IBS-CTPU-PTC

Indirect signals of QCD axion in nuclear or atomic electric dipole moments

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Axions in Seoul, SNU, Korea

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Outline

- CP violation beyond the SM and the strong CP phase
- How QCD axion affects the ratios of nuclear/atomic EDMs
- Predicted patterns of nuclear/atomic EDMs

CP violation in the SM and BSM

$$\mathcal{L}_{\rm CPV}(m_W < \mu < \Lambda_{\rm BSM}) = \underbrace{\mathcal{L}_{\rm KM} + \frac{g_s^2}{32\pi^2}\bar{\theta} G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}}_{\text{SM}} + \underbrace{\mathcal{L}_{\rm dim\ 6} + \cdots}_{\text{BSM}}$$

$$\mathcal{L}_{\rm dim\ 6} = \frac{1}{\Lambda^2_{\rm BSM}}\Big(|H|^2 G\widetilde{G} + f^{abc}G^aG^b\widetilde{G}^c + H\bar{Q}_L\sigma^{\mu\nu}G_{\mu\nu}d_R \\ + H\bar{Q}_L\sigma^{\mu\nu}B_{\mu\nu}d_R + \bar{L}_Le_R\bar{d}_RQ_L + \cdots\Big)$$

Experimental status

Degenkolb, Elmer, Modak, Mühlleitner, Plehn ‘24

System i	Measured d_i [e cm]	Upper limit on $\lvert d_i \rvert$ [e cm]	
n	$(0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{syst}}) \cdot 10^{-26}$	$2.2 \cdot 10^{-26}$	
^{205}Tl	$(-4.0 \pm 4.3) \cdot 10^{-25}$	$1.1 \cdot 10^{-24}$	
^{133}Cs	$(-1.8 \pm 6.7_{\text{stat}} \pm 1.8_{\text{syst}}) \cdot 10^{-24}$	$1.4 \cdot 10^{-23}$	
HfF$^+$	$(-1.3 \pm 2.0_{\text{stat}} \pm 0.6_{\text{syst}}) \cdot 10^{-30}$	$4.8 \cdot 10^{-30}$	$\rightarrow d_e < 4.1 \times 10^{-30}\ e$ cm
ThO	$(4.3 \pm 3.1_{\text{stat}} \pm 2.6_{\text{syst}}) \cdot 10^{-30}$	$1.1 \cdot 10^{-29}$	
YbF	$(-2.4 \pm 5.7_{\text{stat}} \pm 1.5_{\text{syst}}) \cdot 10^{-28}$	$1.2 \cdot 10^{-27}$	
^{199}Hg	$(2.20 \pm 2.75_{\text{stat}} \pm 1.48_{\text{syst}}) \cdot 10^{-30}$	$7.4 \cdot 10^{-30}$	$\rightarrow d_p < 2.0 \times 10^{-25}\ e$ cm
^{129}Xe	$(-1.76 \pm 1.82) \cdot 10^{-28}$	$4.8 \cdot 10^{-28}$	
^{171}Yb	$(-6.8 \pm 5.1_{\text{stat}} \pm 1.2_{\text{syst}}) \cdot 10^{-27}$	$1.5 \cdot 10^{-26}$	
^{225}Ra	$(4 \pm 6_{\text{stat}} \pm 0.2_{\text{syst}}) \cdot 10^{-24}$	$1.4 \cdot 10^{-23}$	
TlF	$(-1.7 \pm 2.9) \cdot 10^{-23}$	$6.5 \cdot 10^{-23}$	

- Up to now, all EDM measurements are consistent with 0: There are only upper limits for EDMs.
- EDMs of charged particles such as electron and proton are currently only indirectly measured from atomic or molecular EDMs.

Experimental limits (2026)

$$d_n < 2.2 \times 10^{-26}\ e\ \text{cm}$$
$$d_p < 2.0 \times 10^{-25}\ e\ \text{cm}$$
$$d_e < 4.1 \times 10^{-30}\ e\ \text{cm}$$

SM predictions

$$d_n \sim d_p \sim (10^{-32} \sin \delta_{\mathrm{KM}} + 10^{-16} \bar{\theta})\ e\ \text{cm}$$
$$d_e \sim (10^{-44} \sin \delta_{\mathrm{KM}} + 10^{-27} \bar{\theta})\ e\ \text{cm}$$

$\delta_{\mathrm{KM}} = 65.7^\circ \pm 1.5^\circ$ (PDG 2025)

$\Rightarrow$ $\bar{\theta} \lesssim 10^{-10}$ (strong CP problem)

- EDMs from δ_{KM} are very small.
- If $\bar{\theta}$ happens to be near 10^{-10}, a non-zero nuclear EDM will show up in near-future experiments.

BSM predictions

$$d \sim \frac{1}{\Lambda_{\mathrm{BSM}}^2} \times \sin\delta_{\mathrm{BSM}} \times (\text{Loop factors, Gauge/Yukawa couplings, } \ldots)$$

Λ_{BSM} : BSM particle mass scale

δ_{BSM} : BSM CP phase

Typically $\Lambda_{\mathrm{BSM}} \lesssim O(100)$ TeV can give rise to sizable EDMs close to the current experimental limits.

Multi-TeV scale new physics (SUSY, WIMP DM, Electroweak baryogenesis, …) can be probed by EDMs.

