The EDM inverse problem: Probing BSM CPV and the PQ quality with electric dipole moments

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KC, S.H. Im, K. Jodlowski, JHEP 04 (2024) 007
and the work in preparation

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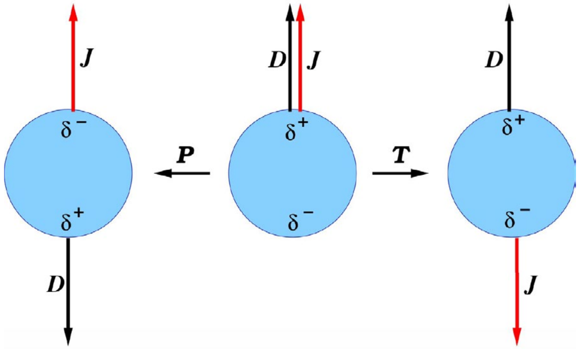
Why Electric Dipole Moments (EDM) are interesting?

Nonzero EDM of non-degenerate quantum system means the violation of P and T (=CP) symmetry.



CP violation is one of the key conditions to generate the asymmetry between matter and antimatter in our universe. Sakharov '67

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

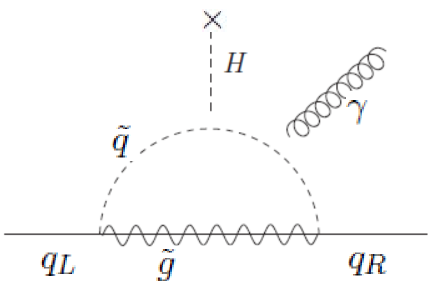
Standard Model (SM) prediction: $(Y_B)_{\rm SM} \lesssim 10^{-15}$

We need "CP-violating new physics beyond the SM", and EDMs may provide a hint about such new physics.

Specifically EDMs can provide an information on the energy scale where "new physics beyond the SM (BSM physics)" appears.

Quark EDM induced by SUSY particles

CP-odd angle



➔ neutron EDM $d_n \propto \dfrac{\sin\delta_{\rm SUSY}}{M_{\rm SUSY}^2}$

$$M_{\rm SUSY} \sim 10\sqrt{\sin\delta_{\rm SUSY}}\left(\frac{10^{-26}e\cdot{\rm cm}}{d_n}\right)^{1/2}\ {\rm TeV}$$

SUSY particle mass

There are many ongoing experiments searching for EDMs of different systems.

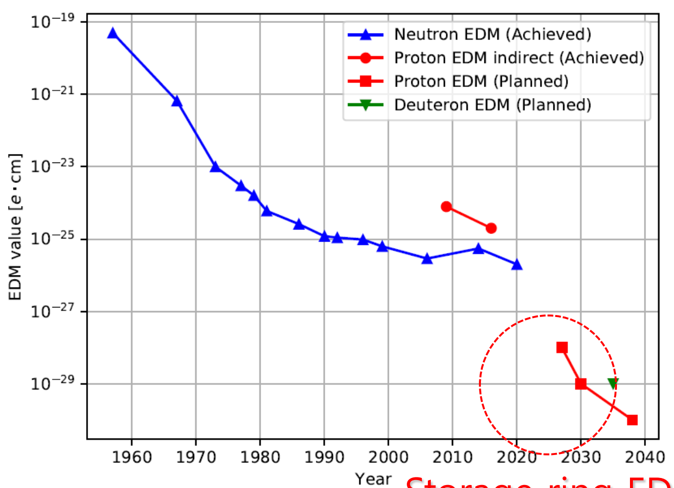
	Result	95% u.l.	
	Paramagnetic systems		
Xe^m	$d_A = (\ \ 0.7 \pm 1.4) \times 10^{-22}$	3.1×10^{-22}	e cm
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	1.4×10^{-23}	e cm
	$d_e = (-1.5 \pm 5.7) \times 10^{-26}$	1.2×10^{-25}	e cm
	$C_S = (2.5 \pm 9.8) \times 10^{-6}$	2×10^{-5}	
	$Q_m = (3 \pm 13) \times 10^{-8}$	2.6×10^{-7}	$\mu_N R_{\mathrm{Cs}}$
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$	1.1×10^{-24}	e cm
	$d_e = (\ \ 6.9 \pm 7.4) \times 10^{-28}$	1.9×10^{-27}	e cm
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27}	e cm
ThO	$d_e = (-2.1 \pm 4.5) \times 10^{-29}$	9.7×10^{-29}	e cm
	$C_S = (-1.3 \pm 3.0) \times 10^{-9}$	6.4×10^{-9}	
HfF^+	$d_e = (0.9 \pm 7.9) \times 10^{-29}$	1.6×10^{-28}	e cm
	Diamagnetic systems		
$^{199}\mathrm{Hg}$	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30}	e cm
$^{129}\mathrm{Xe}$	$d_A = (0.7 \pm 3.3) \times 10^{-27}$	6.6×10^{-27}	e cm
$^{225}\mathrm{Ra}$	$d_A = (4 \pm 6) \times 10^{-24}$	1.4×10^{-23}	e cm
TlF	$d\ = (-1.7 \pm 2.9) \times 10^{-23}$	6.5×10^{-23}	e cm
n	$d_n = (-0.21 \pm 1.82) \times 10^{-26}$	3.6×10^{-26}	e cm
	Particle systems		
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$	1.8×10^{-19}	e cm
τ	$Re(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}$	3.9×10^{-17}	e cm
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$	1.6×10^{-16}	e cm

