JÜLICH
FORSCHUNGSZENTRUM

EDMs of Light Nuclei

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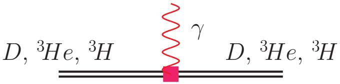
EDMs from $\not{C}\not{P}$ Formfactor (F_3):



Outline:

- CP-violation beyond CKM matrix in the SM: $\mathcal{L}_{QCD}$ θ-term (dim. 4)
  - EDM of the deuteron / EDM of helium-3
  - strategies of testing whether $\bar{\theta}$-term is the origin
- CP-violation from physics beyond the SM: SUSY, multi-Higgs,$\cdots$

$\longrightarrow$ dim. 6 sources: qEDM, qCEDM, gCEDM, 4qEDMs

  - EDM of the deuteron / EDM of helium-3
  - disentangling dim. 6 sources

The $\mathcal{L}_{QCD}$ θ-Term

topologically non trivial vacuum $\rightarrow$ $\not{C}\not{P}$ term in $\mathcal{L}_{QCD}$:

$$\mathcal{L} = \mathcal{L}_{QCD}^{CP} + \theta \frac{g_S^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

$$\ldots + \theta \frac{g_S^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \quad \xrightarrow{U_A(1)} \quad \ldots - \bar{\theta} m^* \sum_f \bar{q}_f i\gamma_5 q_f$$

with $\bar{\theta} = \theta + \arg \det \mathcal{M}$, naive dim. analysis (NDA): $\bar{\theta} \sim \mathcal{O}(1)$

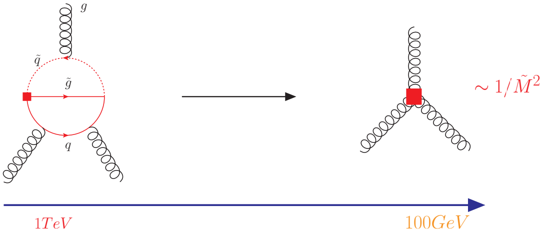
$\mathcal{M}$: quark mass matrix, $m^* = \frac{m_u m_d}{m_u + m_d}$

Physics Beyond SM (BSM):

SUSY, multi-Higgs, Left-Right-Symmetric models, ...

Effective field theory approach:

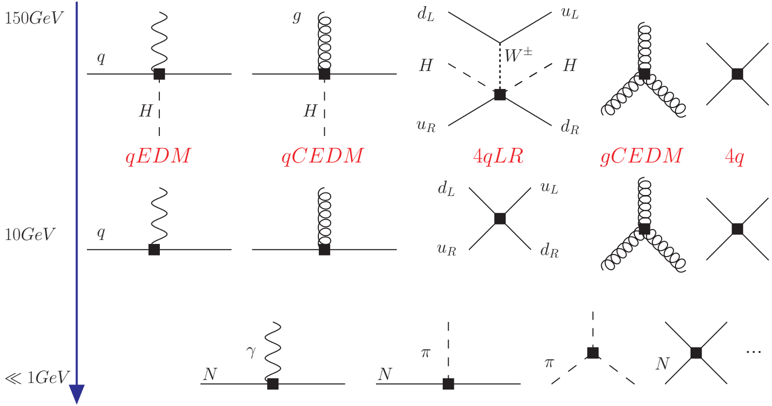
- All degrees of freedom beyond a specified scale are integrated out:
  $\hookrightarrow$ Only SM degrees of freedom remain: q, g, H, $W^{\pm}$,...
- Relics of eliminated BSM physics ‘remembered’ by the values of the low-energy constants (LECs) of the CP-violating contact terms, e.g.



BSM physics continued: CP-violating dim. 6 sources

Removal of the Higgs and transition to hadronic fields (plus mixing)

Add to SM all possible T- and P-odd contact interactions



θ-Term on the Hadronic Level

hadronic level: non perturbative techniques required: e.g. 2-flavor *ChPT*

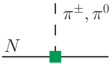
- Symmetries of QCD preserved by the effective field theory (EFT)

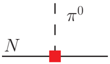
$$\mathcal{L}^{\theta}_{QCD} = -\bar{\theta} m^* \sum_f \bar{q}_f i\gamma_5 q_f : \quad \not{C}\not{P},\ \mathrm{I} \quad \Leftrightarrow \quad \mathcal{M} \to \mathcal{M} + \bar{\theta} m^* i\gamma_5 \qquad m^* = \frac{m_u m_d}{m_u + m_d}$$

