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Identifying high energy sources of CP violation and PQ breaking with EDMs

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Kiwoon Choi, SHI, 2603.xxxxx

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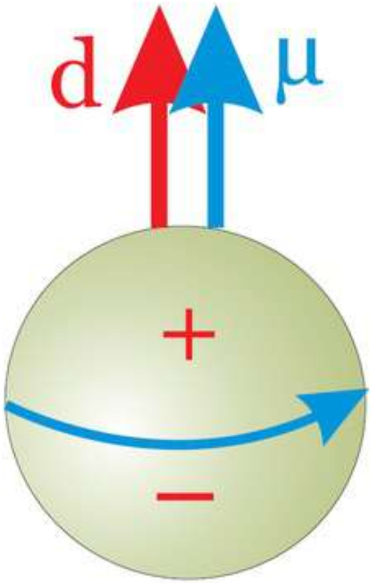
Outline

- CP violation and Electric Dipole Moments (EDMs)
- SM and BSM sources for CP violation and/or PQ breaking
- Nuclear and Atomic EDMs
- Identifying SM and BSM sources from EDM data

EM dipole moments of a particle

An elementary particle or an atom can have a permanent electric dipole moment (EDM) and a magnetic dipole moment (MDM) along the direction of its spin.



$$H = -d\,\vec{S}\cdot\vec{E} - \mu\,\vec{S}\cdot\vec{B}$$

Charge conjugation $C : \mathbf{E} \to -\mathbf{E},\, \mathbf{B} \to -\mathbf{B},\, \mathbf{S} \to -\mathbf{S}$

Parity inversion $P : \mathbf{E} \to -\mathbf{E},\, \mathbf{B} \to +\mathbf{B},\, \mathbf{S} \to +\mathbf{S}$

Time reversal $T : \mathbf{E} \to +\mathbf{E},\, \mathbf{B} \to -\mathbf{B},\, \mathbf{S} \to -\mathbf{S}$

EDM (d) violates P and $T (= CP)$ invariance, while MDM (μ) does not.

A non-zero permanent EDM of an elementary particle or an atom implies CP-violating interactions in underlying short-distance physics.

CP violation is a necessary condition to generate the asymmetry between matter and antimatter in the early universe. Sakharov '67

Observed asymmetry : $Y_B = \frac{n_B}{s} \sim 10^{-10}$

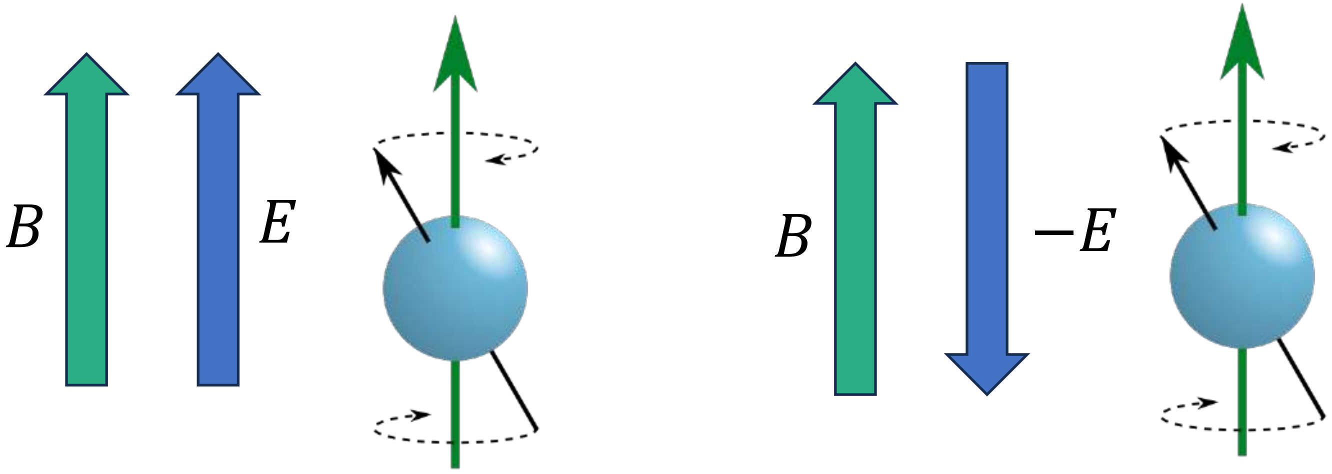
SM prediction : $Y_{B,\,\mathrm{SM}} \lesssim 10^{-15}$

e.g. Konstandin, Prokopec, G. Schmidt '03

SM does not provide an enough CP violation, and we need new physics beyond the SM involving additional CP violation, which may give rise to sizable EDMs of SM particles.

EDM experiments

- Typical method using spin-precession spectroscopy
  (used for neutral particles such as neutrons, atoms, and molecules)