arXiv:1710.02504

Although nonzero EDM is not observed yet in any of these experiments, experimental sensitivity for some elements might be improved by several orders of magnitude over the coming ~ 10 years.

arXiv:2203.08103

Proton & Deuteron EDM
(Helion might be also) from
Storage Ring EDM experiment



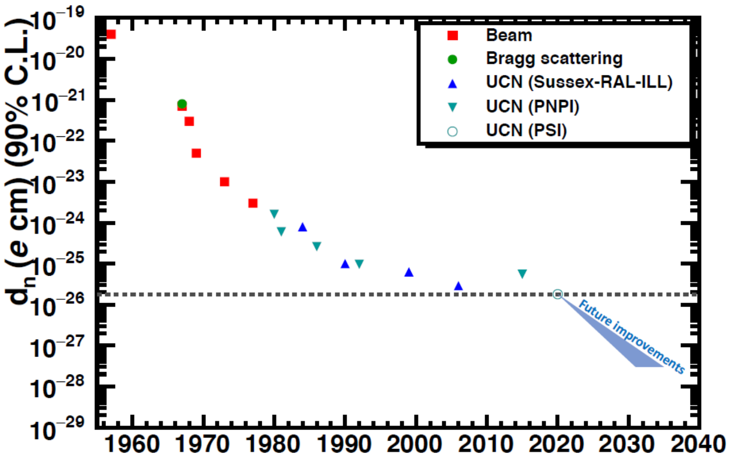
Storage ring EDM

d_p ~ 10^{-29} – 10^{-30} e.cm (${10^{-25}}$)

d_D ~ 10^{-29} e.cm

(d_{He} might be also)

Neutron EDM



d_n ~ 10^{-28} e.cm (1.8 x 10^{-26})

SM predictions

$$\sin\delta_{\rm CKM} \propto \det[y_u y_u^\dagger, y_d y_d^\dagger]$$

$$\bar{\theta} = \theta_{\rm QCD} + \arg\cdot\det(y_u y_d)$$

Due to the suppression from the involved flavor mixings, EDMs from $\delta_{\rm CKM}$ are all well below the experimental sensitivity which can be achieved in near future, while hadronic EDMs from $\bar{\theta}$ can have any value below the current experimental bounds:

$$\frac{d_N}{e\cdot{\rm cm}} \sim 10^{-16}\sin\bar{\theta} + 10^{-31}\sin\delta_{\rm CKM}$$

In addition to the SM CP-violation (CPV), there can also be BSM CPV, which may induce EDMs again at any value below the current experimental bounds.

EDM inverse problem

If a nonzero EDM of any element is experimentally detected, EDMs of many other elements are likely to be detected soon.

To what extent can we extract information on the underlying CPV from the experimentally measured EDMs?

i) Can we discriminate $\bar{\theta}$ from BSM CPV?

ii) If the strong CP problem is solved by a QCD axion, $\bar{\theta} = \langle a \rangle / f_a$.

Can we then identify the origin of axion VEV and determine the piece due to the additional PQ breaking other than the QCD anomaly, e.g. quantum gravity effect, with the EDM data?

