ELECTRIC DIPOLE MOMENTS
of Hadrons and Light Nuclei in Chiral EFT

SSP2018 | June 15, 2018 | Andreas Wirzba | IAS-4, Forschungszentrum Jülich

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Outline:

1. The Permanent Electric Dipole Moment and its Features
2. CP-Violating Sources *Beyond* the Standard Model (BSM)
3. Electric Dipole Moments (EDMs) of the Nucleon
4. Electric Dipole Moments of the Deuteron and Helium-3
5. Conclusions and Outlook

CP violation and Electric Dipol Moments (EDMs)

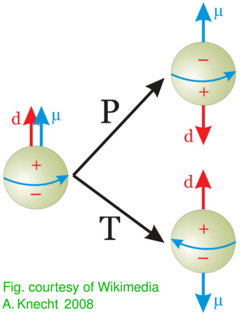


Fig. courtesy of Wikimedia
A. Knecht 2008

EDM: $\vec{d} = \sum_i \vec{r}_i \, e_i \xrightarrow[\text{particles}]{\text{subatomic}} d \cdot \vec{S}/|\vec{S}|$

(polar) (axial)

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

P: $\mathcal{H} = -\mu \frac{\vec{S}}{S} \cdot \vec{B} + d \frac{\vec{S}}{S} \cdot \vec{E}$

T: $\mathcal{H} = -\mu \frac{\vec{S}}{S} \cdot \vec{B} + d \frac{\vec{S}}{S} \cdot \vec{E}$

Any *non-vanishing EDM* of a **non-degenerate** (e.g. subatomic) particle violates **P** & **T**

- Assuming CPT to hold, CP is violated as well (flavor-diagonally)
  ↪ subatomic EDMs: “rear window” to CP violation in early universe
- Strongly suppressed in SM (CKM-matrix): $|d_n| \sim 10^{-31-33} e\,\text{cm}$, $|d_e| \sim 10^{-44} e\,\text{cm}$
- Current bounds: $|d_n| < 3^{\diamond}/1.6^{*} \cdot 10^{-26} e\,\text{cm}$, $|d_p| < 2 \cdot 10^{-25} e\,\text{cm}$, $|d_e| < 1 \cdot 10^{-28} e\,\text{cm}$

n: Pendlebury et al. (2015)$^{\diamond}$, *p* prediction: Dimitriev & Sen’kov (2003)*, *e*: Baron et al.(2014)†

* from $|d_{^{199}\text{Hg}}| < 7.4 \cdot 10^{-30} e\,\text{cm}$ bound of Graner et al. (2016), † from polar ThO: $|d_{\text{ThO}}| \lesssim 10^{-21} e\,\text{cm}$

A *naive* estimate of the scale of the nucleon EDM

Khriplovich & Lamoreaux (1997); Kolya Nikolaev (2012)

- CP & P conserving magnetic moment ~ nuclear magneton μ_N

$$\mu_N = \frac{e}{2m_p} \sim 10^{-14}\, e\,\mathrm{cm}\,.$$

- A nonzero EDM requires

  parity P violation: the price to pay is $\sim 10^{-7}$

  $(\, G_F \cdot F_\pi^2 \sim 10^{-7}$ with $G_F \approx 1.166 \cdot 10^{-5}\mathrm{GeV}^{-2}\,)$,

  and additionally **CP violation**: the price to pay is $\sim 10^{-3}$

  $(\,|\eta_{+-}| \equiv |\mathcal{A}(K_L^0 \to \pi^+\pi^-)|\,/\,|\mathcal{A}(K_S^0 \to \pi^+\pi^-)| = (2.232 \pm 0.011)\cdot 10^{-3}\,)$.