$h\,\nu_1 = 2\mu\,B + 2d\,E$ $h\,\nu_2 = 2\mu\,B - 2d\,E$

$$d = \frac{h\,\Delta\nu}{4E}$$

Experimental status

Degenkolb, Elmer, Modak, Mühlleitner, Plehn ‘24

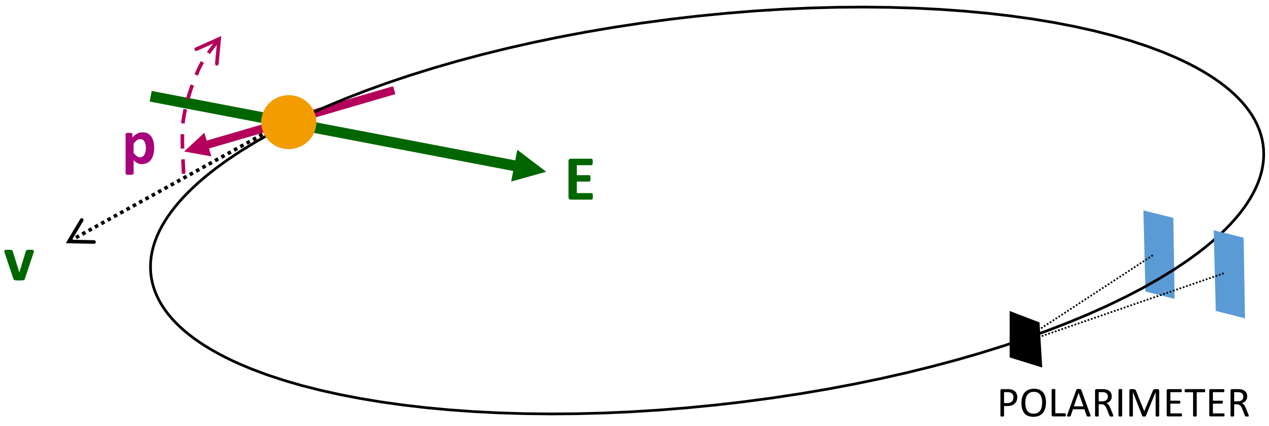
System i	Measured d_i $[e\,\text{cm}]$	Upper limit on $\lvert d_i \rvert$ $[e\,\text{cm}]$	
n	$(0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{syst}}) \cdot 10^{-26}$	$2.2 \cdot 10^{-26}$	
^{205}Tl	$(-4.0 \pm 4.3) \cdot 10^{-25}$	$1.1 \cdot 10^{-24}$	
^{133}Cs	$(-1.8 \pm 6.7_{\text{stat}} \pm 1.8_{\text{syst}}) \cdot 10^{-24}$	$1.4 \cdot 10^{-23}$	
HfF^+	$(-1.3 \pm 2.0_{\text{stat}} \pm 0.6_{\text{syst}}) \cdot 10^{-30}$	$4.8 \cdot 10^{-30}$	$\rightarrow\ d_e < 4.1\times10^{-30}\ e$ 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	$(2.20 \pm 2.75_{\text{stat}} \pm 1.48_{\text{syst}}) \cdot 10^{-30}$	$7.4 \cdot 10^{-30}$	$\rightarrow\ d_p < 2.0\times10^{-25}\ e$ 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.

EDM experiments

- Storage ring experiments (used for "heavy" charged particles such as protons and deuterons)

Currently prototypes at COSY-JEDI and BNL



Particle beams with spins initially aligned to the beam axis will develop a vertical spin component if the particle has a non-zero EDM as the beams circulate in the ring.
This vertical component can be extracted from spin-dependent elastic nuclear scatterings at the polarimeter.

Experimental limits (2025)

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

SM predictions

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

$\delta_{\text{KM}} = 65.7^\circ \pm 1.5^\circ$ (PDG 2024)

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

The SM predictions on EDMs from the KM phase are very small compared with current experimental limits,
while QCD $\bar{\theta} \sim 10^{-10}$ gives rise to sizable EDMs measurable in the near future.

Experimental limits (2025)