(Measuring the quality of the PQ symmetry)

iii) To what extent can we determine the CPV parameters such as the quark EDM or the quark/gluon chromo-EDM from experimental data?

cf: Previous works addressing some of these questions:

Lebedev et al '04; Dekens et al '14; de Vries et al '11, '18, '21, Kaneta et al '23 …

EFT approach for EDM

BSM model at high scales > TeV

↓

Light quark & gluon EFT (including the electron & photon) at ~ 1 GeV, in which flavor-conserving CP-odd interactions are described by

$$\Delta\mathcal{L}_{\rm eff} = \frac{g_s^2}{32\pi^2}\bar{\theta}G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \mathcal{L}_{\rm dipole} + \mathcal{L}_{4-{\rm fermion}}$$

$$\mathcal{L}_{\rm dipole} = -\frac{i}{2}\sum_{f=u,d,s,e} d_f\bar{f}\sigma^{\mu\nu}F_{\mu\nu}\gamma_5 f - \frac{i}{2}\sum_{q=u,d,s}\tilde{d}_q g_s\bar{q}\sigma^{\mu\nu}G_{\mu\nu}\gamma_5 q + \frac{1}{3}w f^{abc}G^{a\mu}_{\alpha}G^{b\delta}_{\mu}\tilde{G}^{c\alpha}_{\delta}$$

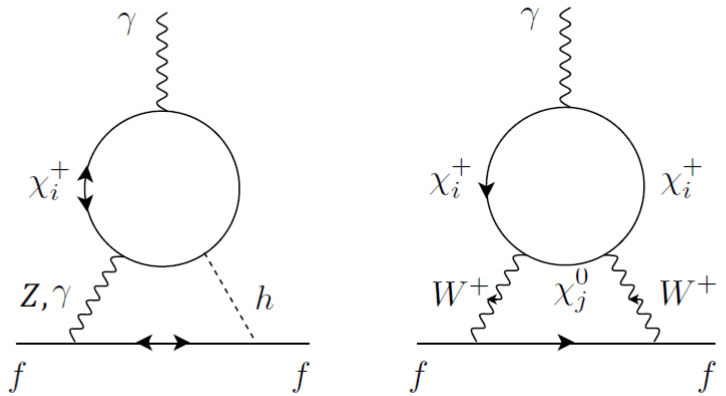
Quark/electron EDM

Quark Chromo-EDM (CEDM)

Gluon CEDM (Weinberg operator)

BSM examples

Split SUSY:



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

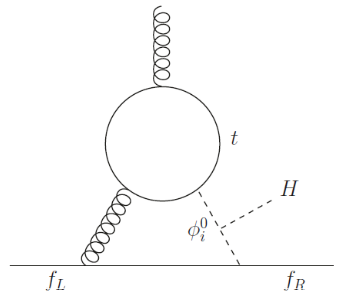
Giudice & Romanino '05

Quark/lepton EDM domination

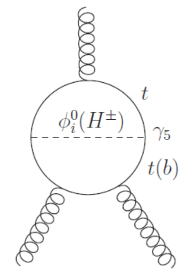
BSM examples

2 Higgs doublets:

Weinberg '89;
Gunion & Wyler '90;
Jung & Pich '14



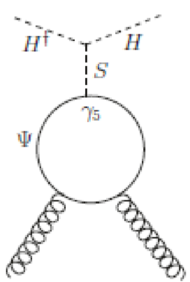
$\bar{q}\sigma^{\mu\nu} i\gamma_5 G_{\mu\nu} q$

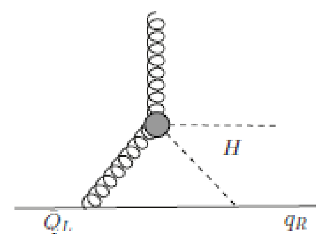


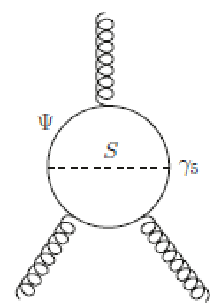
$f^{abc} G^a G^b \widetilde{G}^c$

Vector-like quark:

KC et al '16







Quark/gluon CEDM domination

BSM examples

Models in which 4-fermion interactions can be important:

Left-right symmetric models, Leptoquarks,
SUSY with maximal $\tan\beta$, ...

Here I will focus on BSM models leading to the quark/lepton EDM or quark/gluon CEDM domination at low energy scales.

