JÜLICH FORSCHUNGSZENTRUM

The electric dipole moment of light nuclei in effective field theory

Jülich-Bonn Collaboration (JBC):

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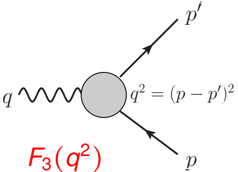
Tbilisi | 23 September 2013 | Andreas Wirzba

Permanent EDMs and Form Factors

- $\langle f(p')|J^\mu_{\rm em}|f(p)\rangle = \bar u_f(p')\,\Gamma^\mu(q^2)\,u_f(p)$



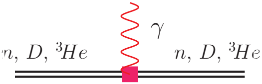
$$\Gamma^\mu(q^2) = \gamma^\mu F_1(q^2) - i\sigma^{\mu\nu} q_\nu \frac{F_2(q^2)}{2m_f} + \sigma^{\mu\nu} q_\nu \gamma_5 \frac{F_3(q^2)}{2m_f} + (\not q\, q^\mu - q^2\gamma^\mu)\gamma_5 F_a(q^2)/m_f^2$$

Dirac $F_1(q^2)$, Pauli $F_2(q^2)$, electric dipole $F_3(q^2)$, and anapole $F_a(q^2)$ FFs

(here for a fermion of mass m_f with spin $s = 1/2$)

$$d := \lim_{q^2\to 0} \frac{F_3(q^2)}{2m_f}\,, \qquad (q \equiv p - p',\ \text{electron charge } e < 0)$$

EDMs from ~~CP~~ Formfactor $F_3(q^2{=}0)/(2m)$



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 the $\bar{\theta}$-term

- 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

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The $\mathcal{L}_{\mathrm{QCD}}$ θ-Term

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

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

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

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

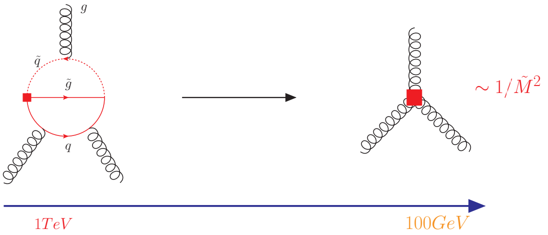
$\mathcal{M}$: quark mass matrix, $m^* = \frac{m_u m_d}{m_u + m_d}$

New Physics Beyond Standard Model (BSM)

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

Effective field theory approach:

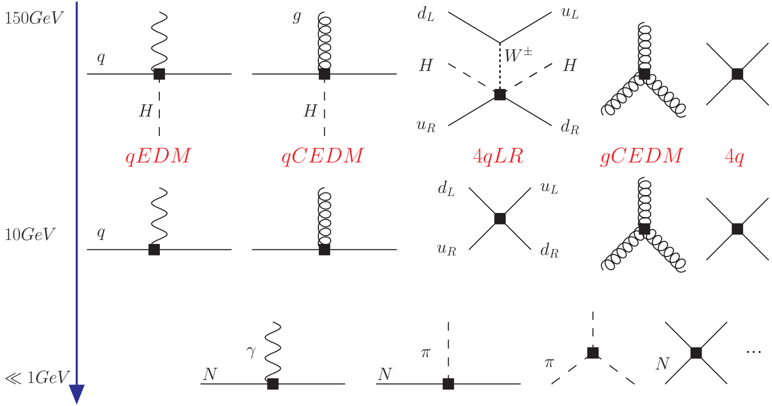
- All degrees of freedom beyond a specified scale are integrated out:
  ↪ Only SM degrees of freedom remain: q, g, H, $W^{\pm}$,...
- Relics of eliminated BSM physics ‘remembered’ by the values of the low-energy constants (LECs) of the CP-violating contact terms, e.g.



