Electric Dipole Moments within and beyond the Standard Model

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New physics searches at the precision frontier
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Outline

EDMs and CP violation

From classical electrodynamics, electric dipole moment and magnetic dipole moment interact with EM fields in the following way:

$$H = -\boldsymbol{d} \cdot \boldsymbol{E} - \boldsymbol{\mu} \cdot \boldsymbol{B}$$

While those two terms look similar in classical physics, they have very different properties under discrete symmetries. $\boldsymbol{d}$ and $\boldsymbol{\mu}$ can only be parallel or anti-parallel to the spin $\boldsymbol{s}$ of a particle, $\boldsymbol{s}$ and $\boldsymbol{B}$ flips the sign under T, but $\boldsymbol{E}$ does not, so under T the Hamiltonian becomes

$$H' = \boldsymbol{d} \cdot \boldsymbol{E} - \boldsymbol{\mu} \cdot \boldsymbol{B}$$

$\boldsymbol{d} \neq 0$ implies T is broken, and if CPT is a good symmetry then CP is also broken.

EDM measurements provide tests for SM CP violation, and if any unexpected EDMs are observed, they will be evidences for existence of BSM CP violation.

Current Experimental Bounds

EDM experiments are mostly done for paramagnetic systems (atoms, molecules, ions with an unpaired electron), diamagnetic systems (atoms, molecules with no unpaired electron), and the neutron.

Type of EDM	Experimental bound
Paramagnetic	$\lvert d_e^{eq}(\text{ThO})\rvert < 1.1 \times 10^{-29} e$cm (90% C.L.) (ACME)
	$\lvert d_e^{eq}(\text{HfF}^+)\rvert < 4.1 \times 10^{-30} e$cm (90% C.L.) (CU Boulder)
Diamagnetic	$\lvert d(^{199}\text{Hg})\rvert < 7.4 \times 10^{-30} e$cm (95% C.L.) (UW)
Neutron	$\lvert d_n\rvert < 1.8 \times 10^{-26} e$cm (90% C.L.) (C. Abel et al. 2020)

The size can be compared with magnetic dipole moments:

$$|\mu_e| = \frac{e}{2m_e} = 1.9 \times 10^{-11} e\text{cm}, \quad |d_e^{eq}(\text{ThO})| < 1.1 \times 10^{-29} e\text{cm}$$

Assuming $d_e/e \simeq m_e/\Lambda_{CP}^2$, any evidence for d_e^{eq} will be a direct probe of physics at 10^3TeV scale.

SM predictions for EDM observables

Within the SM, CP is broken by the phase of the CKM matrix δ_{KM} and the yet unobserved QCD θ angle.

Type of EDM	SM prediction from CKM phase
Paramagnetic	$\lvert d_e^{eq}(\text{ThO})\rvert \approx 1.0 \times 10^{-35} e\text{cm}$
Diamagnetic	$\lvert d(^{199}\text{Hg})\rvert \approx (0.4 - 2.4) \times 10^{-35} e\text{cm}$ (Dmitriev & Sen'kov 2003)
Neutron	$\lvert d_n\rvert \approx (1 - 6) \times 10^{-32} e\text{cm}$ (CY Seng 2015)

Experimental accuracy is improving by nearly two orders of magnitude per decade and is only $\sim$ six orders of magnitude away from the Standard Model predictions.

Outline

Paramagnetic EDM

The EDM of paramagnetic atoms comes from the electron EDM and a CP-odd interaction between the electron and the nucleon:

$$\mathcal{L}_{\cancel{CP}} = \frac{d_e}{2}\bar{e}\sigma_{\mu\nu}\tilde{F}^{\mu\nu}e + C_S\frac{G_F}{\sqrt{2}}(\bar{e}i\gamma_5 e)(\bar{p}p + \bar{n}n)$$

Experiments can only measure a linear combination of them:

$$\hbar\omega^{\mathcal{N}\mathcal{E}} = -d_e\mathcal{E}_{\text{eff}} + W_S C_S$$

The result can be inferred as

$$d_e^{eq} = d_e + \# \times C_S \times \ 10^{-20} e\text{cm}$$

The coefficient $\#$ has some dependence on the specific molecule but is of order 1:

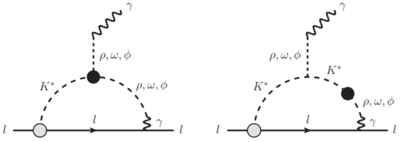
$$d_e^{eq}(\text{ThO}) = d_e + C_S \times 1.5 \times 10^{-20} e\text{cm}$$

$$d_e^{eq}(\text{HfF}^+) = d_e + C_S \times 0.9 \times 10^{-20} e\text{cm}$$

Previous Predictions

Several attempts have been made to calculate paramagnetic EDM, the results were small and uncertain.