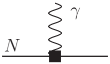
$$\not{C}\not{P},\ \mathrm{I} \qquad\qquad \not{C}\not{P},\ \not{\mathrm{I}} \qquad\qquad \not{C}\not{P},\ \mathrm{I} + \not{\mathrm{I}}$$

$$\mathcal{L}^{ChPT}_{\theta} = g_0^{\theta} N^{\dagger} \vec{\pi} \cdot \vec{\tau} N + g_1^{\theta} N^{\dagger} \pi_3 N + N^{\dagger}(b_0 + b_1 \tau_3) S^{\mu} v^{\nu} F_{\mu\nu} N + \cdots$$

$$\Downarrow \qquad\qquad \Downarrow \qquad\qquad \Downarrow$$





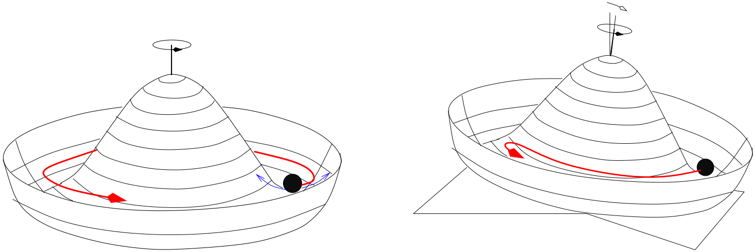


...

dominating for ^3He | dominating for *D* | important for *p*, *n*

Lebedev et al. (2004), Mereghetti et al. (2010), J.B. et al. (2013)

Selection of the Ground State: θ-term



ground state fixed under $\not{C}\not{P}$: readjustment of coordinates
$\rightarrow$ no pion tadpole

$\Rightarrow$ impact on πN-sector:

$$\mathcal{L}_{\pi N} = \underset{\not{C}\not{P},\, \mathrm{I}}{g_0^\theta N^\dagger \vec{\pi}\cdot\vec{\tau} N} + \cdots \longrightarrow \underset{\not{C}\not{P},\, \mathrm{I}}{(g_0^\theta + \delta g_0^\theta) N^\dagger \vec{\pi}\cdot\vec{\tau} N} + \underset{\not{C}\not{P},\, \not{\mathrm{I}}}{g_1^\theta N^\dagger \pi_3 N} + \cdots$$

$$\delta g_0^\theta = \mathcal{O}((\delta M_\pi^2)_{QCD}) \qquad (\delta M_\pi^2)_{QCD} = (M_{\pi^+}^2 - M_{\pi^0}^2)_{QCD}$$

θ-term: $\not{CP}$ πNN-terms related to LECs c_5 and c_1:

Crewther et al. (1979); Ottnad et al. (2010); Mereghetti et al. (2011); de Vries et al. (2011); J.B. et al. (2013)

coupling constants g_0^θ, g_1^θ of $\not{CP}$ πNN-vertices can be fixed!

g_0^θ:

$$\mathcal{L}_{\pi N} = \ldots + c_5 2B\, N^\dagger \left((m_u - m_d)\,\tau_3 + \frac{2m^*\bar\theta}{F_\pi}\vec\pi\cdot\vec\tau \right) N + \ldots$$

$$\delta M_{np}^{str} = 4B(m_u - m_d)c_5 \quad \rightarrow \quad g_0^\theta = \bar\theta\,\delta M_{np}^{str}\,\frac{(1-\epsilon^2)}{\epsilon}\,\frac{1}{4F_\pi}$$

$$\delta M_{np}^{em} \quad \rightarrow \quad \delta M_{np}^{str} = (2.6 \pm 0.5)\mathrm{MeV}$$

Walker-Loud et al. (2012)

$$\longrightarrow g_0^\theta = (-0.018 \pm 0.007)\bar\theta$$

$$\epsilon = (m_u - m_d)/(m_u + m_d)\,, \quad 4Bm^* = M_\pi^2(1-\epsilon^2), \quad m^* = \frac{m_u m_d}{m_u + m_d}$$

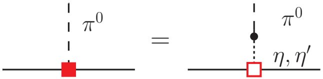
θ-term: $\not{C}\!\!\not{P}$ πNN-terms related to LECs c_5 and c_1:

g_1^θ: $\pi_3 NN$-vertex $\qquad\qquad \epsilon = (m_u - m_d)/(m_u + m_d)$

$$\mathcal{L}_{\pi N} = \ldots + c_1 4B\, N^\dagger \left((m_u + m_d) + \frac{(\delta M_\pi^2)_{QCD}(1-\epsilon^2)\bar{\theta}}{2BF_\pi \epsilon} \pi_3 \right) N + \ldots$$