Light quark/gluon EFT at ~ 1 GeV

⇩

Hadronic EFT of the nucleon & pions (including the electron & photon)

$$\Delta\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{dipole}} + \mathcal{L}_{3\pi} + \mathcal{L}_{\pi N} + \mathcal{L}_{4N} + \mathcal{L}_{eN} + \ldots$$

$$\mathcal{L}_{\text{dipole}} = -\frac{i}{2}\bar{N}\left(d_p\frac{1+\tau_3}{2} + d_n\frac{1-\tau_3}{2}\right)\sigma^{\mu\nu}F_{\mu\nu}\gamma_5 N - \frac{i}{2}d_e\,\bar{e}\,\sigma^{\mu\nu}F_{\mu\nu}\gamma_5 e \qquad N = \begin{pmatrix} p \\ n \end{pmatrix}$$

$$\mathcal{L}_{3\pi} = m_N\Delta_\pi\pi_3\vec{\pi}\cdot\vec{\pi}$$

$$\mathcal{L}_{\pi N} = \bar{g}_0\bar{N}\vec{\tau}\cdot\vec{\pi}N + \bar{g}_1\pi_3\bar{N}N$$

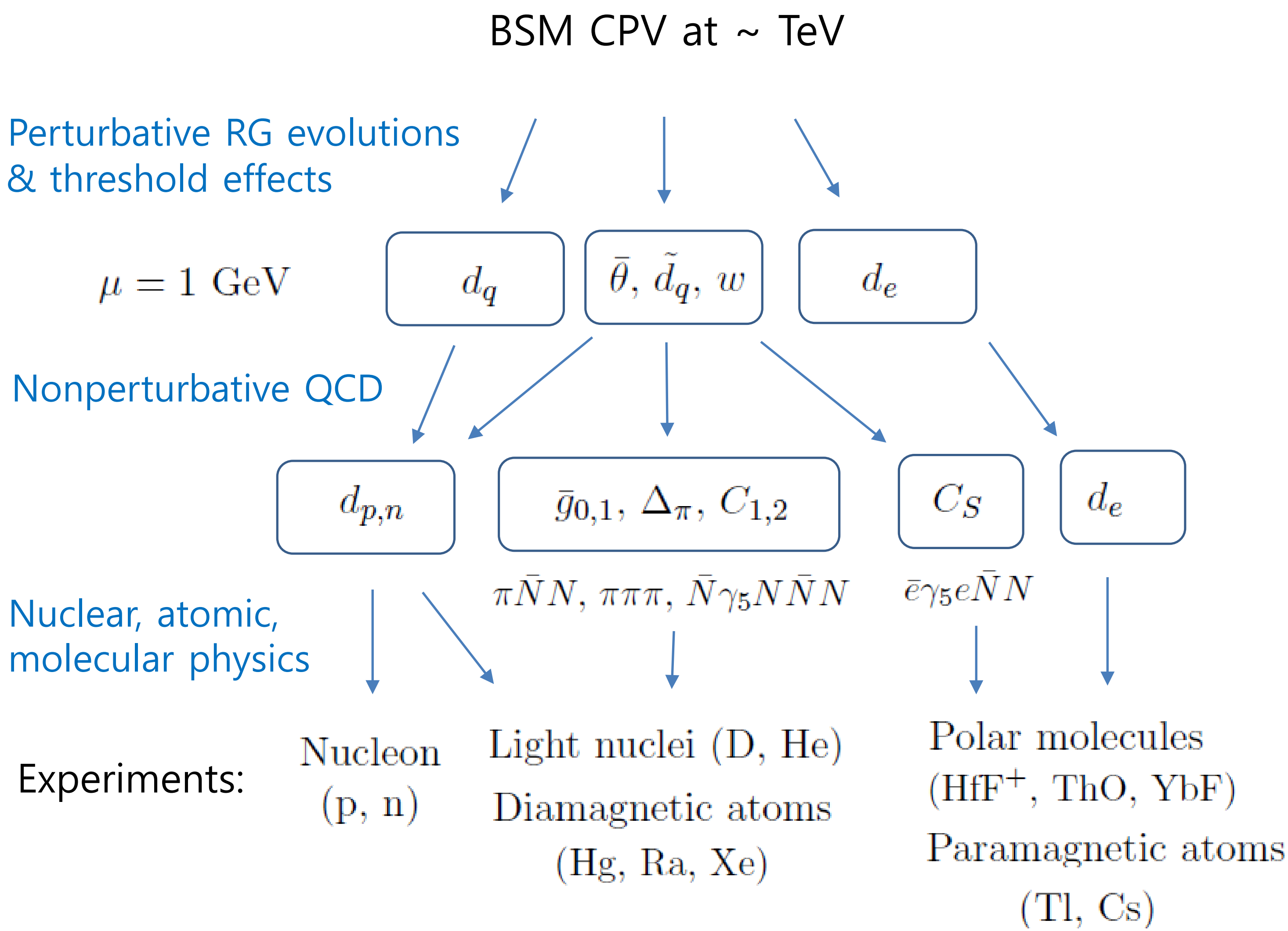
$$\mathcal{L}_{4N} = m_N\left[C_1\bar{N}N\bar{N}i\gamma_5 N + C_2\bar{N}\vec{\tau}N\cdot\bar{N}\vec{\tau}i\gamma_5 N + \ldots\right]$$