5 classes of BSM CPV operators around QCD scale

$$\mathcal{L}_{\text{dim }6} = \frac{1}{\Lambda_{\text{BSM}}^2}\Big(|H|^2 G\widetilde{G} + f^{abc}G^aG^b\widetilde{G}^c + H\bar{Q}_L\sigma^{\mu\nu}G_{\mu\nu}d_R$$
$$+ H\bar{Q}_L\sigma^{\mu\nu}B_{\mu\nu}d_R + \bar{L}_Le_R\bar{d}_RQ_L + \cdots\Big)$$

After EWSB and integrating out heavy SM fields

Around QCD scale ~ 1 GeV

Gluon Chromo-EDM (Weinberg operator)

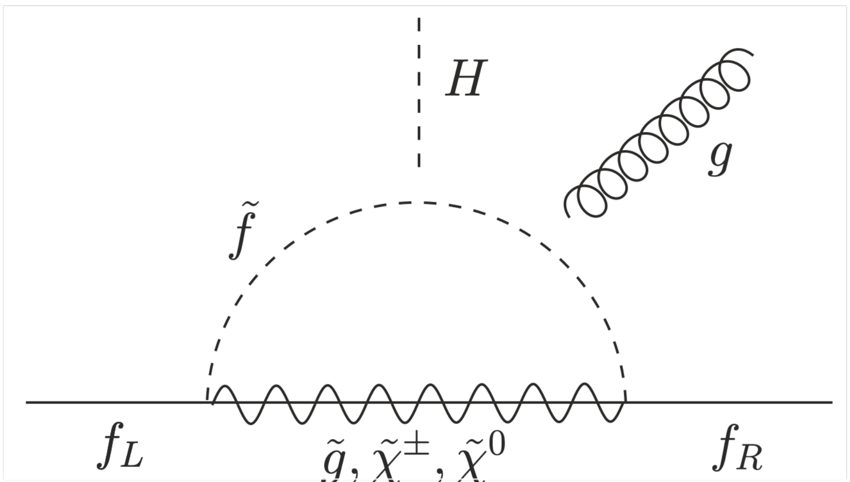
$$f^{abc}G^aG^b\widetilde{G}^c + \bar{q}\sigma^{\mu\nu}i\gamma_5G_{\mu\nu}q$$

Quark Chromo-EDMs (CEDMs)

$$+ \bar{q}\sigma^{\mu\nu}i\gamma_5F_{\mu\nu}q + \bar{e}\sigma^{\mu\nu}i\gamma_5F_{\mu\nu}e + \bar{e}e\bar{q}i\gamma_5q + \bar{q}q\bar{q}i\gamma_5q$$

Quark EDMs | Electron EDM | 4-Fermi operators

BSM example :
MSSM with a universal SUSY particle mass

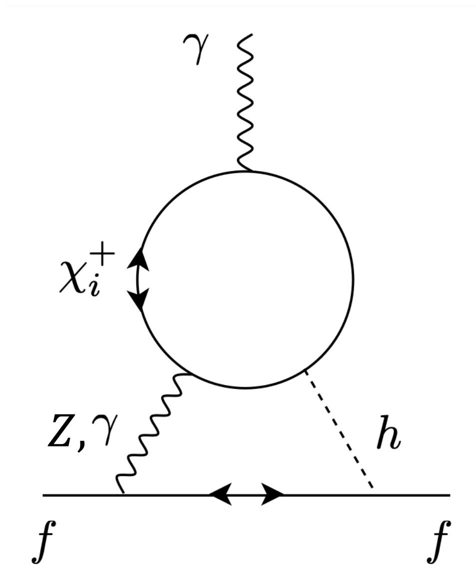


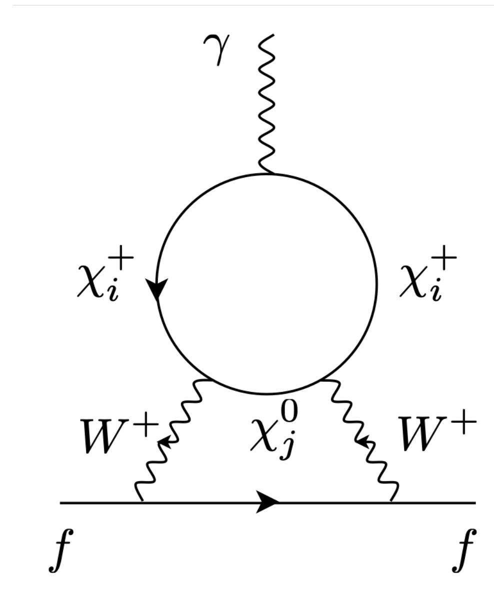
$$\tilde{d}_q \, g_s \, \bar{q}\sigma^{\mu\nu} i \, \gamma_5 G_{\mu\nu} q$$

Quark CEDMs domination

BSM example: Split supersymmetry

J Wells '03
N Arkani-Hamed and S Dimopoulos '04
Giudice and Romanino '04



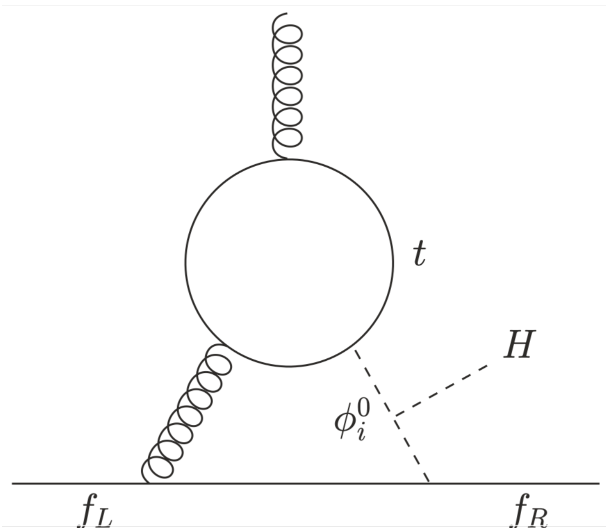


$$d_q\ \bar{q}\sigma^{\mu\nu}i\gamma_5F_{\mu\nu}q + d_e\ \bar{e}\sigma^{\mu\nu}i\gamma_5F_{\mu\nu}e$$