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

BSM predictions

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

Λ_{BSM} : BSM particle mass scale

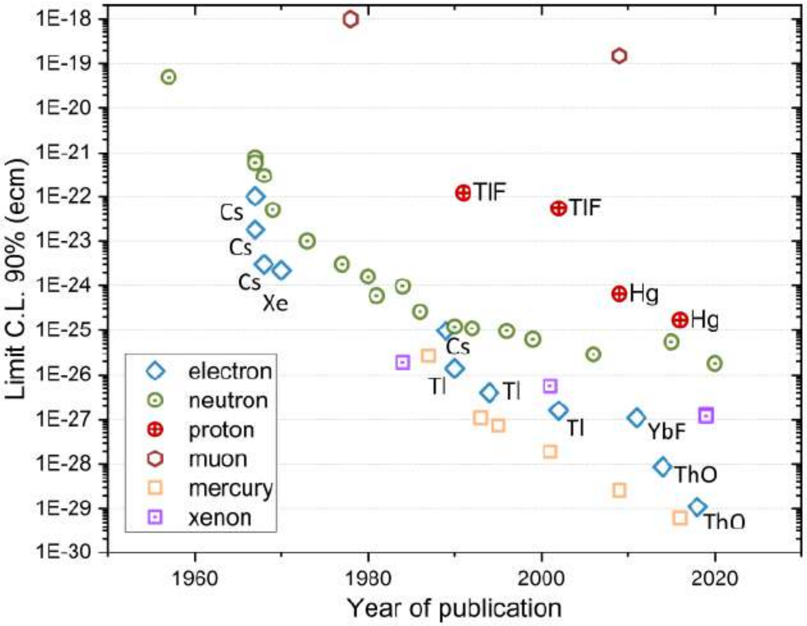
δ_{BSM} : BSM CP phase

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

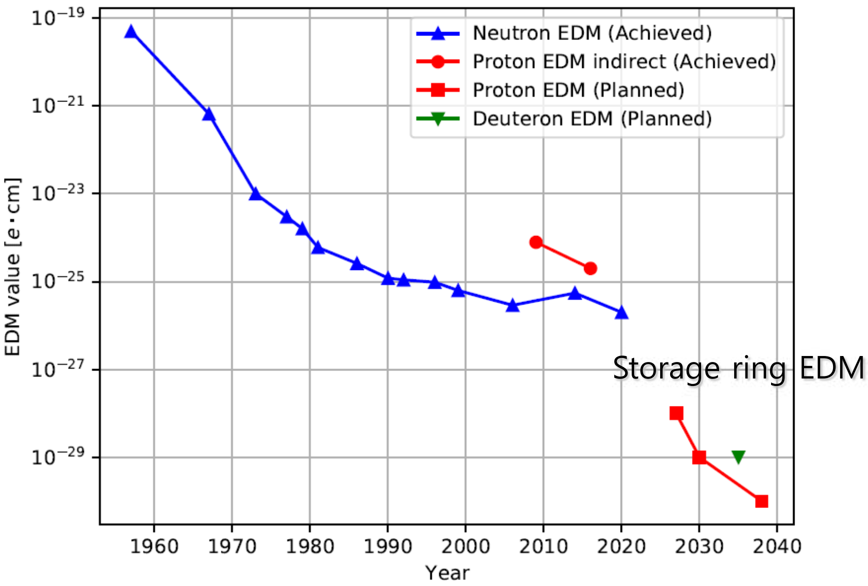
➡ Multi-TeV scale new physics (SUSY, WIMP, Electroweak baryogenesis, …) can be probed by EDMs.

Experimental prospect

K. Kirch, P. Schmidt-Wellenburg 2003.00717



R. Alarcon et al 2203.08103



Storage ring EDM

In a decade, the experimental sensitivity on EDMs of electrons, nucleons, atoms, and molecules is going to be improved by several orders of magnitude.

CP violation in the SM and beyond

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

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

$$+ H\bar{Q}_L\sigma^{\mu\nu}B_{\mu\nu}d_R + \bar{L}_L e_R \bar{d}_R Q_L + \cdots\Big)$$

EWSB and integrating out heavy SM fields

Around the QCD scale ~ 1 GeV

Gluon Chromo-EDM (Weinberg operator)

$$f^{abc}G^aG^b\widetilde{G}^c + \bar{q}\sigma^{\mu\nu}i\gamma_5 G_{\mu\nu}q$$

Quark Chromo-EDMs (CEDMs)

$$+ \bar{q}\sigma^{\mu\nu}i\gamma_5 F_{\mu\nu}q + \bar{e}\sigma^{\mu\nu}i\gamma_5 F_{\mu\nu}e + \bar{q}q\bar{q}q + \bar{e}e\bar{q}q$$

Quark EDMs

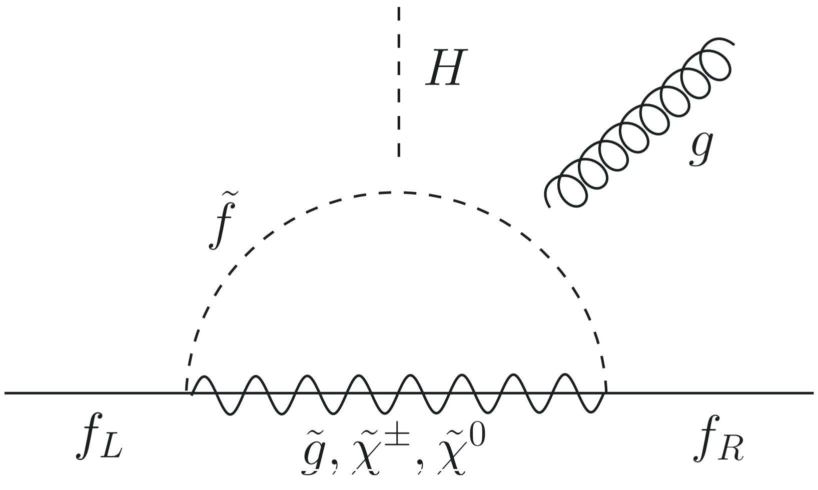
Electron EDM

4-Fermi operators

Since the KM phase contributes very little to nuclear and electron EDMs, potentially dominant sources for the EDMs are

$$\underbrace{\frac{g_s^2}{32\pi^2}\bar{\theta}G\widetilde{G}}_{\text{SM}}\ \underbrace{\begin{aligned}&+ f^{abc}G^aG^b\widetilde{G}^c + \bar{q}\sigma^{\mu\nu}i\gamma_5G_{\mu\nu}q\\ &+ \bar{q}\sigma^{\mu\nu}i\gamma_5F_{\mu\nu}q + \bar{e}\sigma^{\mu\nu}i\gamma_5F_{\mu\nu}e + \bar{q}q\bar{q}q + \bar{e}e\bar{q}q\end{aligned}}_{\text{BSM}}$$