$$\begin{aligned}\mathcal{L}_{eN} = &-\frac{G_F}{\sqrt{2}}(\bar{e}i\gamma_5 e)\bar{N}(C_S^{(0)} + C_S^{(1)}\tau_3)N - \frac{G_F}{\sqrt{2}}(\bar{e}e)\bar{N}(C_P^{(0)} + C_P^{(1)}\tau_3)i\gamma_5 N \\ &-\frac{G_F}{\sqrt{2}}(\bar{e}\sigma^{\mu\nu}e)\bar{N}(C_T^{(0)} + C_T^{(1)}\tau_3)i\sigma_{\mu\nu}\gamma_5 N\end{aligned}$$

⇩

Nuclear, atomic, or molecular EDMs

EDM roadmap



BSM CPV at ~ TeV
Perturbative RG evolutions
& threshold effects
$\mu = 1$ GeV
d_q
$\bar{\theta}$, $\tilde{d}_q$, w
d_e
Nonperturbative QCD
$d_{p,n}$
$\bar{g}_{0,1}$, Δ_π, $C_{1,2}$
C_S
d_e
$\pi \bar{N} N$, $\pi\pi\pi$, $\bar{N}\gamma_5 N \bar{N} N$
$\bar{e}\gamma_5 e \bar{N} N$
Nuclear, atomic,
molecular physics
Experiments:
Nucleon
(p, n)
Light nuclei (D, He)
Diamagnetic atoms
(Hg, Ra, Xe)
Polar molecules
(HfF^+, ThO, YbF)
Paramagnetic atoms
(Tl, Cs)

EDM inverse problem for $\{\bar{\theta},\, d_q,\, \tilde{d}_q,\, w\}$

$$\{\lambda_i\} = \{\bar{\theta},\, d_q,\, \tilde{d}_q,\, w\}$$

⇑

$$d_{p,n}(\lambda_i),\ \bar{g}_{0,1}(\lambda_i),\ \Delta_\pi(\lambda_i),\ C_{1,2}(\lambda_i)$$

⇑

$$d_p,\ d_n,\ d_D,\ d_{He},\ \ldots$$

Nonperturbative matching conditions between the quark/gluon EFT parameters & the hadronic EFT parameters:

lattice, χPT, QCD sum rules

cf: We will be using QCD sum rule results while ignoring the intrinsic uncertainty of the sum rule relations themselves, which is hard to estimate, but taking into account the uncertainty in the involved parameters.

Nucleon EDM from $\{\bar{\theta},\, d_q,\, \tilde{d}_q,\, w\}$

(sum rule & lattice)

$$d_p = -1.11(16)\cdot 10^{-16}\bar{\theta}\, e\,\mathrm{cm} + e\left(-0.41(6)\tilde{d}_u + 0.29(6)\tilde{d}_d + 0.024(5)\tilde{d}_s\right) +0.86(9)d_u - 0.214(22)d_d - 0.0028(17)d_s - 18(11)w\, e\,\mathrm{MeV}$$

$$d_n = 0.74(11)\cdot 10^{-16}\bar{\theta}\, e\,\mathrm{cm} + e\left(-0.30(6)\tilde{d}_u + 0.38(6)\tilde{d}_d - 0.0157(30)\tilde{d}_s\right) -0.214(22)d_u + 0.86(9)d_d - 0.0028(17)d_s + 20(12)w\, e\,\mathrm{MeV}$$

for $w, \tilde{d}_q, d_q$ renormalized at $\mu = 1$ GeV

Pospelov, Ritz '01; Demir et al '02, Hisano et al '12; Hisano et al '15; Haisch et al '19; Yamanaka et al '21

CP-odd pion-nucleon couplings & 3-pion coupling

de Vries et al '15; Chupp et al '19; de Vries et al '21; Osamura et al '22

χPT & lattice

$$\bar{g}_0(\bar{\theta}) \simeq \left(\frac{m_n - m_p}{m_d - m_u}\right) \frac{m_*}{f_\pi}\bar{\theta} = 15.7(17) \times 10^{-3}\bar{\theta}$$

$$\bar{g}_1(\bar{\theta}) \simeq \left(\frac{\sigma_{\pi N}}{m_u + m_d} + \ldots\right)\left(\frac{m_d - m_u}{m_s}\right) \frac{m_*}{f_\pi}\bar{\theta} = -3.4(24) \times 10^{-3}$$

$$\Delta_\pi(\bar{\theta}) = \frac{m_\pi^2}{4m_N} \frac{m_d - m_u}{m_s(m_u + m_d)} \frac{m_*}{f_\pi}\bar{\theta} \simeq 3 \times 10^{-4}\bar{\theta}$$