- In summary: $|d_N| \;\sim\; 10^{-7} \times 10^{-3} \times \mu_N \;\sim\; 10^{-24}\, e\,\mathrm{cm}$

- In SM (without θ term): extra $G_F F_\pi^2$ factor to *undo* flavor change

$$\hookrightarrow \quad \left|d_N^{\mathrm{SM}}\right| \sim 10^{-7} \times 10^{-24}\, e\,\mathrm{cm} \;\sim\; 10^{-31}\, e\,\mathrm{cm}$$

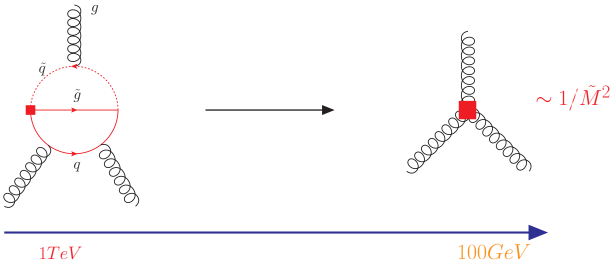
$\hookrightarrow$ *The empirical window* for search of physics BSM(θ=0) is

$$10^{-24}\, e\,\mathrm{cm} > |d_N| > 10^{-30}\, e\,\mathrm{cm}.$$

How to handle CP-violating sources beyond the SM?

Evaluation in Effective Field Theory (EFT) approach

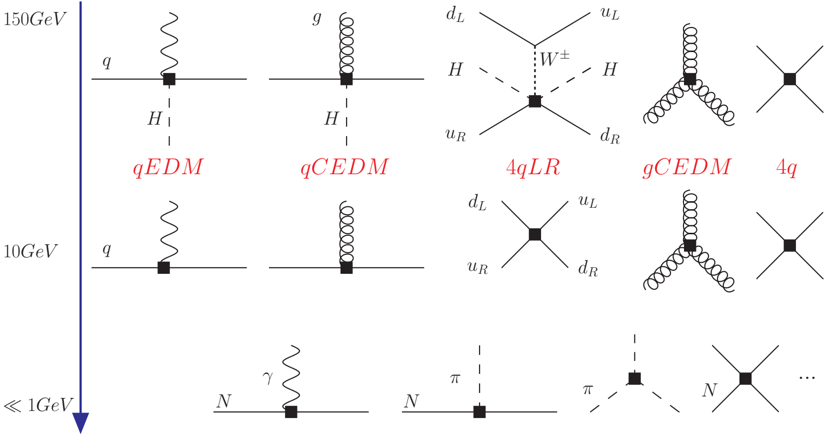
- All degrees of freedom *beyond NP (EW) scale* are integrated out:
  $\hookrightarrow$ Only SM degrees of freedom remain: q, g, (H, Z, $W^{\pm}$, ...)
- Write down *all* interactions for these *active* degrees of freedom that *respect the* SM+ Lorentz *symmetries*: here dim. 6 or higher order
- Need a *power-counting scheme* to order these infinite # interactions
- Relics of eliminated BSM physics 'remembered' by the values of the low-energy constants (LECs) of the CP-violating contact terms, e.g.