Y. Yamaguchi & N. Yamanaka 2020

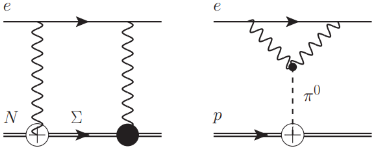


(a) (b)

$$d_e = 6 \times 10^{-40} e\text{cm}$$

$\sim$ 70% uncertainty

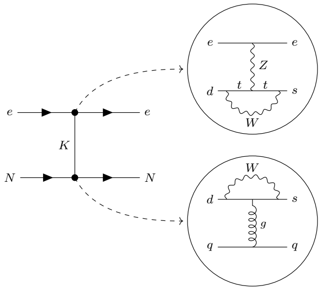
M. Pospelov & A. Ritz 2013



$$C_S \sim 10^{-18} \Rightarrow d_e^{eq} \sim 10^{-38} e\text{cm}$$

$\sim$ an order of magnitude uncertainty

C_S operator from Kaon exchange: Overview



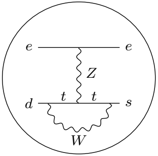
- Our work shows the C_S operator receives the dominate contribution from the Kaon exchange diagram.
- The $K\bar{e}e$ vertex comes from an electroweak penguin.
- The $K\bar{N}N$ vertex is induced by a strong penguin.

Our result is 3 orders of magnitude larger than previous result

$$C_S \simeq 6.9 \times 10^{-16}$$
$$\Rightarrow d_e^{eq} \simeq 1.0 \times 10^{-35} e\text{cm}$$

The uncertainty is $\sim 30\%$, under better control than previous results.

C_S operator from Kaon exchange: Weak penguin



- Full calculation including penguins and box diagrams was done by T. Inami & C. S. Lim in 1981
- The theory is well established and agrees with $B_{s,d} \to \mu^+\mu^-$ and $K_L \to \mu^+\mu^-$ experiments well.

$$\mathcal{L}_{\rm EWP} = -\mathcal{P}_{\rm EW} \times \bar{e}\gamma_\mu\gamma_5 e \times \bar{s}\gamma^\mu(1-\gamma_5)d + (h.c.),$$

$$\mathcal{P}_{\rm EW} = \frac{G_F}{\sqrt{2}} \times V_{ts}^* V_{td} \times \frac{\alpha_{\rm EM}(m_Z)}{4\pi \sin^2\theta_W} I(x_t),$$

$$I(x_t) = \frac{3}{4}\left(\frac{x_t}{x_t-1}\right)^2 \log x_t + \frac{1}{4}x_t - \frac{3}{4}\frac{x_t}{x_t-1}, \quad x_t = \frac{m_t^2}{m_W^2}.$$

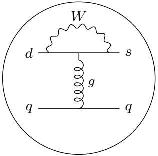
In χPT this gives rise to

$$\mathcal{L}_{Uee} = -\frac{if_0^2}{2}\mathcal{P}_{\rm EW} \times \bar{e}\gamma_\mu\gamma_5 e \times {\rm Tr}\left[h^\dagger\left(\partial^\mu U\right)U^\dagger\right] + (h.c.).$$

At leading order, this is

$$\mathcal{L}_{Kee} = -2\sqrt{2} f_0 m_e \bar{e} i\gamma_5 e\left(K_S \times {\rm Im}\mathcal{P}_{\rm EW} + K_L \times {\rm Re}\mathcal{P}_{\rm EW}\right).$$

C_S operator from Kaon exchange: Strong penguin



- Two possible structures within χPT:

$$\mathcal{L}_{\rm SP} = -a\mathrm{Tr}(\bar{B}\{\xi^\dagger h\xi, B\}) - b\mathrm{Tr}(\bar{B}[\xi^\dagger h\xi, B]) + (h.c.).$$

- Coefficient determined by fit to hyperon non-leptonic decay s-wave amplitudes (Bijnens, Sonoda and Wise 1985)

$$a = 0.56 G_F f_\pi \times [m_{\pi^+}]^2; \quad b = -1.42 G_F f_\pi \times [m_{\pi^+}]^2.$$

- $[m_{\pi^+}] = 139.5\mathrm{MeV}$ is understood as a numerical value rather than the physical pion mass.
- Overall sign fixed by vacuum factorization.