1 $c_1 \longleftrightarrow \sigma_{\pi N}$: $c_1 = (-1.0 \pm 0.3)\ \mathrm{GeV}^{-1}$ Compilation: Baru et al. (2011)

2 $(\delta M_\pi^2)_{QCD} = \dfrac{\epsilon^2}{4} \dfrac{M_\pi^4}{M_K^2 - M_\pi^2}$



$$\longrightarrow g_1^\theta = (0.003 \pm 0.001)\bar{\theta}$$

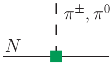
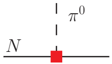
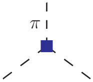
J.B. et al. (2013)

$$\boxed{\frac{g_1^\theta}{g_0^\theta} = -0.20 \pm 0.13 \sim \frac{M_\pi}{m_N}} \gg \epsilon \frac{M_\pi^2}{m_N^2} \sim -0.01 \quad \text{(NDA)}$$

$g_0^\theta(\delta M_{np}^{str})$ is unnaturally small

BSM $\not{CP}$ sources on the hadronic level

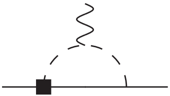
Reliance on Naive Dimensional Analysis (NDA), lattice, ...

	g_0: $\not{CP}$, I	g_1: $\not{CP}$, $\not{I}$	d_0, d_1: $\not{CP}$, I + $\not{I}$	$C_{3\pi}$: $\not{CP}$, $\not{I}$
$\mathcal{L}^{\not{CP}}_{\text{EFT}}$:				
θ-term:	$\mathcal{O}(1)$	$\mathcal{O}(M_\pi/m_N)$	$\mathcal{O}(M_\pi^2/m_N^2)$	$\mathcal{O}(\epsilon M_\pi^2/m_N^2)$
qEDM:	$\mathcal{O}(\alpha_{EM}/(4\pi))$	$\mathcal{O}(\alpha_{EM}/(4\pi))$	$\mathcal{O}(1)$	$\mathcal{O}(\alpha_{EM}/(4\pi))$
qCEDM:	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(M_\pi^2/m_N^2)$	$\mathcal{O}(\epsilon M_\pi^2/m_N^2)$
4qLR:	$\mathcal{O}(M_\pi^2/m_n^2)$	$\mathcal{O}(1)$	$\mathcal{O}(M_\pi^2/m_N^2)$	$\mathcal{O}(1)$
gCEDM:	$\mathcal{O}(M_\pi^2/m_N^2)^*$	$\mathcal{O}(M_\pi^2/m_N^2)^*$	$\mathcal{O}(1)$	$\mathcal{O}(\epsilon M_\pi^2/m_N^2)$
4q:	$\mathcal{O}(M_\pi^2/m_N^2)^*$	$\mathcal{O}(M_\pi^2/m_N^2)^*$	$\mathcal{O}(1)$	$\mathcal{O}(\epsilon M_\pi^2/m_N^2)$

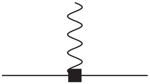
*: Goldstone theorem → relative $\mathcal{O}(M_\pi^2/m_n^2)$ suppression of $N\pi$ interactions

Nucleon EDM: θ-term case

single nucleon EDM: Ottnad et al. (2010)



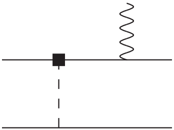
isovector $\approx$ $\ll$ isoscalar



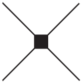
"controlled" two counter terms

$\longrightarrow$ lattice QCD required Guo, Meißner (2012)

two nucleon EDM: Sushkov, Flambaum, Khriplovich (1984)



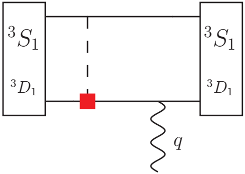
$\gg$



controlled unknown

D $\not{CP}$ form factor computation technique:

plane wave: multiple rescatterings:



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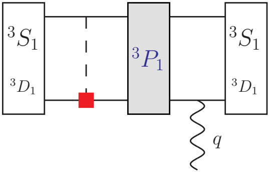


+ perm.