Quark and Electron EDMs

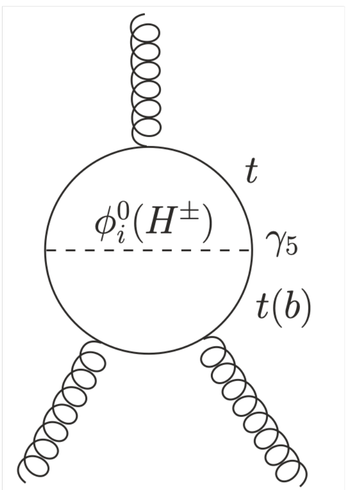
Giudice and Romanino '05

BSM example :
2 Higgs-doublet models



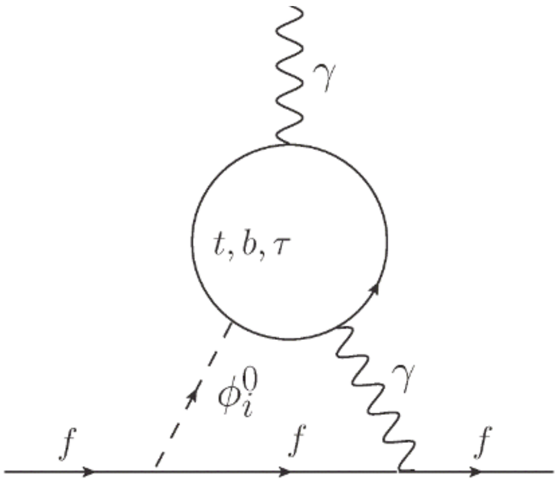
$\tilde{d}_q\, g_s\, \bar{q}\sigma^{\mu\nu} i\, \gamma_5 G_{\mu\nu} q$

Quark CEDMs



$w\, f^{abc} G^a G^b \tilde{G}^c$

Gluon CEDM
(Weinberg operator)



$d_e\, \bar{e}\sigma^{\mu\nu} i\gamma_5 F_{\mu\nu} e$

Electron EDM

S. Weinberg '89, Gunion, Wyler '90
Chang, Keung, Yuan '90, Jung, Pich '14

Potentially dominant sources for the EDMs

$$\underbrace{\frac{g_s^2}{32\pi^2}\bar{\theta}G\widetilde{G}}_{\text{SM}} + \underbrace{w\, f^{abc}G^aG^b\widetilde{G}^c + \tilde{d}_q\, g_s\, \bar{q}\sigma^{\mu\nu}i\gamma_5 G_{\mu\nu}q + d_q\, \bar{q}\sigma^{\mu\nu}i\gamma_5 F_{\mu\nu}q + d_e\, \bar{e}\sigma^{\mu\nu}i\gamma_5 F_{\mu\nu}eq + C_{\bar{e}e\bar{q}q}\bar{e}e\bar{q}i\gamma_5 q + \bar{q}q\bar{q}i\gamma_5 q}_{\text{BSM}}$$

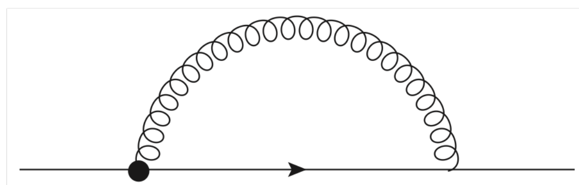
A specific BSM scenario can be characterized by typically one or two dominant operators among them.

Key question: If non-zero nuclear or atomic EDMs are observed in the future, can we experimentally determine the origin of the EDMs among those operators? How does QCD axion affect the EDM signals?

Hadronic BSM CPV and strong CP phase

For example, let's consider a quark CEDM.

$$\frac{m_q}{\Lambda_{\rm BSM}^2} g_s\, \bar{q}\sigma^{\mu\nu}G_{\mu\nu}i\gamma_5 q \quad \Rightarrow \quad m_q\delta\theta\, \bar{q}i\gamma_5 q \qquad \delta\theta \sim \frac{\alpha_s}{4\pi}$$



$$\tilde{d}_q\left(=\frac{m_q}{\Lambda_{\rm BSM}^2}\right) \qquad g_s$$

Hadronic BSM CPV spoils UV solution (like Nelson-Barr) to the strong CP problem by radiatively generating a large $\bar{\theta}$.

J. de Vries, P. Draper, K. Fuyuto, J. Kozaczuk, D. Sutherland '18
J. de Vries, P. Draper, K. Fuyuto, J. Kozaczuk, B. Lillard '21

Hadronic BSM CPV requires an IR solution to the strong CP problem.

Dynamical $\bar{\theta}$
(QCD axion)

vs

Non-dynamical $\bar{\theta}$

- Simply fine-tuned $\bar{\theta}$
- Unknown IR mechanism to suppress $\bar{\theta}$?

Hadronic BSM CPV with QCD axion

$$\bar{\theta} = \frac{\langle a \rangle}{f_a} \simeq \underbrace{\frac{i}{m_a^2 f_a^2} \int d^4x \, \langle G\tilde{G}(x) O_{\mathrm{BSM}}(0) \rangle_{a=0}}_{\bar{\theta}_{\mathrm{BSM}}} + \text{Other explicit PQ breakings (quantum gravity, etc)}$$

$$O_{\mathrm{BSM}} = \frac{m_q}{\Lambda_{\mathrm{BSM}}^2} g_s \bar{q} \sigma^{\mu\nu} G_{\mu\nu} i \gamma_5 q, \ldots$$

$$\bar{\theta}_{\mathrm{BSM}} \sim (4\pi)^n \frac{f_\pi^2}{\Lambda_{\mathrm{BSM}}^2} \sim 10^{-10} \, (4\pi)^n \left(\frac{10 \text{ TeV}}{\Lambda_{\mathrm{BSM}}} \right)^2 \quad n = 2 \text{ (qCEDM)}, 1 \text{ (gCEDM)}, \ldots$$

The size of $\bar{\theta}$ has a lower bound set by BSM CPV.

$$\bar{\theta}_{\mathrm{BSM}} \leq \bar{\theta} < 10^{-10}$$

Hadronic BSM CPV without QCD axion

Given large radiative correction to $\bar{\theta}$ from hadronic BSM CPV, how to solve the strong CP problem without QCD axion?

I. Simply fine-tuned $\bar{\theta}$
II. Unknown IR mechanism to suppress $\bar{\theta}$?

➡ No lower bound on $\bar{\theta}$ set by BSM CPV

The size of $\bar{\theta}$ is independent of BSM CPV.

d_n and d_p from hadronic CPV sources

Naïve dimensional analysis (NDA) e.g. S. Weinberg '89

$$\Lambda_\chi = 4\pi f_\pi$$

$$d_n \sim d_p \sim \frac{em_*}{\Lambda_\chi^2}\,\bar{\theta} + \frac{e\Lambda_\chi}{4\pi} w + e\,\tilde{d}_q + d_q \qquad m_* \simeq \frac{m_u m_d}{m_u + m_d}$$

$$\simeq 0.4\times 10^{-16}\,[e\text{ cm}]\,\bar{\theta} + 92\text{ MeV}\,e\,w + e\,\tilde{d}_q + d_q$$

at $\mu = 225$ MeV

In this analysis, we do not include CPV 4-quark operators, which are typically small, unless we consider LR symmetric models.