BSM example :
MSSM with a universal SUSY particle mass



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

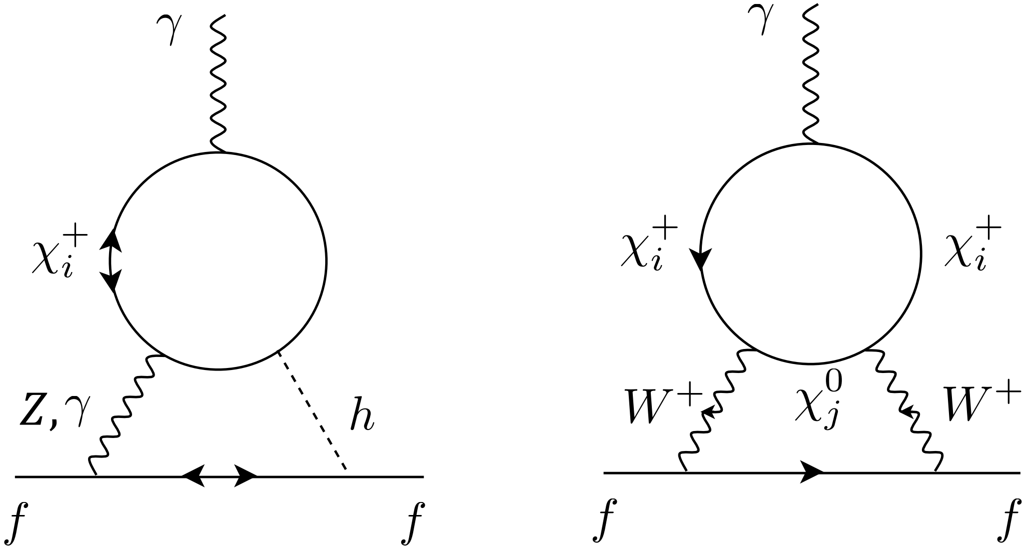
Quark CEDMs domination

BSM example: Split supersymmetry

J Wells ’03

N Arkani-Hamed and S Dimopoulos ’04

Giudice and Romanino ‘04

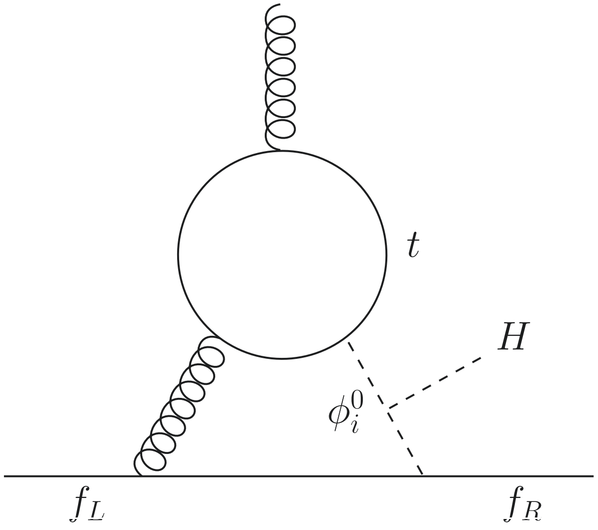


$$d_q \; \bar{q}\sigma^{\mu\nu} i\gamma_5 F_{\mu\nu} q + d_e \; \bar{e}\sigma^{\mu\nu} i\gamma_5 F_{\mu\nu} e$$

Quark and Electron EDMs

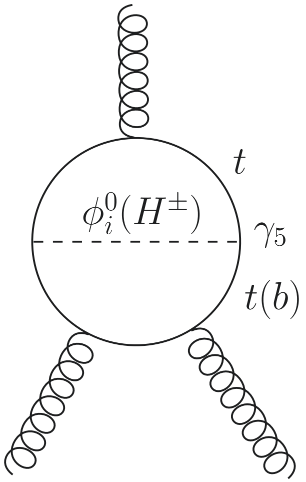
Giudice and Romanino ‘05

BSM example :
2 Higgs-doublet models



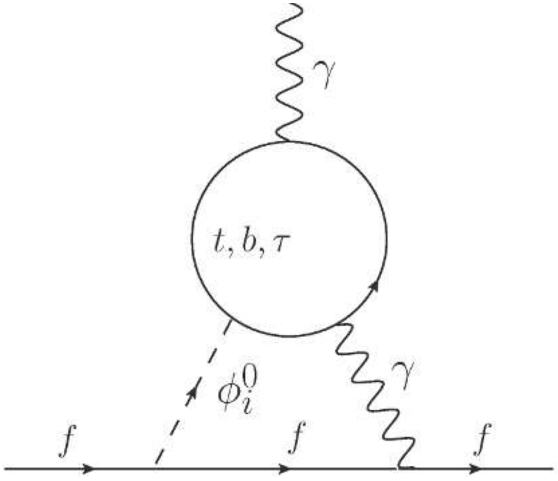
$\tilde{d}_q\; g_s\; \bar{q}\sigma^{\mu\nu} i\; \gamma_5 G_{\mu\nu} q$

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

BSM example: QCD axion

$\bar{\theta} = \frac{\langle a \rangle}{f_a} = 0$ if the axion potential is from only $\frac{a}{f_a} G\tilde{G}$

In general, there must be additional contributions to the axion potential from quantum gravity and the BSM CP violating operators.

$$\bar{\theta} = \frac{\langle a \rangle}{f_a} \sim \frac{1}{\Lambda_{QCD}^4}\left[\left(\sum_{n\geq 7} c_n \frac{f_a^{4+n}}{M_P^n} + \Lambda^4\, e^{-S_{\mathrm{ins}}}\right) + \int d^4x \,\left\langle G\tilde{G}\; O_{BSM}\right\rangle\right]$$

➡ $\bar{\theta}$ can be any value below 10^{-10}.

$$O_{BSM} = \frac{1}{\Lambda_{BSM}^2} G\tilde{G}, \frac{m_q}{\Lambda_{BSM}^2} \bar{q}\sigma^{\mu\nu} G_{\mu\nu} i\gamma_5 q, \ldots$$

- The quantum gravity effect contributes to the EDMs *only via* $\bar{\theta}$.
- The BSM CP violating operators contribute to the EDMs *not only via* $\bar{\theta}$ *but also by themselves.*

➡ EDM ratios may be different depending on the dominant origin of $\bar{\theta} \neq 0$.