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)

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

$$\not{CP}, \mathrm{I} \qquad\qquad \not{CP}, \not{\mathrm{I}} \qquad\qquad \not{CP}, \mathrm{I} + \not{\mathrm{I}}$$

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

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

dominating for *n*, *p* & ^3He

dominating for *D*

important for *n*, *p*

Lebedev et al. (2004), Mereghetti et al. (2010), Bsaisou et al. (2013)

θ-term: $\not{CP}$ πNN vertices determined from LECs

Leading g_0^θ coupling (from c_5)

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

g_0^θ: $N^\dagger \vec{\pi}\cdot\vec{\tau} N$-vertex

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

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

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

Walker-Loud et al. (2012)

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

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

θ-term: subleading g_1^θ coupling (from c_1 LEC)

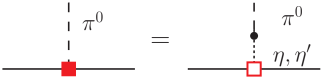
g_1^θ: $\pi_3 NN$-vertex

$\epsilon := (m_u - m_d)/(m_u + m_d)$

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

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

2. $(\delta M_\pi^2)_{QCD} \approx \frac{\epsilon^2}{4}\frac{M_\pi^4}{M_K^2 - M_\pi^2}$



$$\longrightarrow \quad g_1^\theta = (0.003 \pm 0.002)\bar\theta$$

Bsaisou et al. (2013)

$$\frac{g_1^\theta}{g_0^\theta} = -0.20 \pm 0.13 \sim \frac{M_\pi}{m_N}$$

Bsaisou et al. (2013)

$$\gg \quad \epsilon \frac{M_\pi^2}{m_N^2} \sim -0.01 \quad \text{(NDA)}$$

de Vries et al. (2011)

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

Scalings of $\not{CP}$ hadronic vertices (from θ and BSM sources)

In BSM case: reliance on Naive Dimensional Analysis (NDA), lattice, ...

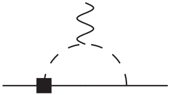
$\mathcal{L}_{\mathrm{EFT}}^{\not{CP}}$:

	g_0: $\not{CP}$, I	g_1: $\not{CP}$, $\not{I}$	d_0, d_1: $\not{CP}$, I + $\not{I}$	$C_{3\pi}$: $\not{CP}$, $\not{I}$
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

θ-Term Induced Nucleon EDM

single nucleon EDM:

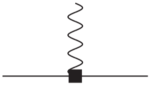


isovector

$\approx$

$\ll$

isoscalar



"controlled"

two "unknown" coefficients

Guo & Meißner (2012): also in SU(3) case

$$d_n\big|_{\text{loop}}^{\text{isovector}} = e\,\frac{g_{\pi NN}\, g_0^\theta}{4\pi^2}\,\frac{\ln(M_N^2/m_\pi^2)}{2M_N} \sim \bar\theta\, m_\pi^2 \ln m_\pi^2$$

Crewther, di Vecchia, Veneziano & Witten (1979); Pich & de Rafael (1991); Ottnad et al. (2010)

$$g_0^\theta = \frac{(m_n - m_p)^{\text{strong}}(1-\epsilon^2)}{4F_\pi\epsilon}\,\bar\theta \approx (-0.018 \pm 0.007)\bar\theta \qquad \left(\text{where } \epsilon \equiv \frac{m_u - m_d}{m_u + m_d}\right)$$

$$\hookrightarrow\ d_n\big|_{\text{loop}}^{\text{isovector}} \sim -(2.1 \pm 0.9)\cdot 10^{-16}\,\bar\theta\, \mathrm{e\,cm}$$

Ottnad et al. (2010); Bsaisou et al. (2013)

θ-Term Induced Nucleon EDM

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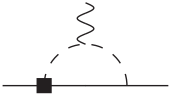
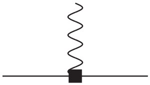


“controlled”

isovector $\approx$ $\ll$ isoscalar



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But what about the two “unknown" coefficients of the contact terms?