QCD sum rules

Pospelov, Ritz '99 Hisano, Lee, Nagata, Shimizu '12
Yamanaka, Hiyama '20

Non-perturbative quantity = $\sum_n C_n \langle O_n \rangle$

Wilson coefficient (short-distance interactions)

Quark and Gluon condensates (long-distance interactions)

$$\kappa\, d_n(\bar\theta, \tilde d_q, d_q) = \frac{\langle \bar q \sigma_{\mu\nu} q\rangle}{e_q F_{\mu\nu}} m_* \left[(4e_d - e_u)\left(\bar\theta - \frac{g_s}{2}\frac{\langle \bar q G^{\mu\nu}\sigma_{\mu\nu} q\rangle}{\langle \bar q q\rangle}\frac{\tilde d_s}{m_s}\right) + \frac{g_s}{2}\frac{\langle \bar q G^{\mu\nu}\sigma_{\mu\nu} q\rangle}{\langle \bar q q\rangle}(\tilde d_d - \tilde d_u)\left(\frac{4e_d}{m_u} + \frac{e_u}{m_d}\right)\right]$$

$$+ \frac{g_s}{4}\left(\frac{\langle \bar q G_{\mu\nu} q\rangle}{e_q F_{\mu\nu}} - \frac{\langle \bar q i\gamma_5 \tilde G_{\mu\nu} q\rangle}{e_q F_{\mu\nu}}\right)(4e_d \tilde d_d - e_u \tilde d_u) + (4d_d - d_u) + \underset{< O(10\%)}{\underline{\text{higher order terms}}}$$

$$\kappa\, d_p(\bar\theta, \tilde d_q, d_q) = (u \leftrightarrow d)$$

- Agree with NDA up to $O(1)$ factor.
- The major theoretical uncertainty is from the overall normalization κ which is uncertain by unknown matrix elements of nucleon's excited states: the EDM ratio d_p/d_n is free from this uncertainty.

QCD sum rules

Pospelov, Ritz '99 Hisano, Lee, Nagata, Shimizu '12
Yamanaka, Hiyama '20

If QCD axion exists, $\bar{\theta}$ is correlated with BSM CPV parameters.

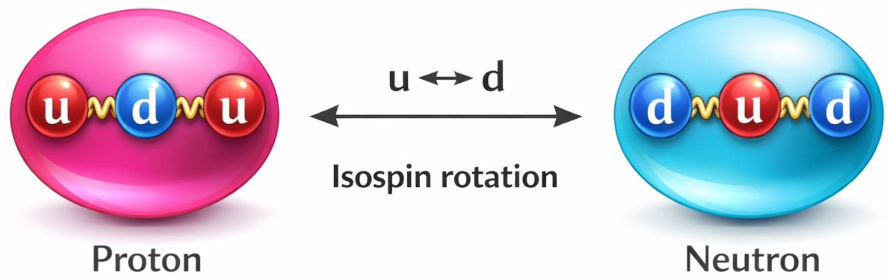
$$\bar{\theta} = \bar{\theta}_{\rm QG} + \frac{g_s}{2} \frac{\langle \bar{q} G^{\mu\nu} \sigma_{\mu\nu} q \rangle}{\langle \bar{q} q \rangle} \sum_{q=u,d,s} \frac{\tilde{d}_q}{m_q} + \mathcal{O}(4\pi f_\pi^2 w)$$

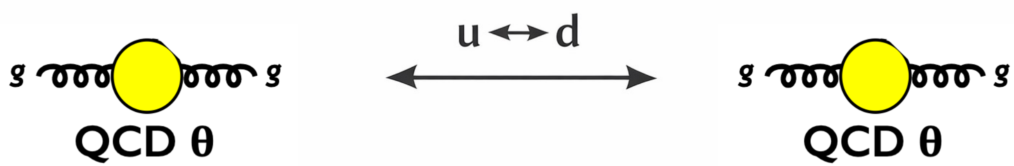
$$\kappa\, d_n^{\rm PQ}(\bar{\theta}_{\rm QG}, \tilde{d}_q, d_q) = \frac{\langle \bar{q} \sigma_{\mu\nu} q \rangle}{e_q F_{\mu\nu}} m_* (4e_d - e_u) \bar{\theta}_{\rm QG} + (4d_d - d_u)$$
$$+ \frac{g_s}{4} \left(\frac{\langle \bar{q} G_{\mu\nu} q \rangle}{e_q F_{\mu\nu}} - \frac{\langle \bar{q} i \gamma_5 \tilde{G}_{\mu\nu} q \rangle}{e_q F_{\mu\nu}} + 2 \frac{\langle \bar{q} \sigma_{\mu\nu} q \rangle}{e_q F_{\mu\nu}} \frac{\langle \bar{q} G^{\mu\nu} \sigma_{\mu\nu} q \rangle}{\langle \bar{q} q \rangle} \right) (4e_d \tilde{d}_d - e_u \tilde{d}_u)$$

$$\kappa\, d_p^{\rm PQ}(\bar{\theta}_{\rm QG}, \tilde{d}_q, d_q) = (u \leftrightarrow d\,)$$

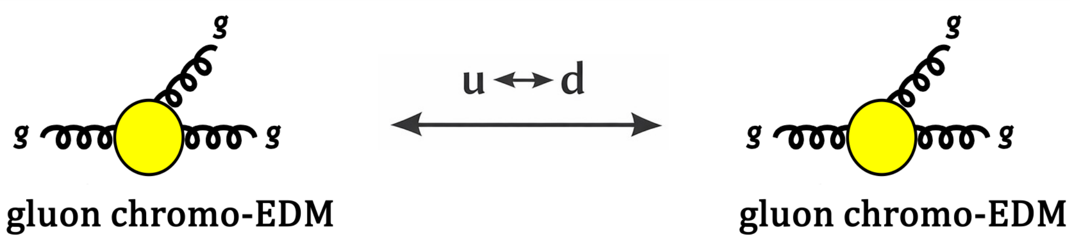
The nucleon EDMs from quark CEDMs significantly change by the presence of QCD axion.