Potentially dominant sources for the EDMs

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

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

Key question: Once non-zero EDMs are observed in the future, can we experimentally determine the origin of the EDMs among those operators?

cf) J de Vries et al 1109.3604, 1809.10143, 2107.04046

d_n and d_p from hadronic CPV sources

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

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

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

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

at $\mu = 225$ MeV

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)

$$\begin{aligned}\kappa\, d_n(\bar\theta, \tilde d_q, d_q) = {}& \frac{\langle \bar q \sigma_{\mu\nu} q\rangle}{e_q F_{\mu\nu}} m_* \left[(4e_d - e_u)\left(\bar\theta - \frac{g_s}{2}\frac{\langle \bar q G^{\mu\nu}\sigma_{\mu\nu} q\rangle}{\langle \bar q q\rangle}\frac{\tilde d_s}{m_s}\right) + \frac{g_s}{2}\frac{\langle \bar q G^{\mu\nu}\sigma_{\mu\nu} q\rangle}{\langle \bar q q\rangle}(\tilde d_d - \tilde d_u)\left(\frac{4e_d}{m_u} + \frac{e_u}{m_d}\right)\right] \\ & + \frac{g_s}{4}\left(\frac{\langle \bar q G_{\mu\nu} q\rangle}{e_q F_{\mu\nu}} - \frac{\langle \bar q i\gamma_5 \tilde G_{\mu\nu} q\rangle}{e_q F_{\mu\nu}}\right)(4e_d \tilde d_d - e_u \tilde d_u) + (4d_d - d_u) + \underbrace{\text{higher order terms}}_{< O(10\%)}\end{aligned}$$

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

- Agree with NDA up to $O(1)$ factor.
- The major theoretical uncertainty is from the overall normalization κ which is uncertain by the unknown single pole contribution to the correlator of the nucleon-interpolating field.
- 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 (i.e. the PQ mechanism works for solving the strong CP problem),

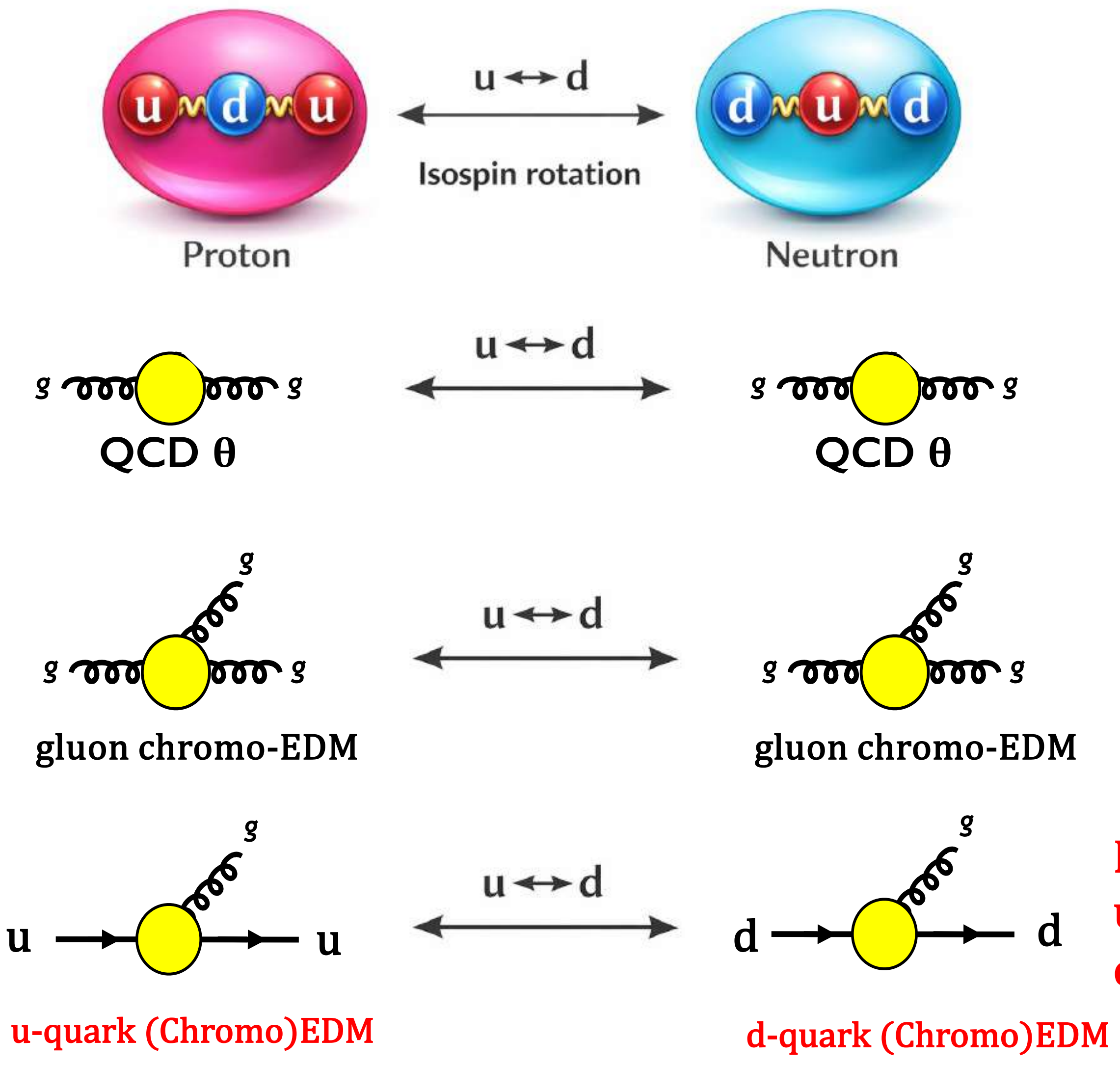
$$\bar{\theta} = \bar{\theta}_{\rm QG} + \frac{g_s}{2}\frac{\langle \bar{q} G^{\mu\nu}\sigma_{\mu\nu} q\rangle}{\langle \bar{q} q\rangle}\sum_{q=u,d,s}\frac{\tilde{d}_q}{m_q} + \mathcal{O}(4\pi f_\pi^2 w)$$

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

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

The quark CEDM contributions to the nucleon EDMs are significantly changed by the presence of QCD axion.