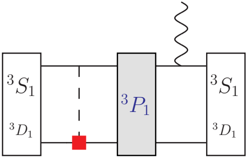
$$\langle D |\, V^{12}_{\not{CP}}\, G_0\, \mathcal{O}_2(\vec{q})\, | D \rangle \quad + \quad \langle D |\, V^{12}_{\not{CP}}\, G_0\, V_{12}\, G\, \mathcal{O}_2(\vec{q})\, | D \rangle \quad + \text{perm.}$$

$$G = G_0 + G_0\, t_{12}\, G_0 \qquad\qquad t_{12} = (1 - V_{12}\, G_0)^{-1}\, V_{12}$$

Note:

- Complementary Monte Carlo based test for plane wave contribution
- Additional analytic computation utilizing PEST separable potential

EDM of the Deuteron at LO: θ-term



LO: $\cancel{g_0^\theta N^\dagger \vec{\pi}\cdot\vec{\tau} N}$ ($\not{CP}$,I) → Isospin select.

NLO: $g_1^\theta N^\dagger \pi_3 N$ ($\not{CP}$, $\not{I}$) → LO

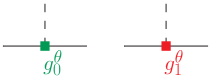
in units of g_1^θ e · fm · $(g_A\, m_N / F_\pi)$

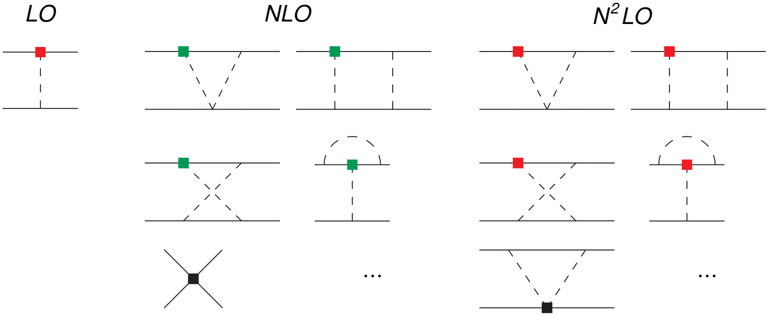
refs.	potential	no $^3P_1$-int	with $^3P_1$-int	total
JBC (2013)*	Av_{18}	-1.93×10^{-2}	0.48×10^{-2}	-1.45×10^{-2}
JBC (2013)	CD BONN	-1.95×10^{-2}	0.51×10^{-2}	-1.45×10^{-2}
JBC (2013)*	ChPT(N^2LO)†	-1.94×10^{-2}	0.65×10^{-2}	-1.29×10^{-2}
Song (2013)	Av_{18}	-	-	-1.45×10^{-2}
Liu (2004)	Av_{18}	-	-	-1.43×10^{-2}
Afnan (2010)	Reid93	-1.93×10^{-2}	0.40×10^{-2}	-1.43×10^{-2}

*: in preparation †: cutoffs at 600 MeV (LS) and 700 MeV (SFR)

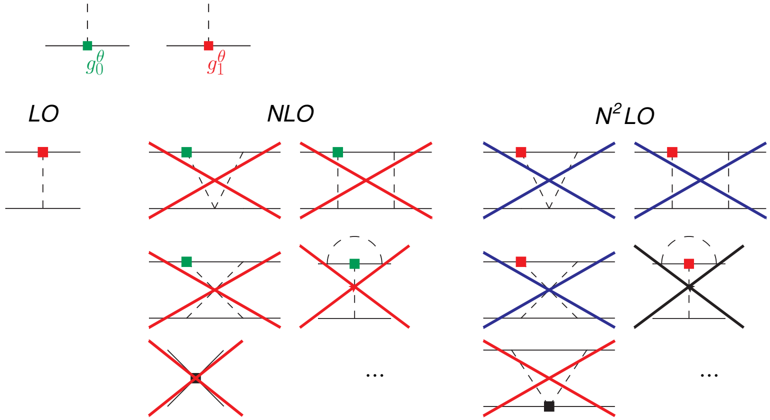
BSM $\not{CP}$ sources: LO g_1 πNN-vertex also for qCEDM and 4qLR