Isospin symmetry

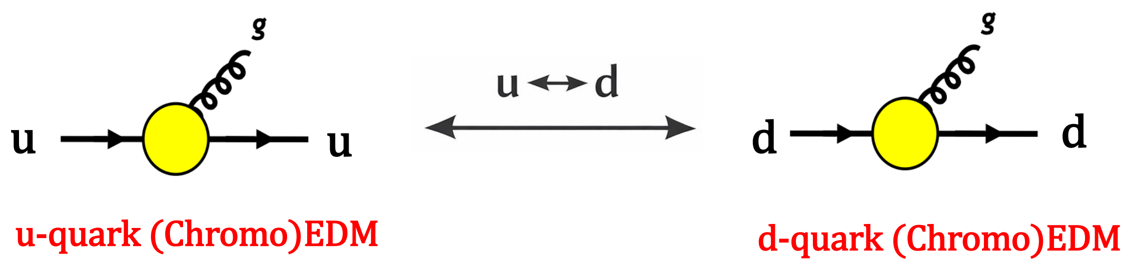




Invariant



Invariant



Breaking unless
u-quark (C)EDM =
d-quark (C)EDM

$$d_N \sim Q_{\mathrm{EM}} \times \delta_{\mathrm{CP}}$$

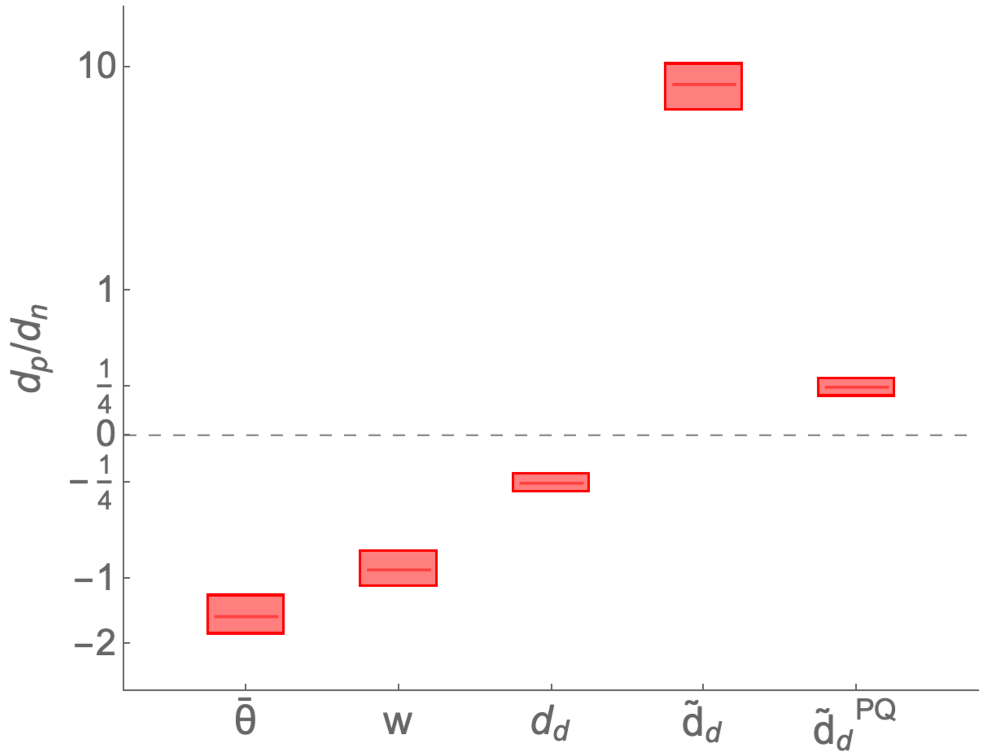
$$d_N = \begin{pmatrix} d_p & 0 \\ 0 & d_n \end{pmatrix} = d_0 \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + d_1 \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

isoscalar isovector

$$Q_{\mathrm{EM}} = \begin{pmatrix} 2/3 & 0 \\ 0 & -1/3 \end{pmatrix} = \frac{1}{6} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Since Q_{EM} is approximately an isovector, isospin-conserving CPV parameters contribute to d_1 more than d_0 so that $d_p \approx -d_n$.

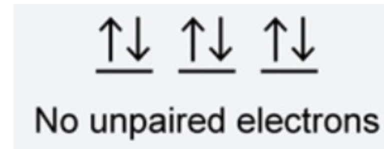
The prediction on the ratio d_p/d_n from QCD sum rules



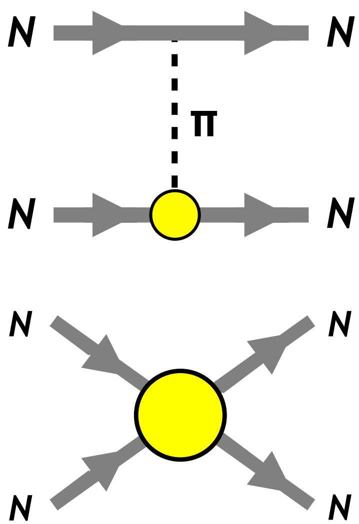
- The isospin-conserving operators ($\bar{\theta}$ and gluon CEDM) predict d_p/d_n near -1, while the isospin-breaking operators (quark (C)EDMs) predict different values.
- The presence of QCD axion affects the ratio, if quark CEDM is the dominant source of nucleon EDMs. In the other cases, QCD axion does not make difference.

EDMs of light nuclei and diamagnetic atoms

In diamagnetic atoms, all electrons are paired.