QCD sum rules

$$\bar{g}_0(\tilde{d}_q) \simeq \frac{g_s\langle\bar{q}G^{\mu\nu}\sigma_{\mu\nu}q\rangle}{16\pi f_\pi^2\langle\bar{q}q\rangle}\left(\frac{m_n - m_p}{m_d - m_u}\right) 4\pi f_\pi(\tilde{d}_u + \tilde{d}_d) \simeq \frac{1}{3} \times (4\pi)^2 f_\pi \frac{\tilde{d}_u + \tilde{d}_d}{2}$$

$$\bar{g}_1(\tilde{d}_q) \simeq \frac{g_s\langle\bar{q}G^{\mu\nu}\sigma_{\mu\nu}q\rangle}{8\pi f_\pi^2\langle\bar{q}q\rangle}\left(\frac{\sigma_{\pi N}}{m_u + m_d}\right) 4\pi f_\pi \left(\tilde{d}_u - \tilde{d}_d\right) \simeq 6 \times (4\pi)^2 f_\pi \frac{\tilde{d}_u - \tilde{d}_d}{2}$$

$$\bar{g}_1(w) \simeq \langle 0|\frac{1}{3}GG\tilde{G}|\pi_0\rangle \left(\frac{\sigma_{\pi N}}{m_\pi^2 f_\pi^2} + \frac{5g_A^2}{64\pi}\frac{m_\pi}{f_\pi^4}\right) w \quad = \pm(2.6 \pm 1.5) \times 10^{-3} w\,\mathrm{GeV}^2$$

Remarks:

Isospin-violating CP-odd pion-nucleon coupling $\bar{g}_1(\tilde{d}_q)$ induced by the quark CEDM is significantly bigger than the value expected by the naïve dimensional analysis:

$$\left(\frac{\bar{g}_1(\tilde{d}_q)}{\bar{g}_0(\tilde{d}_q)}\right)_{\mathrm{SR}} \simeq \frac{2\sigma_{\pi N}}{m_n - m_p}\left(\frac{m_d - m_u}{m_d + m_u}\right)\left(\frac{\tilde{d}_u - \tilde{d}_d}{\tilde{d}_u + \tilde{d}_d}\right) \simeq (15\text{–}18)\times\left(\frac{\tilde{d}_u - \tilde{d}_d}{\tilde{d}_u + \tilde{d}_d}\right)$$

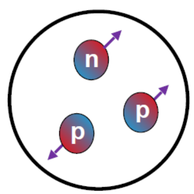
$$= \mathcal{O}(10) \times \left(\frac{\bar{g}_1(\tilde{d}_q)}{\bar{g}_0(\tilde{d}_q)}\right)_{\mathrm{NDA}}$$

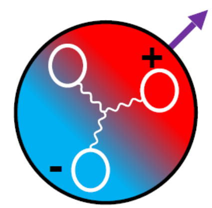
This has an important consequence for the light nuclei EDM induced by the quark CEDM, as it receives the dominant contribution from the pion-mediated CP-odd nuclear force.

Light nuclei EDM

Mostly determined bv the nucleon EDM and the CPV nuclear forces induced by $\bar{g}_{0,1},\, \Delta_\pi,\, C_{1,2}$:

$$\left(\pi\bar{N}N,\ \pi\pi\pi,\ \bar{N}\gamma_5 N\bar{N}N\right)$$





Bsaisou et al '15

$$d_D = 0.94(1)(d_n + d_p) + \left[0.18(2)\bar{g}_1 + 0.0028(3)\bar{g}_0 - 0.75(14)\Delta_\pi\right] e\,\mathrm{fm}$$

$$d_{\mathrm{He}} = 0.9 d_n - 0.03(1) d_p + \left[0.11(1)\bar{g}_0 + 0.14(2)\bar{g}_1 - 0.63(15)\Delta_\pi\right] e\,\mathrm{fm} - \left(0.25(13) C_1 - 0.57(13) C_2\right) \times 10^{-2} (4\pi f_\pi)^2 f_\pi\, e\,\mathrm{fm}$$