EDM of the Deuteron: *NLO*- and N^2LO-Potentials



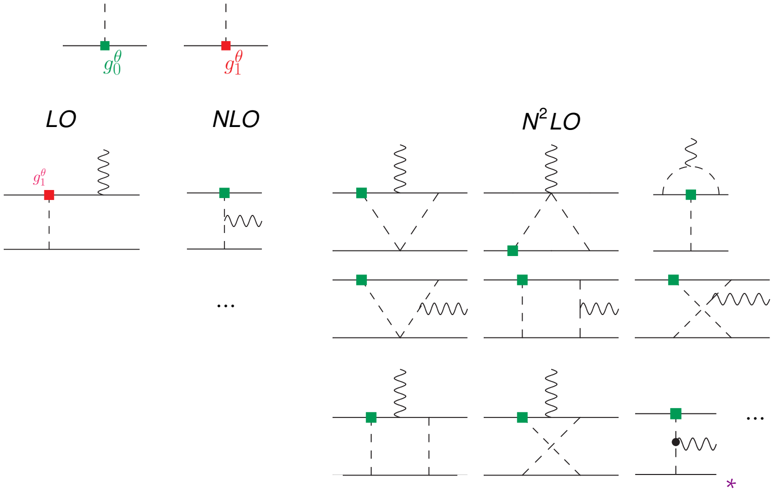


EDM of the Deuteron: *NLO*- and N^2LO-Potentials



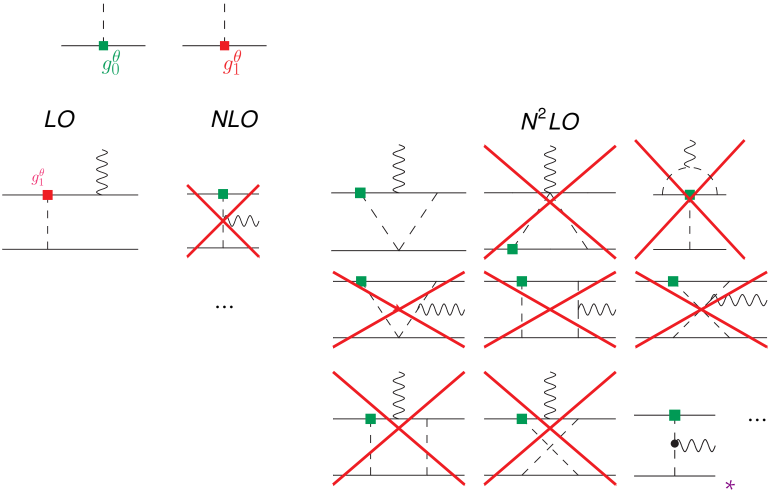
- ×: vanishing by selection rules, ×: sum of diagrams vanishes
  ×: vertex correction

EDM of the Deuteron: *NLO*- and N^2LO-Currents



∗: de Vries et al. (2011), J.B. et al. (2013)

EDM of the Deuteron: *NLO*- and N^2LO-Currents



$\ast$: de Vries et al. (2011), J.B. et al. (2013)

- ×: vanishing by selection rules, ×: sum of diagrams vanishes

Deuteron EDM from the θ-term

J.B. et al. (2013)

total deuteron EDM: $d_D = d_n + d_p + d_D(2N)$

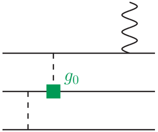
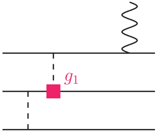
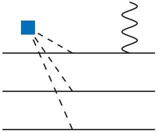
- single-nucleon contribution: EFT *alone* has no predictive power
  $\longrightarrow$ *Experiment* or *Lattice QCD* needed in addition

- two-nucleon contribution $d_D(2N)$: EFT *has* predictive power

$$d_D(2N) = \underbrace{-(0.59 \pm 0.39) \cdot 10^{-16}\, \bar{\theta}\, e\,\text{cm}}_{\text{LO}} \quad + \quad \underbrace{(0.05 \pm 0.02) \cdot 10^{-16}\, \bar{\theta}\, e\,\text{cm}}_{\text{N}^2\text{LO}}$$

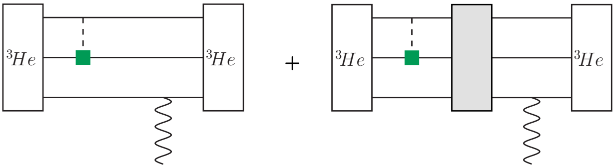
^3He EDM: Power Counting

Utilizing Schroedinger equation $|\psi\rangle = G_0 V|\psi\rangle$ to compare $NN \sim 3N$ ops.