Isospin symmetry



Proton u ↔ d Isospin rotation Neutron

QCD θ u ↔ d QCD θ

Invariant

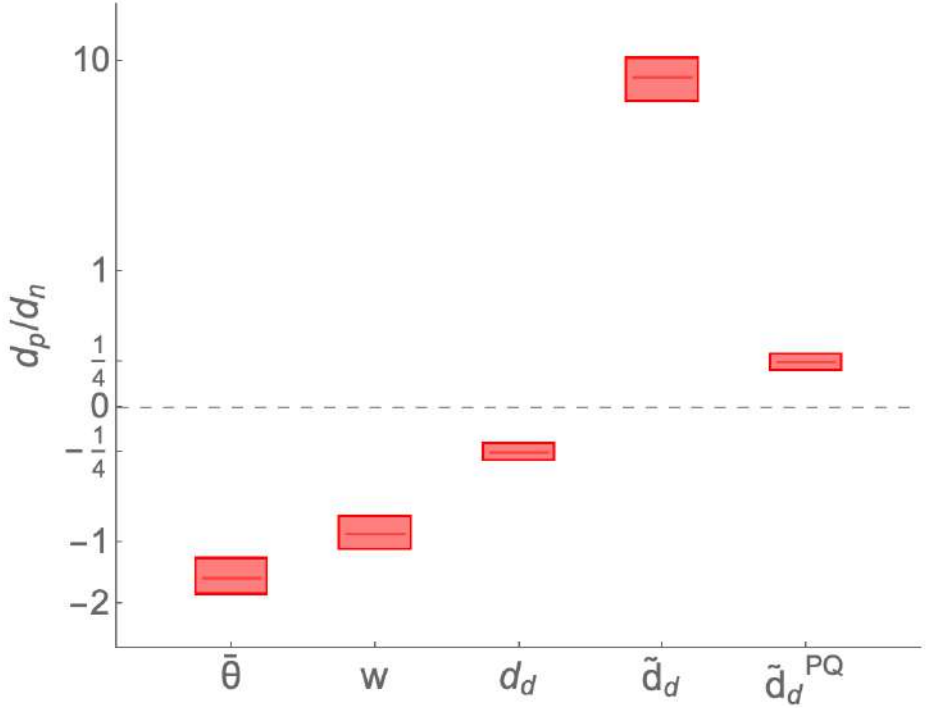
gluon chromo-EDM u ↔ d gluon chromo-EDM

Invariant

u-quark (Chromo)EDM u ↔ d d-quark (Chromo)EDM

Not invariant if u-quark (C)EDM ≠ d-quark (C)EDM

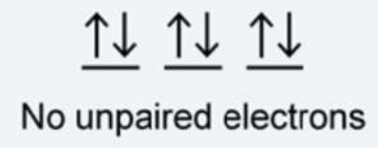
The prediction on the ratio d_p/d_n from QCD sum rules



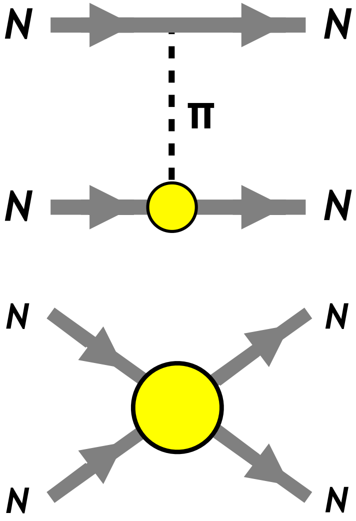
- If the measured ratio d_p/d_n is significantly different from -1, it indicates that the origin of the nucleon EDMs must be beyond the SM (i.e. not from QCD $\bar{\theta}$) which violates the isospin symmetry.
- Furthermore, we may be able to get a clue on the existence of the QCD axion and the origin of the QCD axion VEV from the measured nucleon EDM ratio.

EDMs of light nuclei and diamagnetic atoms

In diamagnetic atoms, all electrons are paired.



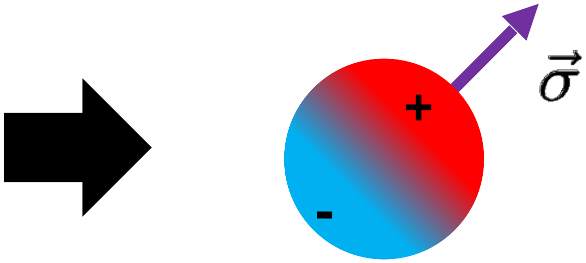
The permanent EDM of a diamagnetic atom or a nucleus is mainly from polarization of the nucleus due to P and CP-odd nuclear forces as well as n and p EDMs.



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

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

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

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

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

Diamagnetic atoms with heavy nuclei

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

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

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

$\bar{g}_1 \pi^0 \bar{N} N$ from hadronic CPV sources

NDA $$\bar{g}_1 \sim 4\pi \frac{(m_u - m_d)}{m_s} \frac{m_*}{\Lambda_\chi} \bar{\theta} + (m_u - m_d)\Lambda_\chi w + 4\pi\, \Lambda_\chi\, (\tilde{d}_u - \tilde{d}_d)$$

Agree up to
O(1) factor ⇕

χPT & QCD sum rules;
(Osamura, Gubler, Yamanaka '22)

$$\bar{g}_1 = (3.4 \pm 2.4)\times 10^{-3}\bar{\theta} \pm (2.6 \pm 1.5)\times 10^{-3}\mathrm{GeV}^2 w$$