We'll always have ... the lattice

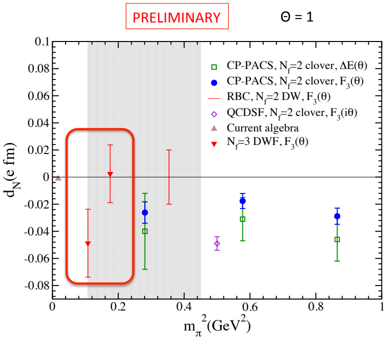
Don't mention the ... light nuclei

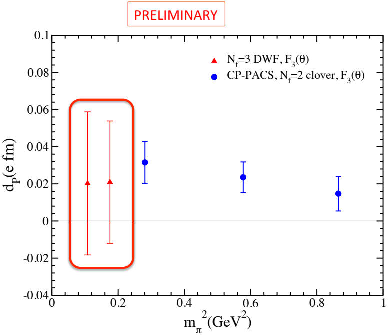
We'll always have ... the lattice

However, *It's a long way to Tipperary ...*

Results from *full* QCD calculations (no systematical errors!) for the

neutron EDM and proton EDM





(adapted from Taku Izubuchi (BNL), *Lattice-QCD calculations for EDMs*, Fermilab, Feb. 14, 2013)

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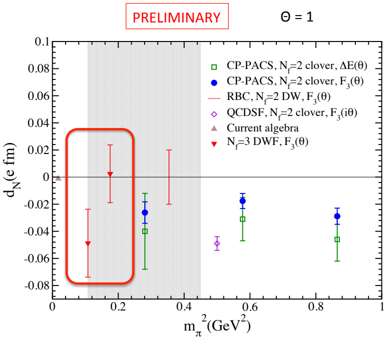

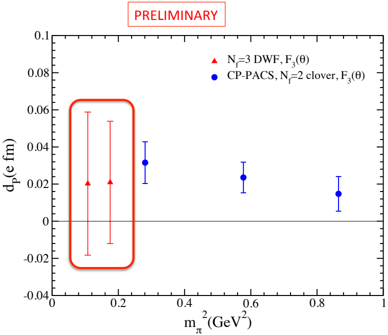

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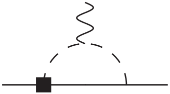

isovector
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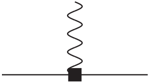


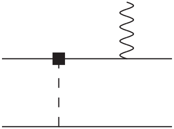
"controlled" "unknown" coefficients

$\longrightarrow$ lattice QCD required

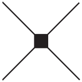
Guo, Meißner (2012)

two nucleon EDM:

Sushkov, Flambaum, Khriplovich (1984)



$\gg$



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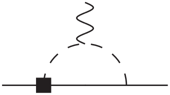

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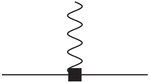

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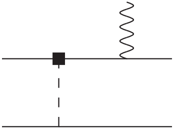
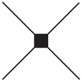


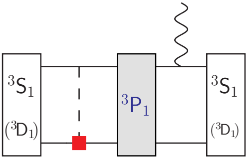
controlled

$\gg$



unknown coefficient

EDM of the Deuteron at LO: quantitative θ-term results



LO: $\cancel{g_0^\theta N^\dagger \vec{\pi}\cdot\vec{\tau} N}$ ($\cancel{CP}$,I) → Isospin excl.

NLO: $g_1^\theta N^\dagger \pi_3 N$ ($\cancel{CP}$, $\cancel{I}$) → "LO"

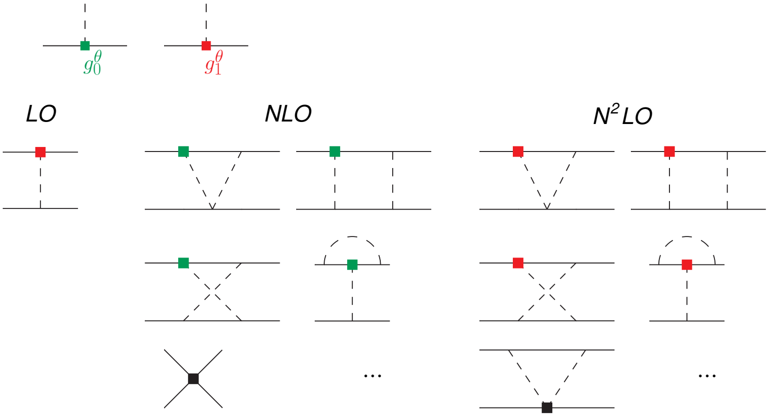
in units of g_1^θ e · fm · $(g_A\, m_N/F_\pi)$