	θ-term	qCEDM	4qLR
	A_θ (LO)	A_{qC} (LO)	A_{4q} (N^2LO)
	$A_\theta \times \frac{M_\pi}{m_N}$ (NLO)	A_{qC} (LO)	$A_{4q} \times \frac{m_N^2}{M_\pi^2}$ (LO)
	$A_\theta \times \frac{M_\pi^2}{m_N^2}$ (N^2LO)	$A_{qC} \times \frac{M_\pi^2}{m_N^2}$ (N^2LO)	$A_{4q} \times \frac{m_N^2}{M_\pi^2}$ (LO)

^3He $\not{CP}$ form factor computation technique: Faddeev approach

plane wave: multiple rescatterings:



+ perm.

$$\langle {}^3He|\, V^{12}_{\not{CP}}\, G_0\, \mathcal{O}_3(\vec{q})\, |{}^3He\rangle \quad + \quad \langle {}^3He|\, V^{12}_{\not{CP}}\, G_0\, V\, G\, \mathcal{O}_3(\vec{q})\, |{}^3He\rangle + \text{perm.}$$

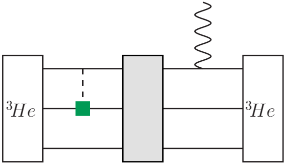
$\Rightarrow$ Faddeev equation: $(1+P)|U_{(3)}\rangle \equiv V\,G\,(1+P)\mathcal{O}_3(\vec{q})\,|{}^3He\rangle$

$$|U_{(3)}(\vec{q})\rangle = t_{12}\, G_0\, (1+P)\mathcal{O}_3(\vec{q})|{}^3He\rangle \; + \; t_{12}\, G_0\, P\,|U_{(3)}\rangle + (3NF)$$

$P = P_{12}P_{23} + P_{13}P_{23}$

Note: complementary Monte-Carlo based test for plane wave contribution

^3He EDM: quantitative results for g_0 exchange



$g_0 N^\dagger \vec{\pi} \cdot \vec{\tau} N$ ($\not{CP}$, I)

θ-term, qCEDM → LO

4qLR → N^2LO

units: $g_0 (g_A m_N / F_\pi)\, e\,\mathrm{fm}$

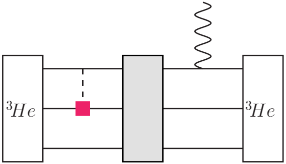
author	potential	no int.	with int.	total
JBC (2013)*	Av_{18}UIX	-0.45×10^{-2}	-0.13×10^{-2}	-0.57×10^{-2}
JBC (2013)*	CD BONN TM	-0.56×10^{-2}	-0.12×10^{-2}	-0.67×10^{-2}
JBC (2013)*	ChPT (N^2LO)†	-0.56×10^{-2}	-0.19×10^{-2}	-0.76×10^{-2}
Song (2013)	Av_{18}UIX	-	-	-0.59×10^{-2}
Stetcu (2008)	Av_{18} UIX	-	-	-1.21×10^{-2}

*: in preparation †: cutoffs at 600 MeV (LS) and 700 MeV (SFR)

Results for ^3H also available (not shown)

JBC (2013)* ~ Song (2013) ~ Stetcu (2008)/2

^3He EDM: quantitative results for g_1 exchange



$g_1 N^\dagger \pi_3 N$ ($\not{CP}$, $\not{I}$)

θ-term → NLO

qCEDM, 4qLR → LO !

units: $g_1 (g_A m_N / F_\pi)\, e\,\mathrm{fm}$

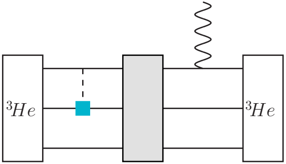
Ref.	potential	no int.	with int.	total
JBC (2013)*	Av_{18}UIX	-1.09×10^{-2}	-0.02×10^{-2}	-1.11×10^{-2}
JBC(2013)*	CD BONN TM	-1.11×10^{-2}	-0.03×10^{-2}	-1.14×10^{-2}
JBC (2013)*	ChPT (N^2LO)†	-1.09×10^{-2}	-0.14×10^{-2}	-0.96×10^{-2}
Song (2013)	Av_{18}UIX	-	-	-1.08×10^{-2}
Stetcu (2008)	Av_{18} UIX	-	-	-2.20×10^{-2}

*: in preparation †: cutoffs at 600 MeV (LS) and 700 MeV (SFR)

Results for ^3H also available (not shown)

JBC (2013)* ~ Song (2013) ~ Stetcu (2008)/2

For completeness: irrelevant results for g_2 exchange



$$g_2 N^\dagger (3\,\tau_3\pi_3 - \vec{\tau}\cdot\vec{\pi})N \quad (\not{CP}, \not{I})$$

units: $g_2(g_A m_N/F_\pi)\,e\,\mathrm{fm}$

Ref.	potential	no int.	with int.	total
JBC (2013)*	Av_{18}UIX	-1.36×10^{-2}	-0.35×10^{-2}	-1.71×10^{-2}
JBC(2013)*	CD BONN TM	-1.46×10^{-2}	-0.37×10^{-2}	-1.83×10^{-2}
JBC (2013)*	ChPT (N^2LO)†	-1.42×10^{-2}	-0.14×10^{-2}	-1.56×10^{-2}
Song (2013)	Av_{18}UIX	-	-	-0.66×10^{-2}
Stetcu (2008)	Av_{18} UIX	-	-	-3.40×10^{-2}
Stetcu (2008)	CD BONN TM	-	-	-3.50×10^{-2}