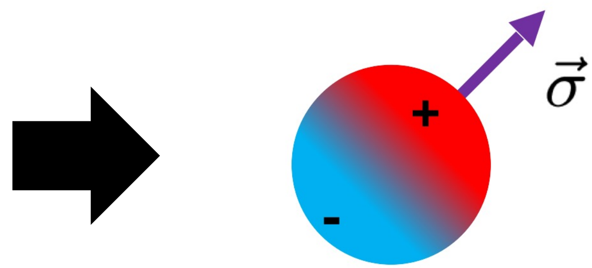
The permanent EDM of a diamagnetic atom or a nucleus is mainly from polarization of the nucleus due to P and CP-odd nuclear forces as well as n and p EDMs.



$$\bar{g}_0 \bar{N}\, \vec{\tau} \cdot \vec{\pi}\, N$$
$$+\bar{g}_1 \pi^3 \bar{N} N$$

$$C_1 \bar{N} N\, D_\mu (N^+ S^\mu N)$$
$$+C_2 \bar{N} \vec{\tau} N \cdot D_\mu (N^+ \vec{\tau}\, S^\mu N)$$

P and CP-odd nuclear forces



Polarization of nucleus

→ *Atomic electric dipole moment*

$$d_A = d_A(d_n, d_p, \bar{g}_0, \bar{g}_1, C_1, C_2)$$

Light nuclei

Bsaisou, Meissner, Nogga, Wirzba '14

$$d_D = 0.94(1)(d_n + d_p) + 0.18(2)\bar{g}_1\, e\,\mathrm{fm}$$

$$d_{\mathrm{He}} = 0.9 d_n - 0.03(1) d_p + \Big[0.11(1)\bar{g}_0 + 0.14(2)\bar{g}_1 - (0.04(2)C_1 - 0.09(2)C_2)\,\mathrm{fm}^{-3}\Big]\, e\,\mathrm{fm}$$

Diamagnetic atoms with heavy nuclei

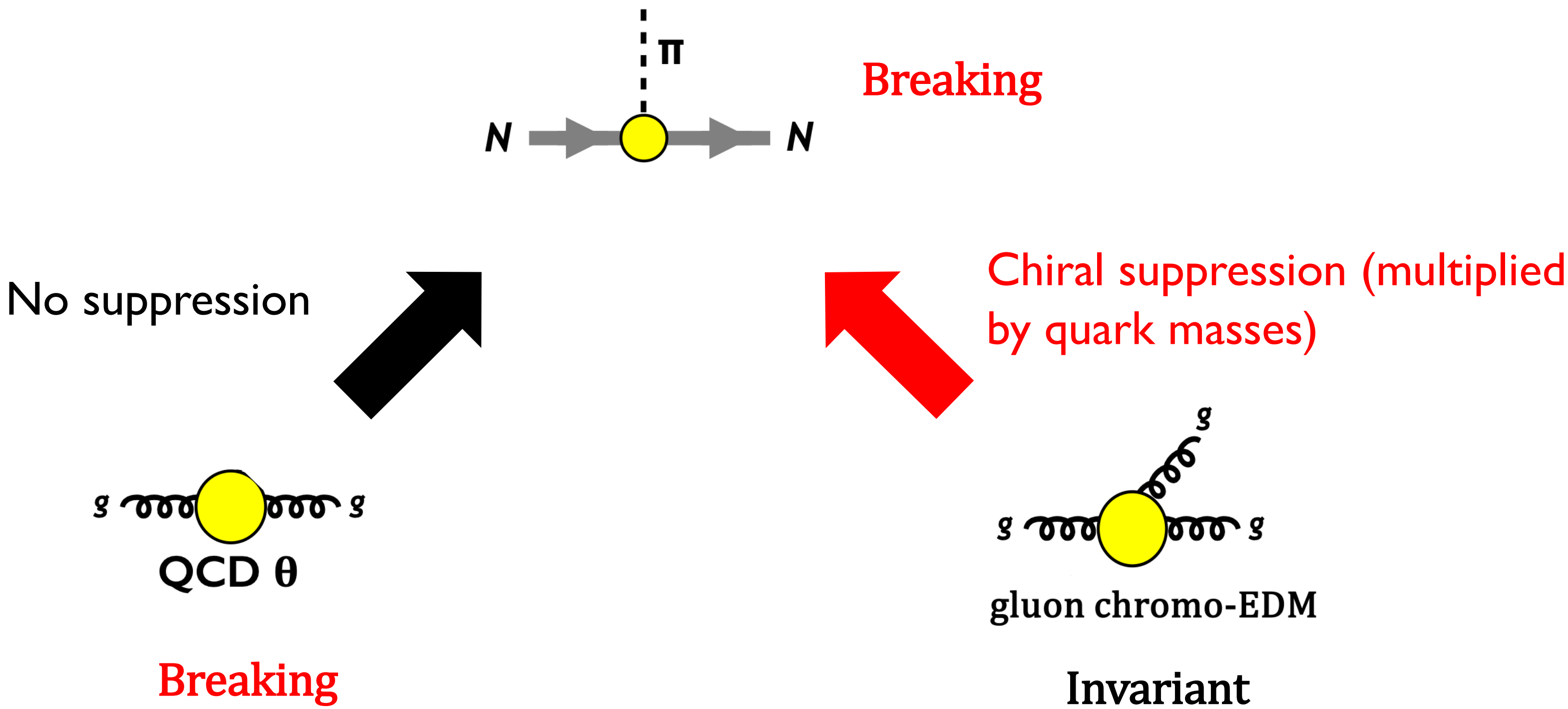
e.g.) Engel, Ramsey-Musolf, Kolck '13
Fleig, Jung '18

$$d_{\mathrm{Hg}} = -2.26(23)\cdot 10^{-4}\left[0.6^{+1.33}_{-0.12} d_n + 0.06^{+0.20}_{-0.01} d_p + \frac{g_A m_N}{f_\pi}\left(0.01^{+0.04}_{-0.005}\,\bar{g}_0 + 0.02^{+0.07}_{-0.05}\,\bar{g}_1\right) e\,\mathrm{fm}\right]$$

$$d_{\mathrm{Ra}} = -8.5^{+0.25}_{-0.3}\cdot 10^{-4}\Big[0.63^{+0.16}_{-0.12} d_n + 0.14^{+0.04}_{-0.03} d_p + \frac{g_A m_N}{f_\pi}\left(-0.2(6)\,\bar{g}_0 + 5(3)\,\bar{g}_1\right) e\,\mathrm{fm} + m_N^3\left(-0.01(3)C_1 + 0.03(2)C_2\right) e\,\mathrm{fm}\Big]$$