The expansion contains $2^{1/2} f_0^{-1}((b-a)\bar{p}p + 2b\bar{n}n)K_S$. Restoring CKM matrix elements leads to the $K\bar{N}N$ coupling

$$\mathcal{L}_{KNN} \simeq -\frac{\sqrt{2}\,G_F \times [m_{\pi^+}]^2 f_\pi}{|V_{ud}V_{us}|f_0} \times 2.84(0.7\bar{p}p + \bar{n}n) \times (\mathrm{Re}(V_{ud}^* V_{us})K_S + \mathrm{Im}(V_{ud}^* V_{us})K_L)$$

C_S operator from Kaon exchange: LO result

The diagram gives the result

$$C_S \simeq \mathcal{J} \times \frac{N + 0.7Z}{A} \times \frac{13[m_{\pi^+}]^2 f_\pi m_e G_F}{m_K^2} \times \frac{\alpha_{\rm EM} I(x_t)}{\pi \sin\theta_W^2}$$

$\mathcal{J}$ is the Jarlskog invariant

$$\mathcal{J} = {\rm Im}(V_{ts}^* V_{td} V_{ud}^* V_{us}) \simeq 3.1 \times 10^{-5}$$

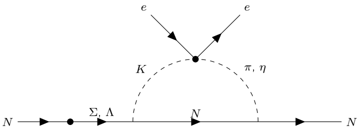
The overall scaling is

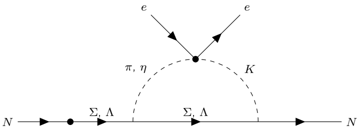
$$G_F C_S \propto \mathcal{J} G_F^3 m_t^2 m_e m_s^{-1} \Lambda_{\rm hadr}^2$$

Numerically,

$$C_S({\rm LO}) \simeq 5 \times 10^{-16}.$$

C_S operator from Kaon exchange: NLO contribution and final result





The next-to-leading order contribution comes from baryon pole diagrams, they scale as $(m_s/\Lambda_{\rm hadr})^{1/2}$ relative to the LO diagram, the results are

$$\frac{C_{S,NLO}(p)}{C_{S,LO}(p)} = \frac{m_K^3(0.77D^2 + 2.7DF - 2.3F^2)}{24\pi f_0^2(m_{\Sigma^+} - m_p)} \simeq 30\%$$

$$\frac{C_{S,NLO}(n)}{C_{S,LO}(n)} = \frac{m_K^3}{24\pi f_0^2}\left(\frac{(a/b+3)}{2\sqrt{6}(m_\Lambda - m_n)} \times (-0.44D^2 + 3.2DF + 1.3F^2) + \frac{a/b-1}{2\sqrt{2}(m_{\Sigma^0} - m_n)}(-0.53D^2 - 1.9DF + 1.6F^2)\right) \simeq 40\%$$

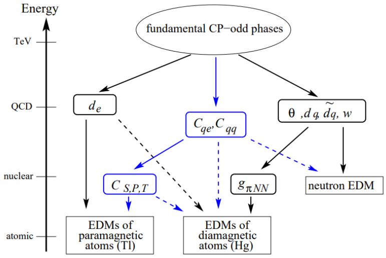
Combining LO and NLO result gives

$$C_S \simeq [5.0(\text{LO}) + 1.9(\text{NLO})] \times 10^{-16}, \quad d_e^{eq} \simeq 1.0 \times 10^{-35} e\text{cm}$$

There are proposals to measure d_e^{eq} at similar order of magnitude (Vutha, Horbatsch, Hessels, 1710.08785 and 1806.06774)

Outline

BSM EDMs



(Pospelov & Ritz 2005)

- BSM CP violations are expected from baryogenesis
- Fundamental CP violation will generate SM higher dimensional CP-violating operators
- These operators will contribute to EDM observables