Ref.	potential	no $^3P_1$-int	with $^3P_1$-int	total
JBC (2013)*	Av_{18}	-1.93×10^{-2}	$+0.48\times10^{-2}$	-1.45×10^{-2}
JBC (2013)	CD Bonn	-1.95×10^{-2}	$+0.51\times10^{-2}$	-1.45×10^{-2}
JBC (2013)*	ChPT (N^2LO)†	-1.94×10^{-2}	$+0.65\times10^{-2}$	-1.29×10^{-2}
Song (2013)	Av_{18}	-	-	-1.45×10^{-2}
Liu (2004)	Av_{18}	-	-	-1.43×10^{-2}
Afnan (2010)	Reid 93	-1.93×10^{-2}	$+0.40\times10^{-2}$	-1.43×10^{-2}

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

BSM $\cancel{CP}$ sources: LO g_1 πNN-vertex also exists in qCEDM and 4qLR cases

EDM of the Deuteron: *NLO*- and *N²LO*-Potentials



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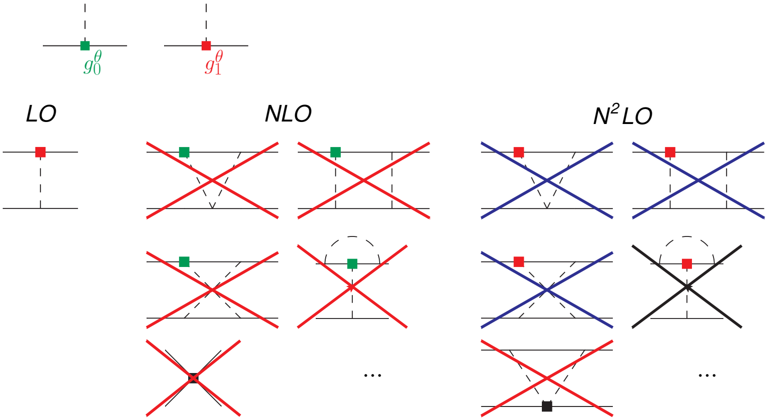
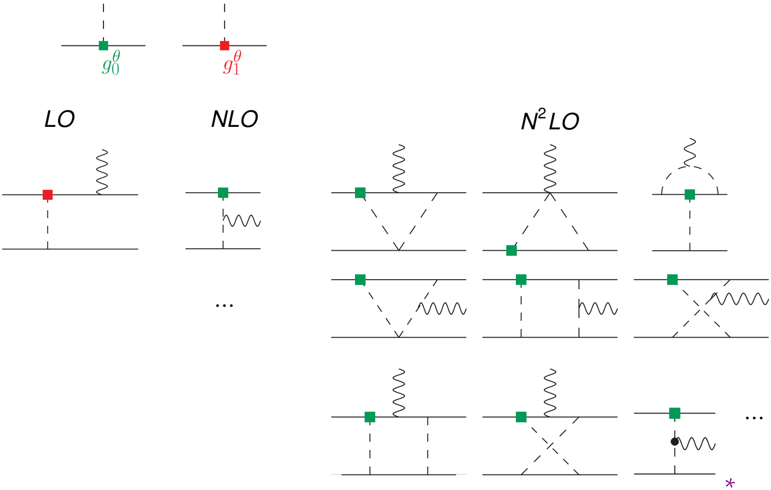