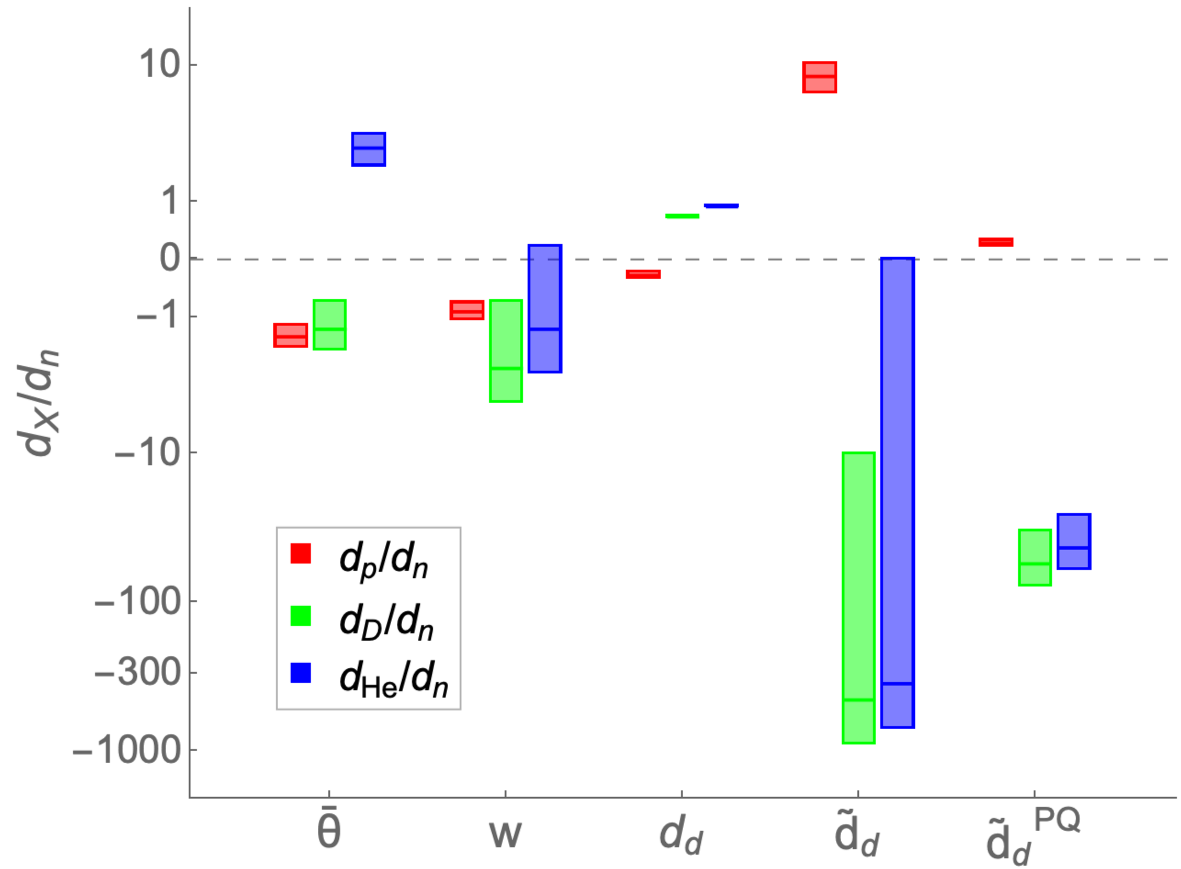
Chiral symmetry

$$q_L \to U_L q_L, \qquad q_R \to U_R q_R$$



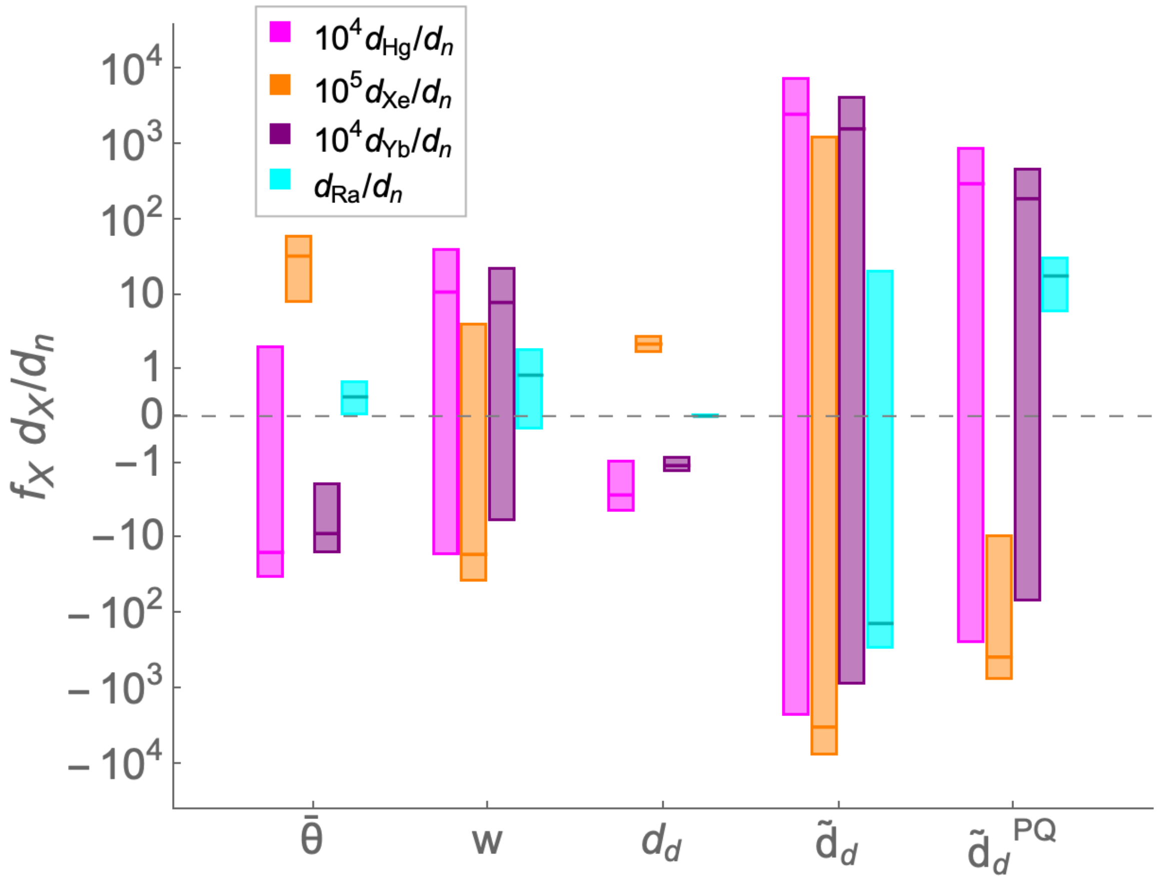
The CP-violating pion-nucleon couplings may discriminate between the QCD θ and the gluon CEDM.