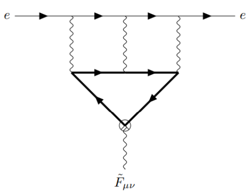
$$\mathcal{L}^{\text{dim } 6}_{\not{CP}} = \sum_i \frac{d_i}{2} \bar{\psi}_i (\tilde{F}\sigma)\psi_i + \sum_i \frac{g_s \tilde{d}_i}{2} \bar{\psi}_i (\tilde{G}\sigma)\psi_i + \frac{1}{3} w f^{abc} \tilde{G}^{a\mu}_{\nu} G^{b\nu}_{\rho} G^{c\rho}_{\mu} + \sum_{i,j} C_{ij} (\bar{\psi}_i \psi_i)(\bar{\psi}_j i\gamma^5 \psi_j) + \cdots$$

A number of measurements have been or will be done to probe BSM EDMs (muon: g-2(BNL), PSI, J-PARC, tau: Belle, Belle II, c and b quarks: LEP, LHCb).

We consider how existing atomic and nuclear EDM experiments indirectly constrain those EDMs, by doing this we take a large loop penalty, but use superior accuracy of atomic and nuclear measurements.

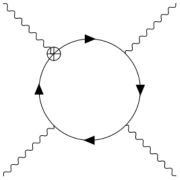
Heavy lepton EDM: Pathways to atomic EDMs

Heavy lepton EDM



electron EDM

$$d_e = \left(\frac{19}{4}\zeta(3) - \frac{71}{24}\right)\frac{m_e}{m_L}\left(\frac{\alpha}{\pi}\right)^3 d_L$$



CP-odd light-by-light operator

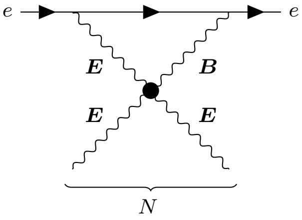
$$\mathcal{L} = -\frac{(d_L/e)}{96\pi^2 m_L^3} e^4 F_{\alpha\beta}F^{\alpha\beta}F_{\gamma\delta}\tilde{F}^{\gamma\delta}$$

C_S operator

Schiff moment

paramagnetic EDM

diamagnetic EDM



On the electron side,

$$\boldsymbol{E_e} \cdot \boldsymbol{B_e} \to -\frac{3\alpha m_e}{2\pi} \ln\left(\frac{m_\mu}{m_e}\right) \bar{e} i \gamma^5 e$$

On the nucleus side,

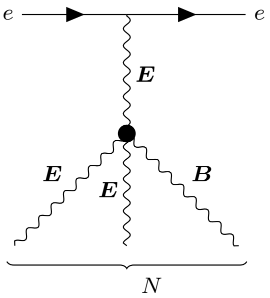
$$(e\boldsymbol{E}_{\mathsf{nucl}})^2 \to \kappa \delta(\boldsymbol{r}) \times \frac{4\pi (Z\alpha)^2}{R_N} \times \frac{6}{5}$$

Fudge factor κ introduced to account for difference between $\bar{N}N$ distribution and $\boldsymbol{E}^2_{\mathsf{nucl}}$ distribution.

$$C_S^{eq} = \kappa \frac{\sqrt{2}}{G_F} \frac{4Z^2\alpha^4}{\pi A} \times \frac{m_e (d_\mu / e)}{m_\mu^3 R_N} \times \ln\left(\frac{m_\mu}{m_e}\right) = 3.1 \times 10^{-10} \left(\frac{d_\mu}{10^{-20} e\mathrm{cm}}\right)$$

- We combine it with the muon EDM contribution to d_e. Based on the ThO experiment, we arrive at the constraint $|d_\mu| < 1.7 \times 10^{-20} e$cm.
- Recent HfF$^+$ experiment refines the result: $|d_\mu| < 8.9 \times 10^{-21} e$cm.
- Factor of $\sim$20 better than previous BNL direct measurement $|d_\mu| < 1.8 \times 10^{-19} e$cm.
- For tau lepton we are getting $|d_\tau| < 1.1 \times 10^{-18} e$cm, better than previous Belle result $|d_\tau| = (1.15 \pm 1.70) \times 10^{-17} e$cm.