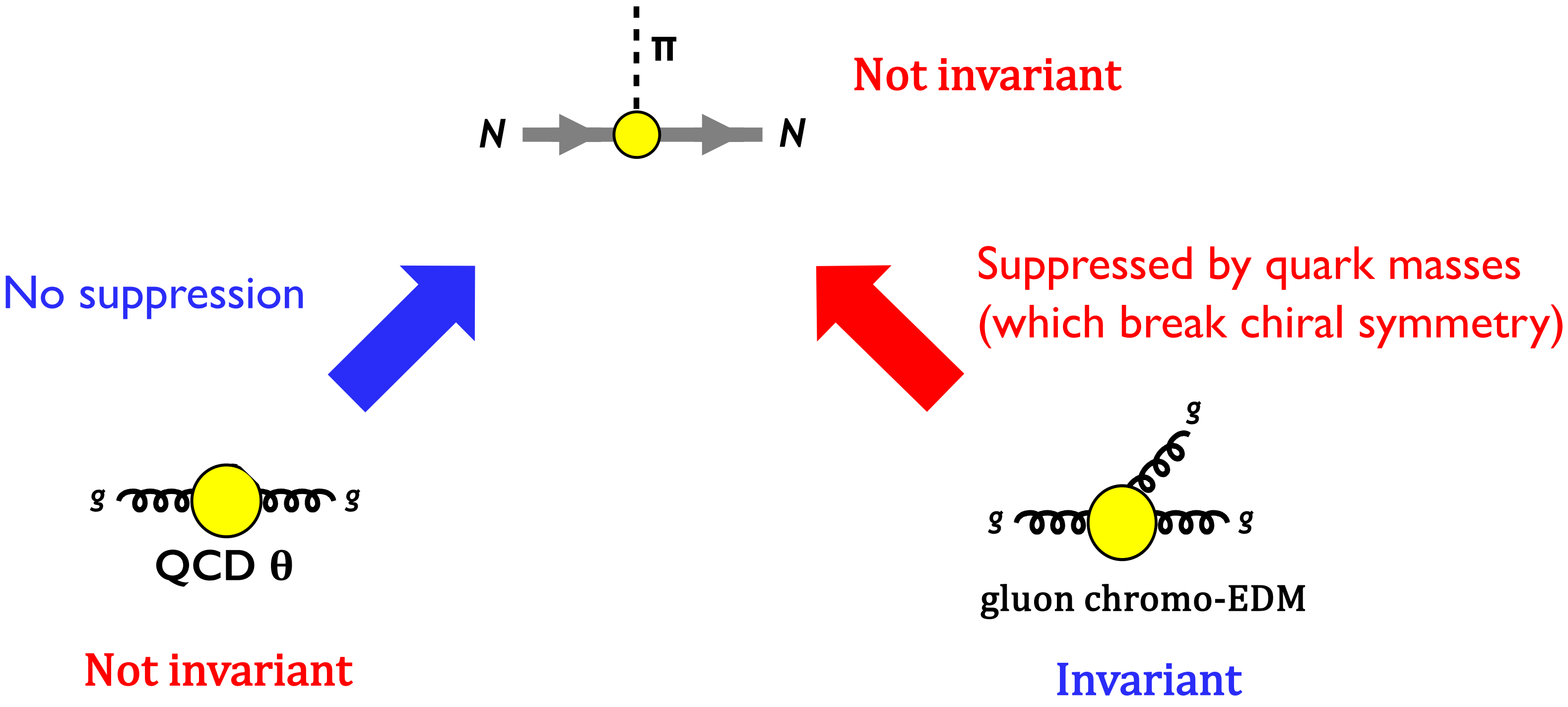
$$+(38 \pm 13)\mathrm{GeV}\, (\tilde{d}_u - \tilde{d}_d)$$

χPT & baryon spectrum;
(de Vries, Mereghetti,
Walker-Loud '15)

χPT & QCD sum rules;
(de Vries et al '21)

Chiral symmetry

$$q_L \to q_L e^{i\alpha}, \qquad q_R \to q_R e^{-i\alpha}$$



Not invariant

No suppression

Suppressed by quark masses
(which break chiral symmetry)

