\gamma_\mu(1+\gamma_5)u)\,(\bar{d}\gamma^\mu(1-\gamma_5)d)$$

and define

$$\mathcal{L}_{\rm np} = -\frac{G_F}{\sqrt{2}} \sin\theta_C \cos\theta_C \sum_k c_k O_k\,,$$

Unfortunately, this effect has almost disappeared.

- Some of the operators contain right handed quarks:
  This can lift the helicity suppression
- Crude estimate of the matrix elements based on the 2012 data:

	$-i\langle\pi^+\pi^-\|O_k\|D^0\rangle$	$\|\sin\delta_{\rm FSI}\,{\rm Im}\,c_k\|$	$d_n,\ e\cdot cm$
O_1	$8\sqrt{2}\pi\alpha\, q_d\, f_\pi f_+^{D\to\pi}(0) M_D^2$	$5.2\cdot 10^{-2}$	$2\cdot 10^{-27}$
O_2	$4\pi g_s\sqrt{3}\, f_\pi f_+^{D\to\pi}(0) M_D^2$	$1.0\cdot 10^{-4}$	$8\cdot 10^{-30}$ | $3\cdot 10^{-30}$
O_3	$-f_\pi f_+^{D\to\pi}(0) M_D^2$	$2\ \cdot 10^{-3}$	10^{-30}
O_4	$f_\pi f_+^{D\to\pi}(0) M_D^2\ \frac{1}{N_c}\ \frac{2m_\pi^2}{(m_u+m_d)m_c}$	$4.6\cdot 10^{-3}$	$5\cdot 10^{-30}$

Estimates for the additional effects:

- $O_1 = e\, m_c \bar{c}\, i(\sigma F)\gamma_5 u$: $\quad d_n \sim 10^4 d_n^{(SM)}$
- $O_2 = g_s m_c \bar{c}\, i(\sigma G)\gamma_5 u$: $\quad d_n \sim 30 d_n^{(SM)}$ (right handed c)
- $O_3 = [\bar{c}\Gamma_\mu u]([\bar{s}\Gamma^\mu s] + [\bar{d}\Gamma^\mu d])$: $\quad d_n \sim 10 d_n^{(SM)}$
- $O_4 = (\bar{c}\gamma_\mu(1+\gamma_5)u)\,(\bar{d}\gamma^\mu(1-\gamma_5)d)$: $\quad d_n \sim 50 d_n^{(SM)}$

The current experimental limits are safe w/r to charm CPV

Outlook

- The neutron EDM remains one of the most stringent constrains on flavor diagonal CPV form New Physics
- ... although a precise prediction in the SM remains difficult due to the unknown hadronic matrix elements
- The "loop-less" contribution could turn out to be the most important one
- ... although it is difficult to estimate.
- The experimental limit is still several orders of magnitude away from the SM prediction
- ... despite of the uncertainties.
- There is a good motivation to improve the limits on the neutron EDM