*: in preparation †: cutoffs at 600 MeV (LS) and 700 MeV (SFR)

Results for ^3H also available (not shown)

Pattern reinforced: JBC (2013)* ~ Stetcu (2008) / 2

JÜLICH FORSCHUNGSZENTRUM

Quantitative EDM results in the θ-term scenario

Single Nucleon (with adjusted signs for consistency; note here $e < 0$):

$$-d_1^{\text{loop}} \equiv \frac{1}{2}(d_n - d_p)^{\text{loop}}$$

$$= (2.1 \pm 0.9) \cdot 10^{-16}\,\bar{\theta}\,e\,\text{cm} \qquad \text{(Bsaisou et al. (2013))}$$

$$d_n = +(2.9 \pm 0.9) \cdot 10^{-16}\,\bar{\theta}\,e\,\text{cm} \qquad \text{(Guo \& Meißner (2012))}$$

$$d_p = -(1.1 \pm 1.1) \cdot 10^{-16}\,\bar{\theta}\,e\,\text{cm} \qquad \text{(Guo \& Meißner (2012))}$$

Deuteron:

$$d_D = d_n + d_p - \left[(0.59 \pm 0.39) - (0.05 \pm 0.02)\right] \cdot 10^{-16}\,\bar{\theta}\,e\,\text{cm}$$

$$= d_n + d_p - (0.54 \pm 0.39) \cdot 10^{-16}\,\bar{\theta}\,e\,\text{cm} \qquad \text{(Bsaisou et al. (2013))}$$

Helium-3:

$$d_{^3He} = \tilde{d}_n + \left[(1.52 \pm 0.60) - (0.46 \pm 0.30)\right] \cdot 10^{-16}\,\bar{\theta}\,e\,\text{cm}$$

$$= \tilde{d}_n + (1.06 \pm 0.67) \cdot 10^{-16}\,\bar{\theta}\,e\,\text{cm} \qquad \text{(JBC (2013))}$$

with $\tilde{d}_n = 0.88 d_n - 0.047 d_p$ (de Vries et al. (2011))

Testing Strategies in the θ EDM scenario

Remember:

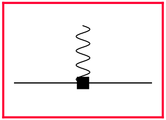
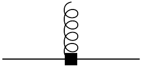
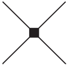
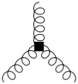
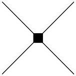
$$d_D = d_n + d_p - (0.54 \pm 0.39) \cdot 10^{-16}\, \bar{\theta}\, e\,\text{cm} \qquad \text{(Bsaisou et al. (2013))}$$

$$d_{^3He} = \tilde{d}_n + (1.06 \pm 0.67) \cdot 10^{-16}\, \bar{\theta}\, e\,\text{cm} \qquad \text{(JBC (2013))}$$

Testing strategies:

- plan A: measure d_n, d_p, and d_D $\xrightarrow{d_D(2N)} \bar{\theta} \xrightarrow{\text{test}} d_{^3He}$
- plan A': measure d_n, (d_p), and $d_{^3He}$ $\xrightarrow{d_{^3He}(2N)} \bar{\theta} \xrightarrow{\text{test}} d_D$
- plan B: measure d_n (or d_p) + Lattice QCD $\rightsquigarrow \bar{\theta} \xrightarrow{\text{test}} d_D$
- plan B': measure d_n (or d_p) + Lattice QCD $\rightsquigarrow \bar{\theta} \xrightarrow{\text{test}} d_p$ (or d_n)

If $\bar{\theta}$-term tests fail: effective BSM dim. 6 sources: de Vries et al. (2011)

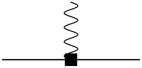
qEDM	*qCEDM*	*4qLR*	*gCEDM* + *4qEDM*
$d_D \approx d_p + d_n$	$d_D > d_p + d_n$	$d_D > d_p + d_n$	$d_D \sim d_p + d_n$
$d_{^3He} \approx d_n$	$d_{^3He} > d_n$	$d_{^3He} > d_n$	$d_{^3He} \sim d_n$

$$\longrightarrow \quad g_0,\, g_1 \propto \alpha/(4\pi)$$

2N contribution suppressed by photon loop!