QCD θ

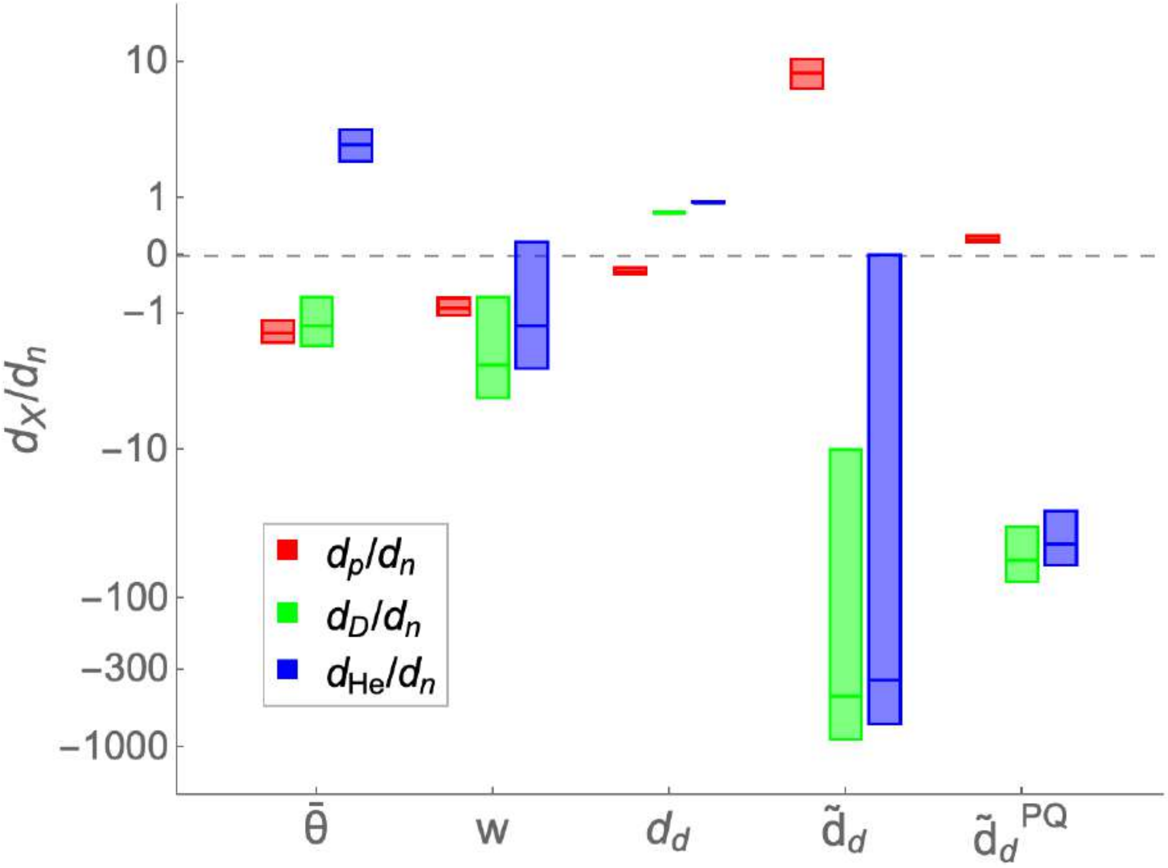
Not invariant

gluon chromo-EDM

Invariant

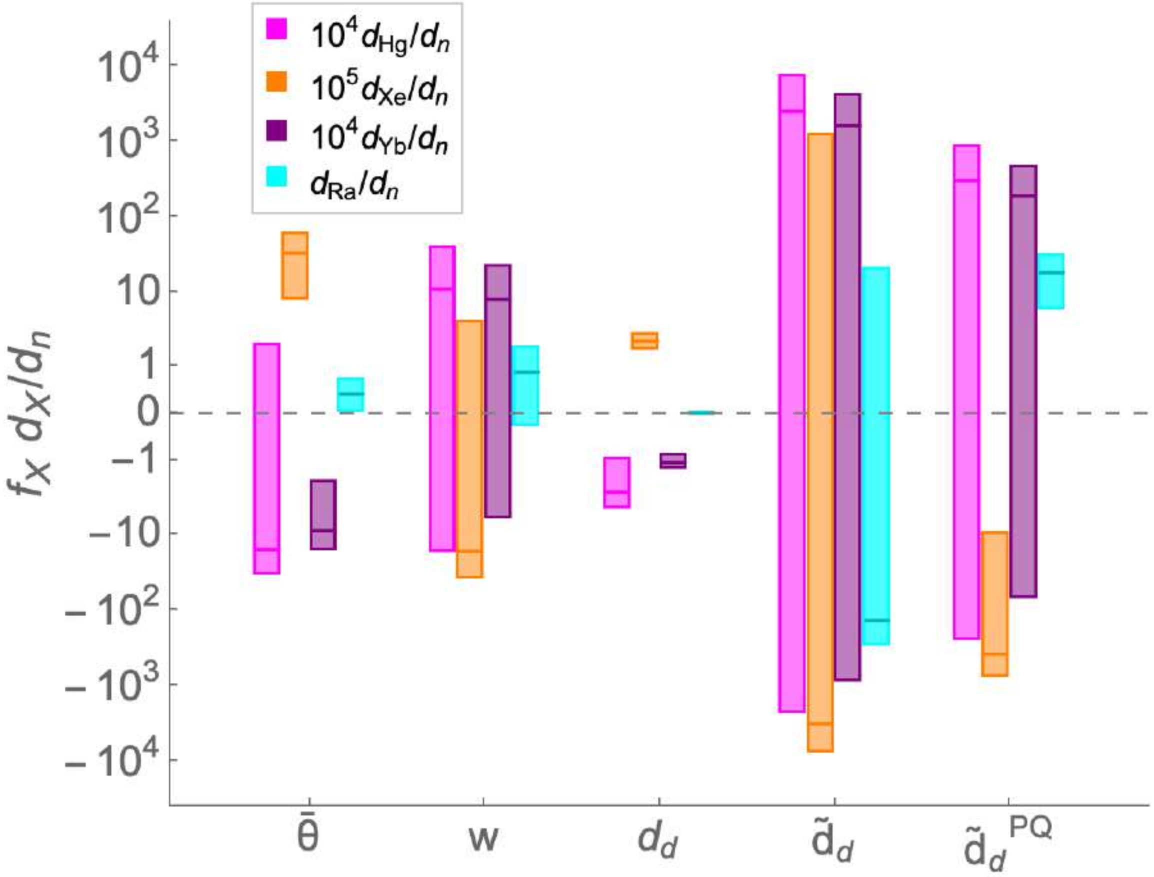
The CP-violating pion-nucleon couplings may discriminate between the QCD θ and the gluon CEDM.

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.

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 source.

Conclusions

- Nuclear, atomic, and molecular permanent 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”
- In particular, we examine whether the source of the QCD axion VEV can be identified from future EDM data.
- We find that EDM data of three light nuclei can identify the leading CP-odd operator (among $\bar{\theta}$, gluon CEDM, and quark (C)EDMs), while heavy atoms can provide only suggestive information.
- The identification of the leading CP-odd operator also provides us with information on PQ symmetry and its breaking.