Muon EDM: Constraint from Diamagnetic Schiff Moment



The $\boldsymbol{E}^2\boldsymbol{B}$ connected to the nucleus effectively acts as a dipole polarization density $\boldsymbol{P}$, which leads to a Schiff moment

$$H = -4\pi\alpha(\boldsymbol{S}_N/e)\cdot\boldsymbol{\nabla}\delta(\boldsymbol{r})$$

$$\boldsymbol{S} = \frac{1}{6}\int \mathrm{d}^3 r r^2 \boldsymbol{P} - \frac{1}{6}\boldsymbol{d} r_c^2 + \frac{1}{5}\int \mathrm{d}^3 r((\boldsymbol{P}\cdot\boldsymbol{r})\boldsymbol{r} - \frac{1}{3}r^2\boldsymbol{P})$$

Numerically,

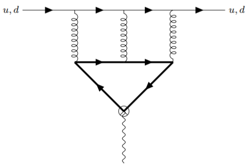
$$S_{^{199}\mathrm{Hg}}/e \simeq (d_\mu/e)\times 4.9\times 10^{-7}\mathrm{fm}^2$$

$$|d_\mu| < 6.4\times 10^{-20} e\mathrm{cm}$$

Factor of $\sim$3 better than previous BNL direct measurement, provides an independent check for the constraint from paramagnetic EDM

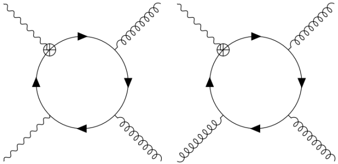
c and b quark EDM: Pathways to atomic and neutron EDMs

c and b quark EDM



light quark EDM

$$d_q = \frac{5(8\zeta(3)-7)}{72}\left(\frac{\alpha_s}{\pi}\right)^3 \frac{m_q}{m_Q} d_Q$$



CP-odd photon-gluon operators

$$\mathcal{L}_{eff,Q} = \frac{eQ_Q d_Q g_s^2}{24\pi^2 m_Q^3} \mathrm{Tr}_c\left[\tilde{F}_{\mu\nu} G^{\mu\nu} F_{\alpha\beta} G^{\alpha\beta} - \tilde{F}_\mu^\nu G_\nu^\alpha F_\alpha^\beta G_\beta^\mu\right] + \frac{d_Q g_s^3}{48\pi^2 m_Q^3} \mathrm{Tr}_c\left[-\tilde{F}_{\mu\nu} G^{\mu\nu} G_{\alpha\beta} G^{\alpha\beta} + 2\tilde{F}_\mu^\nu G_\nu^\alpha G_\alpha^\beta G_\beta^\mu\right]$$

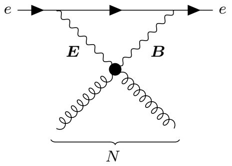
C_S operator

neutron EDM

paramagnetic EDM

c and b quark EDM: indirect constraints

Paramagnetic EDM



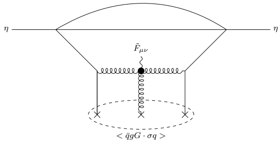
$$C_S \frac{G_F}{\sqrt{2}} = -\frac{4Q_Q\alpha^2}{27}\frac{m_N m_e}{m_Q^3} \times \ln\left(\frac{m_Q}{m_e}\right)\frac{d_Q}{e}$$

$|d_c| < 1.3 \times 10^{-20}e\text{cm}$,

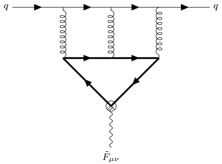
$|d_b| < 7.6 \times 10^{-19}e\text{cm}$

Neutron EDM

non-perturbative contribution



perturbative contribution



$$d_n = \frac{5\alpha_s^2 m_n m_0^2 \ln(\frac{M^2}{\Lambda_{IR}^2})}{2^7 3^3 \pi^2 m_Q^3} d_Q + \frac{5(8\zeta(3)-7)}{72}(\frac{\alpha_s}{\pi})^3 \frac{4m_d - m_u}{3m_Q} d_Q$$

$|d_c| < 6 \times 10^{-22}e\text{cm}, \quad |d_b| < 2 \times 10^{-20}e\text{cm}$

Summary

- New SM prediction for paramagnetic EDM

$$d_e^{eq} \simeq 1.0 \times 10^{-35} e\text{cm}$$

  - Uncertainty under control.
  - Within the reach of future experiments.

- New indirect constraints on muon, tau lepton, and charm and bottom quark EDM

$$|d_\mu| < 1.7 \times 10^{-20} e\text{cm}, \quad |d_\tau| < 1.1 \times 10^{-18} e\text{cm}$$
$$|d_c| < 6 \times 10^{-22} e\text{cm}, \quad |d_b| < 2 \times 10^{-20} e\text{cm}$$

  - Provide important benchmark for future experiments.

Thank you!