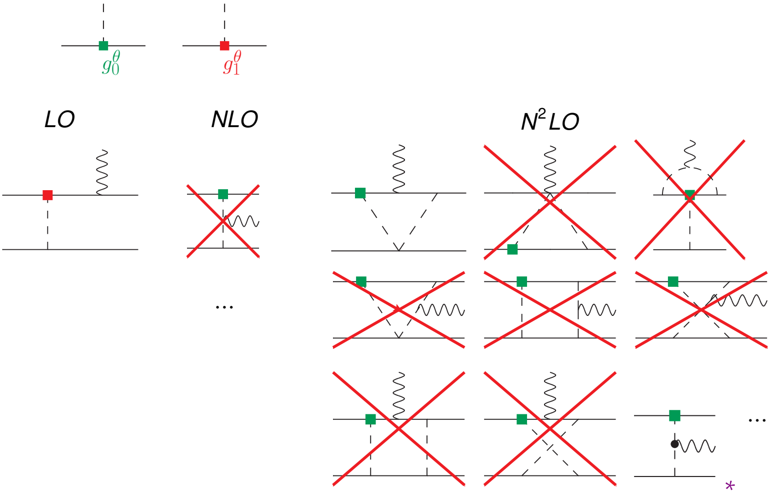
- ×: vanishing by selection rules, ×: sum of diagrams vanishes
  ×: vertex correction

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



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

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



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

Deuteron EDM from the $\bar{\theta}$-term

Bsaisou et al. (2013)

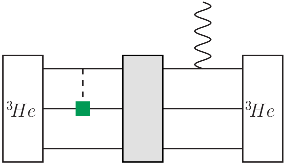
total deuteron EDM: $d_D = d_n + d_p + d_D(2N)$

- 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

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

^3He EDM: quantitative results for g_0 exchange



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

θ-term, qCEDM $\rightarrow$ LO

4qLR $\rightarrow$ N^2LO

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

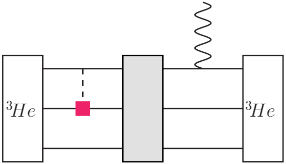
author	potential	no int.	with int.	total
JBC (2013)*	Av_{18}UIX	-0.45×10^{-2}	-0.13×10^{-2}	-0.57×10^{-2}
JBC (2013)*	CD BONN TM	-0.56×10^{-2}	-0.12×10^{-2}	-0.67×10^{-2}
JBC (2013)*	ChPT (N^2LO)†	-0.56×10^{-2}	-0.19×10^{-2}	-0.76×10^{-2}
Song (2013)	Av_{18}UIX	-	-	-0.59×10^{-2}
Stetcu (2008)	Av_{18}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

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

Results for ^3H also available (not shown)

Note: calculation finally under control !

^3He EDM: quantitative results for g_1 exchange



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

θ-term $\rightarrow$ NLO

qCEDM, 4qLR $\rightarrow$ LO !

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

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)

In the pipeline: $\not{CP}$ 3π-vertex contribution (4qLR: LO)

Quantitative EDM results in the θ-term scenario

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

$$-d_1^{\text{loop}} \equiv \tfrac{1}{2}(d_n - d_p)^{\text{loop}}$$
$$= (2.1 \pm 0.9) \cdot 10^{-16}\,\bar{\theta}\, e\,\text{cm} \qquad \text{(Bsaisou et al. (2013))}$$

$$d_n = +(2.9 \pm 0.9) \cdot 10^{-16}\,\bar{\theta}\, e\,\text{cm} \qquad \text{(Guo \& Meißner (2012))}$$
$$d_p = -(1.1 \pm 1.1) \cdot 0^{-16}\,\bar{\theta}\, e\,\text{cm} \qquad \text{(Guo \& Meißner (2012))}$$