$\bar{\theta}$ with QCD axion: $$\bar{\theta} = \frac{\langle a \rangle}{f_a} = \bar{\theta}_{\rm SM} + \bar{\theta}_{\rm BSM} + \bar{\theta}_{\rm UV}$$

i) PQ-breaking by the QCD anomaly & the SM CPV:

$$\bar{\theta}_{\rm SM} \sim \mathcal{O}(10^{-18} - 10^{-19}) \sin \delta_{\rm CKM}$$

ii) PQ-breaking by the QCD anomaly & the BSM CPV:

$$\bar{\theta}_{\rm BSM} = \frac{g_s \langle \bar{q} G^{\mu\nu} \sigma_{\mu\nu} q \rangle}{2 \langle \bar{q} q \rangle} \sum_q \frac{\tilde{d}_q}{m_q} + \text{negligible part from } d_q \text{ and } w$$

(QCD sum rule)

iii) Additional PQ-breaking other than the QCD anomaly, most notably by quantum gravity

$$\bar{\theta}_{\rm UV} \sim \frac{\delta V_{\rm UV}(a)}{m_\pi^2 f_\pi^2} \sim \frac{m_{3/2} M_{\rm Pl}^3}{f_\pi^2 m_\pi^2} e^{-S_{\rm ins}}$$

String/brane instantons

$\bar{\theta}_{\rm UV}$ characterizes the quality of the PQ symmetry (=the strength of the additional PQ breaking by quantum gravity)

Scenario in which one particular part of $\{\bar{\theta},\, d_q,\, \tilde{d}_q,\, w\}$ provides the dominant source of CPV:

* $\bar{\theta}$ domination (w/ or w/o axion)

* Gluon CEDM domination (w/ or w/o axion)

* Quark EDM domination (w/ or w/o axion)

* Quark CEDM domination w/o axion

* Quark CEDM domination w/ axion

  (For simplicity, assume the theory-motivated relation $\tilde{d}_s/\tilde{d}_d = m_s/m_d$)

	$\bar{\theta}$	w	d_q	$\tilde{d}_q$ (w/o axion)	$\tilde{d}_q^{\mathrm{PQ}}$ (w/ axion)
d_p/d_n	-1.5	-0.9	$\frac{4d_u-d_d}{4d_d-d_u}$	$10.5\times\left(\frac{\tilde{d}_d-0.52\tilde{d}_u}{\tilde{d}_d-4.25\tilde{d}_u}\right)$	$-0.25\times\left(\frac{\tilde{d}_d+8\tilde{d}_u}{\tilde{d}_d+0.5\tilde{d}_u}\right)$
d_D/d_p	1.1	1.7	$0.9(1+d_n/d_p)$	$-45\times\left(\frac{\tilde{d}_d-\tilde{d}_u}{\tilde{d}_d-0.52\tilde{d}_u}\right)$	$200\times\left(\frac{\tilde{d}_d-\tilde{d}_u}{\tilde{d}_d+8\tilde{d}_u}\right)$
d_{He}/d_p	-1.6	$\pm\mathcal{O}(1)$	$d_D/d_p-0.93$	$-36\times\left(\frac{\tilde{d}_d-0.97\tilde{d}_u}{\tilde{d}_d-0.52\tilde{d}_u}\right)$	$140\times\left(\frac{\tilde{d}_d-1.1\tilde{d}_u}{\tilde{d}_d+8\tilde{d}_u}\right)$

Origin of the large coefficients in the quark CEDM domination scenario

i) Accidental cancellation between $\left(\frac{\partial d_n}{\partial \tilde{d}_s}\right)_{\text{w/o axion}}$ and $\left(\frac{\partial d_n}{\partial \tilde{d}_d}\right)_{\text{w/o axion}}$ for $\frac{\tilde{d}_s}{\tilde{d}_d}=\frac{m_s}{m_d}\simeq 20$

ii) Significantly larger value of $\bar{g}_1(\tilde{d}_q)$ compared to the NDA estimation and also an enhancement $\sim m_N/m_\pi$ due to the long range nature of the pion-mediated CP-odd nuclear force induced by $\bar{g}_1(\tilde{d}_q)$

* Due to the uncertainties in the involved sum rule & χPT results, the gluon CEDM and $\bar{\theta}$ can not be discriminated from each other.

  The best place to lift this degeneracy appears to be the Helion EDM, for which a theoretical calculation of the 4-nucleon contact interactions induced by the gluon CEDM ($\partial C_{1,2}/\partial w$) is required.

* The quark EDM domination scenario predicts concrete relations (with the least uncertainty) between the nucleon & light nuclei EDMs, and those predictions allow us to determine the light quark EDMs from experimental data.