here: only absolute values considered

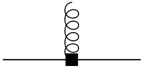
If $\bar{\theta}$-term tests fail: **effective BSM dim. 6 sources:** **de Vries et al. (2011)**



$qEDM$

$d_D \approx d_p + d_n$

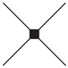
$d_{^3He} \approx d_n$



$qCEDM$

$d_D > d_p + d_n$

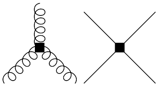
$d_{^3He} > d_n$



$4qLR$

$d_D > d_p + d_n$

$d_{^3He} > d_n$



$gCEDM + 4qEDM$

$d_D \sim d_p + d_n$

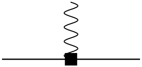
$d_{^3He} \sim d_n$

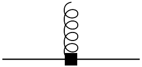
$\longrightarrow \quad g_0, \; g_1$

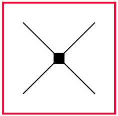
$2N$ contribution enhanced!

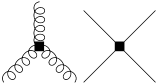
here: only absolute values considered

If $\bar{\theta}$-term tests fail: effective BSM dim. 6 sources: de Vries et al. (2011)









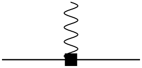
qEDM	*qCEDM*	*4qLR*	*gCEDM + 4qEDM*
$d_D \approx d_p + d_n$	$d_D > d_p + d_n$	$d_D > d_p + d_n$	$d_D \sim d_p + d_n$
$d_{^3He} \approx d_n$	$d_{^3He} > d_n$	$d_{^3He} > d_n$	$d_{^3He} \sim d_n$

$\longrightarrow g_1 \gg g_0$, 3π-coupling (unsuppressed)

$2N$ contribution enhanced!

here: only absolute values considered

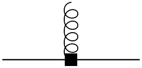
If $\bar{\theta}$-term tests fail: effective BSM dim. 6 sources: de Vries et al. (2011)



qEDM

$d_D \approx d_p + d_n$

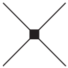
$d_{^3He} \approx d_n$



qCEDM

$d_D > d_p + d_n$

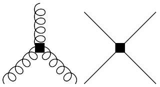
$d_{^3He} > d_n$



4qLR

$d_D > d_p + d_n$

$d_{^3He} > d_n$



gCEDM + 4qEDM

$d_D \sim d_p + d_n$

$d_{^3He} \sim d_n$

$\longrightarrow g_1, g_0, 4N$ – coupling

2N contribution difficult to assess!

here: only absolute values considered

Summary and Outlook

- θEDM: relevant low-energy couplings quantifiable

  strategy A: measure d_n, d_p, d_D $\xrightarrow{d_D(2N)}$ $\bar{\theta}$ $\xrightarrow{\text{test}}$ $d_{^3He}$

  strategy A': measure d_n, (d_p), $d_{^3He}$ $\xrightarrow{d_{^3He}(2N)}$ $\bar{\theta}$ $\xrightarrow{\text{test}}$ d_D

  strategy B: measure d_n (or d_p) + Lattice QCD $\rightsquigarrow$ $\bar{\theta}$ $\xrightarrow{\text{test}}$ d_D

  strategy B': measure d_n (or d_p) + Lattice QCD $\rightsquigarrow$ $\bar{\theta}$ $\xrightarrow{\text{test}}$ d_p (or d_n)

- qEDM, qCEDM, 4QLR:
  - NDA required to assess sizes of low-energy couplings
  - disentanglement possible by measurements of d_n, d_p, d_D & $d_{^3He}$

- gCEDM, 4quark chiral singlet:

  controlled calculation/disentanglement difficult (lattice ?)

- Ultimate progress may eventually come from Lattice QCD

  $\hookrightarrow$ the $\not{C}\not{P}$ $NN\pi$ couplings may be accessible even for dim-6 sources

  $\hookrightarrow$ then *quantifiable* d_D ($d_{^3He}$) EFT predictions feasible in BSM case

Conclusions

- (Hadronic) EDMs play a key role in probing new sources of $\not{CP}$
- Measurements of hadronic EDMs are low-energy measurements
  $\hookrightarrow$ Predictions have to be given in the *empirical language of hadrons*
  $\hookrightarrow$ only reliable methods: *ChPT/EFT* and/or ultimately *Lattice QCD*
- Deuteron and helium-3 nuclei serve as isospin filters for EDMs

At least the EDMs of p, n, d, and ^{3}He
have to be measured
to disentangle the underlying physics