Predicted ratios of the EDMs of light nuclei



The helion EDM can distinguish between $\bar{\theta}$ and w (gluon CEDM).

Predicted ratios of the EDMs of heavy nuclei



The information can be only suggestive due to large theoretical uncertainties in nuclear physics.

Summary

- Nuclear or atomic EDMs are powerful probes for BSM above TeV scale.
- A key question is the feasibility of identifying the UV source of CP violation via EDM measurements: "The EDM inverse problem"
- Solutions to the strong CP problem including QCD axion crucially affect the pattern of nuclear or atomic EDMs.
- We find that EDM data of light nuclei (n, p, D, He) can identify the leading hadronic CP-odd operator, while heavy atoms can provide only suggestive information.
- In particular, if quark CEDM is the dominant CP-odd operator responsible for nucleon EDMs, it can give us an indirect experimental evidence of QCD axion.

Predicted ratios of nuclear and atomic EDMs

	$\bar{\theta}$	$w,\ w^{\mathrm{PQ}}$	d_q	$\tilde{d}_q$	$\tilde{d}_q^{\mathrm{PQ}}$
$\frac{d_p}{d_n}$	-1.5	-0.90(3)	$-\frac{4d_u-d_d}{d_u-4d_d}$	$\frac{0.81(6)\tilde{d}_u-1.51(4)\tilde{d}_d}{0.64(4)\tilde{d}_u-0.18(4)\tilde{d}_d}$	$\frac{8\tilde{d}_u+\tilde{d}_d}{2\tilde{d}_u+4\tilde{d}_d}$
$\frac{d_D}{d_n}$	-1.3(6)	$-5.1(35)r(\Lambda)+0.09(21)$	$\frac{-2.82(3)(d_u+d_d)}{d_u-4d_d}$	$\frac{-541(196)(\tilde{d}_u-\tilde{d}_d)}{4.4(8)\tilde{d}_u-1.2(11)\tilde{d}_d}$	$\frac{110(43)(\tilde{d}_u-\tilde{d}_d)}{\tilde{d}_u+2\tilde{d}_d}$
$\frac{d_{\mathrm{He}}}{d_n}$	2.7(7)	$-3.9(28)r(\Lambda)+0.77(31)$	$0.9+0.03(1)\frac{4d_u-d_d}{d_u-4d_d}$	$\frac{-422(157)(\tilde{d}_u-\tilde{d}_d)}{4.4(8)\tilde{d}_u-1.2(11)\tilde{d}_d}$	$\frac{86(34)(\tilde{d}_u-\tilde{d}_d)}{\tilde{d}_u+2\tilde{d}_d}$
$10^4\frac{d_{\mathrm{Hg}}}{d_n}$	$-16(18)$	$25(53)r(\Lambda)-2.4(20)$	$\frac{-1.3(19)d_u+11(7)d_d}{d_u-4d_d}$	$\frac{3(5)\times10^3(\tilde{d}_u-\tilde{d}_d)}{4.4(8)\tilde{d}_u-1.2(11)\tilde{d}_d}$	$\frac{-0.6(11)\times10^3(\tilde{d}_u-\tilde{d}_d)}{\tilde{d}_u+2\tilde{d}_d}$
$10^5\frac{d_{\mathrm{Xe}}}{d_n}$	$33(25)$	$-36(40)r(\Lambda)+1.9(17)$	$\frac{0.3(7)d_u-8.9(21)d_d}{d_u-4d_d}$	$\frac{-4(4)\times10^3(\tilde{d}_u-\tilde{d}_d)}{4.4(8)\tilde{d}_u-1.2(11)\tilde{d}_d}$	$\frac{0.78(75)\times10^3(\tilde{d}_u-\tilde{d}_d)}{\tilde{d}_u+2\tilde{d}_d}$
$10^4\frac{d_{\mathrm{Yb}}}{d_n}$	$-9(7)$	$17(26)r(\Lambda)-1.0(8)$	$\frac{-0.66(27)d_u+4.3(10)d_d}{d_u-4d_d}$	$\frac{1.9(25)\times10^3(\tilde{d}_u-\tilde{d}_d)}{4.4(8)\tilde{d}_u-1.2(11)\tilde{d}_d}$	$\frac{-0.38(51)\times10^3(\tilde{d}_u-\tilde{d}_d)}{\tilde{d}_u+2\tilde{d}_d}$
$\frac{d_{\mathrm{Ra}}}{d_n}$	0.31(29)	$1.6(14)r(\Lambda)+0.00(7)$	$\frac{-0.6(17)d_u+21(5)d_d}{d_u-4d_d}\cdot10^{-4}$	$\frac{170(118)(\tilde{d}_u-\tilde{d}_d)}{4.4(8)\tilde{d}_u-1.2(11)\tilde{d}_d}$	$\frac{-35(25)(\tilde{d}_u-\tilde{d}_d)}{\tilde{d}_u+2\tilde{d}_d}$

Assumption: EDMs are originated from a single type of CPV operator

EDM data of at least three nuclei or atoms can determine the CPV source.