* Although it suffers from large uncertainties, the quark CEDM domination scenario implies the light nuclei EDMs >> the nucleon EDMs.

  Also, in this scenario, QCD axion can dramatically alter the pattern of the nucleon/nuclei EDM through the induced axion VEV.

Probing the PQ quality with EDM

(Measuring $\bar{\theta}_{\rm UV}$ with EDM data)

a) $d_p \sim -d_n, \ \dfrac{d_D}{d_p} = \mathcal{O}(100) \quad \Rightarrow \quad \{\bar{\theta}, \tilde{d}_d\}$-domination

In SUSY or two-Higgs doublet models with large tan β:

$$\tilde{d}_d/m_d \sim (\tan\beta \text{ or } \tan^2\beta) \times \tilde{d}_u/m_u$$

Lattice-improved QCD sum rule

$$\begin{pmatrix} d_n \\ d_p \end{pmatrix} [e\,\mathrm{cm}]^{-1} = \begin{pmatrix} 0.74(11)\cdot 10^{-16} & 1.41(27)\cdot 10^{-14} \\ -1.11(16)\cdot 10^{-16} & -3.5(7)\cdot 10^{-15} \end{pmatrix} \begin{pmatrix} \bar{\theta}_{\rm UV} \\ \tilde{d}_d\,[\mathrm{GeV}] \end{pmatrix}$$

$$\Rightarrow \quad \begin{pmatrix} \bar{\theta}_{\rm UV} \\ \tilde{d}_d\,[\mathrm{GeV}] \end{pmatrix} = \begin{pmatrix} -2.7(4)\cdot 10^{15} & -1.09(16)\cdot 10^{16} \\ 0.85(16)\cdot 10^{14} & 0.57(11)\cdot 10^{14} \end{pmatrix} \begin{pmatrix} d_n \\ d_p \end{pmatrix} [e\,\mathrm{cm}]^{-1}$$

b) d_X $(X = p, n, D)$ are all comparable to each other w/o clear correlation $\Rightarrow$ $\{\bar{\theta}, d_q\}$-domination

$$\begin{pmatrix} d_n \\ d_p \\ d_D \end{pmatrix} [e\,\mathrm{cm}]^{-1} = \begin{pmatrix} 0.74(11)\cdot 10^{-16} & -4.2(4)\cdot 10^{-15} & 1.69(17)\cdot 10^{-14} \\ -1.11(16)\cdot 10^{-16} & 1.69(17)\cdot 10^{-14} & -4.2(4)\cdot 10^{-15} \\ -1.0(4)\cdot 10^{-16} & 1.19(12)\cdot 10^{-14} & 1.19(12)\cdot 10^{-14} \end{pmatrix} \begin{pmatrix} \bar{\theta}_{\mathrm{UV}} \\ d_u\,[\mathrm{GeV}] \\ d_d\,[\mathrm{GeV}] \end{pmatrix}$$

$$\Rightarrow \begin{pmatrix} \bar{\theta}_{\mathrm{UV}} \\ d_u\,[\mathrm{GeV}] \\ d_d\,[\mathrm{GeV}] \end{pmatrix} = \begin{pmatrix} 1.5(11)\cdot 10^{16} & 1.5(11)\cdot 10^{16} & -1.6(12)\cdot 10^{16} \\ 1.0(8)\cdot 10^{14} & 1.5(12)\cdot 10^{14} & -0.9(7)\cdot 10^{14} \\ 2(5)\cdot 10^{13} & -2.9(24)\cdot 10^{13} & 4.7(35)\cdot 10^{13} \end{pmatrix} \begin{pmatrix} d_n \\ d_p \\ d_D \end{pmatrix} [e\,\mathrm{cm}]^{-1}$$

Significant amplification of the errors in three-parameter case

To determine the CPV quark/gluon EFT parameters and also measure the PQ quality with the EDM data in more generic case, we need substantial improvement of the accuracy of the involved nonperturbative matching conditions.

Conclusion

Once nonzero EDM of multiple elements are experimentally measured, by solving the EDM inverse problem, we can get many information on the underlying CPV BSM physics & the PQ quality.

If CPV is dominated by one of the EFT parameters $\{\bar{\theta},\, d_q,\, \tilde{d}_q,\, w\}$, each scenario leads to a distinctive pattern of the nucleon and light nuclei EDMs.

Then, with a substantial improvement in quantitative understanding of the involved nonperturbative matching conditions, we will be able to identify the dominant EFT parameter and also determine its value from the EDM data.

Similarly we will be able to measure the PQ quality with the EDM data in case that the strong CP problem is solved by a QCD axion.