Deuteron:

$$d_D = d_n + d_p - \big[(0.59 \pm 0.39) - (0.05 \pm 0.02)\big] \cdot 10^{-16}\,\bar{\theta}\, e\,\text{cm}$$
$$= d_n + d_p - (0.54 \pm 0.39) \cdot 10^{-16}\,\bar{\theta}\, e\,\text{cm} \qquad \text{(Bsaisou et al. (2013))}$$

Helium-3:

$$d_{^3He} = \tilde{d}_n + \big[(1.52 \pm 0.60) - (0.46 \pm 0.30)\big] \cdot 10^{-16}\,\bar{\theta}\, e\,\text{cm}$$
$$= \tilde{d}_n + (1.06 \pm 0.67) \cdot 10^{-16}\,\bar{\theta}\, e\,\text{cm} \qquad \text{(JBC (2013))}$$

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:

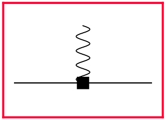
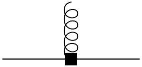
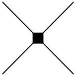
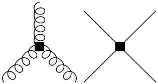
$$d_D = d_n + d_p - (0.54 \pm 0.39) \cdot 10^{-16}\, \bar{\theta}\, e\,\mathrm{cm} \quad \text{(Bsaisou et al. (2013))}$$

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

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: use effective BSM dim. 6 sources   de Vries et al. (2011)

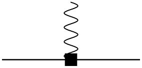
qEDM	*qCEDM*	*4qLR*	*gCEDM* + *4qEDM*
$d_D \approx d_p + d_n$	$d_D > d_p + d_n$	$d_D > d_p + d_n$	$d_D \sim d_p + d_n$
$d_{^3He} \approx d_n$	$d_{^3He} > d_n$	$d_{^3He} > d_n$	$d_{^3He} \sim d_n$

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

2*N* contribution suppressed by photon loop!

here: only absolute values considered

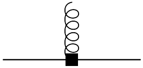
If $\bar{\theta}$-term tests fail: use effective BSM dim. 6 sources   de Vries et al. (2011)



qEDM

$d_D \approx d_p + d_n$

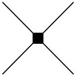
$d_{^3He} \approx d_n$



qCEDM

$d_D > d_p + d_n$

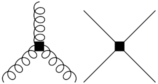
$d_{^3He} > d_n$



4qLR

$d_D > d_p + d_n$

$d_{^3He} > d_n$



gCEDM + 4qEDM

$d_D \sim d_p + d_n$

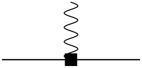
$d_{^3He} \sim d_n$

$\longrightarrow \quad g_0, \; g_1$

2*N* contribution enhanced!

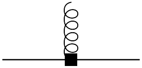
here: only absolute values considered

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



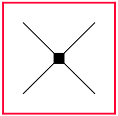
qEDM

$d_D \approx d_p + d_n$
$d_{^3He} \approx d_n$



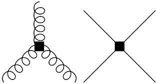
qCEDM

$d_D > d_p + d_n$
$d_{^3He} > d_n$



4qLR

$d_D > d_p + d_n$
$d_{^3He} > d_n$



gCEDM + 4qEDM

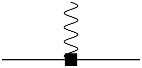
$d_D \sim d_p + d_n$
$d_{^3He} \sim d_n$

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

$2N$ contribution enhanced!

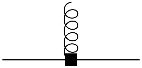
here: only absolute values considered

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



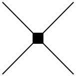
qEDM

$d_D \approx d_p + d_n$
$d_{^3He} \approx d_n$



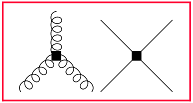
qCEDM

$d_D > d_p + d_n$
$d_{^3He} > d_n$



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 asses!

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 asses 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 $\not{CP}$ $NN\pi$ 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
  ↪ Predictions have to be given in the *empirical language of hadrons*
  ↪ only reliable methods predicting *uncertainties* as well:
  ChPT/EFT and/(or ultimately) *Lattice QCD*
- EDMs of light nuclei provide independent information to nucleon EDMs and may be even larger and even simpler
- 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
by applying methods of EFT and lattice QCD

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