CP-violating BSM sources of dimension 6 above EW scale

to the hadronic counterparts below 1 GeV

W. Dekens & J. de Vries *JHEP* '13



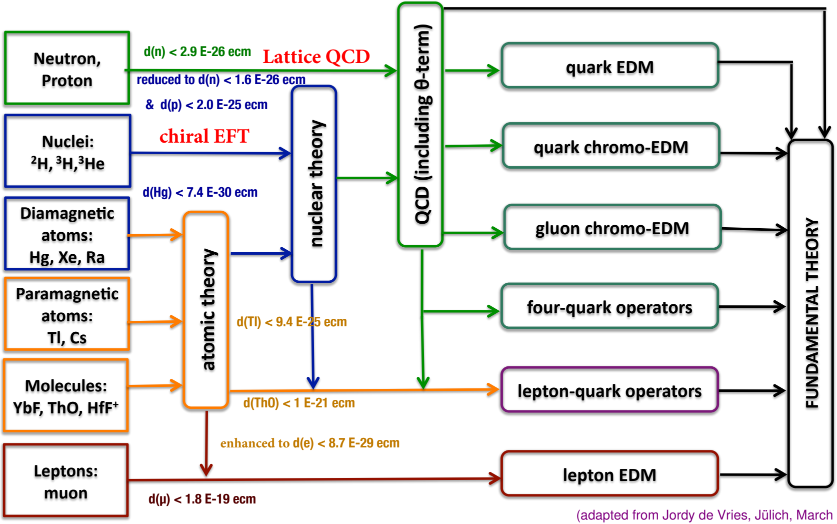
Total # $=$ 1$(\bar\theta)$ + 2*(qEDM)* + 2*(qCEDM)* + 1*(4qLR)* + 1*(gCEDM)* + 2*(4q)* [+3(semi)+1(lept)]

$=$ 1(dim-four) + 8(dim-six) [+3+1] [Caveat: $m_s \gg m_u, m_d$ (& $m_\mu \gg m_e$) assumed]

↪ 5 discriminable classes

Road map from EDM Measurements to EDM Sources

Experimentalist's point of view → ← Theorist's point of view



(adapted from Jordy de Vries, Jülich, March 14, 2013)

EDM Translator
from ‘quarkish/machine’ to ‘hadronic/human’ language?

3-CPO & R2-D2 Dirk Vorderstraße

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Symmetries (esp. chiral one) plus Goldstone Theorem

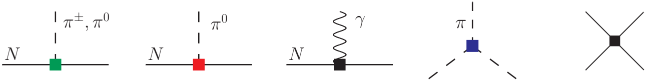
↪ Low-Energy Effective Field Theory with External Sources

i.e. Chiral Perturbation Theory (suitably extended)

Scalings of $\not{CP}$ hadronic vertices – from θ to BSM sources

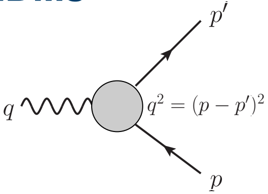
5 discriminable cases:

Mereghetti et al., *AP* **325** ('10); de Vries et al., *PRC* **84** ('11); Bsaisou et al., *EPJA* **49** ('13)

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

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

Calculation: from form factors to EDMs



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

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

Dirac FF | Pauli FF | electric dipole FF ($\not{CP}$) | anapole FF ($\not{P}$)

$$\hookrightarrow \quad d_f := \lim_{q^2\to 0} \frac{F_3(q^2)}{2m_f} \qquad \text{for } s = 1/2 \text{ fermion}$$

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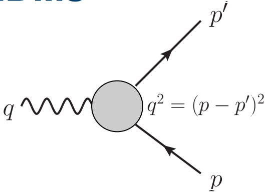

$$\Gamma^\mu(q^2) = \gamma^\mu F_1(q^2) - \mathrm{i}\sigma^{\mu\nu} q_\nu \frac{F_2(q^2)}{2m_f} + \sigma^{\mu\nu} q_\nu \gamma_5 \frac{F_3(q^2)}{2m_f} + (\not{q}\, q^\mu - q^2\gamma^\mu)\gamma_5 \frac{F_a(q^2)}{m_f^2}$$

Dirac FF — Pauli FF — electric dipole FF ($\not{CP}$) — anapole FF ($\not{P}$)

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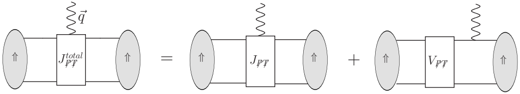
Nucleus A

$\langle \Uparrow | J^0_{\not{P}\not{T}}(q)\,|\Uparrow\rangle$ in Breit frame



$$= -\mathrm{i}q^3 \underbrace{\frac{F_3^A(\vec q^{\,2})}{2m_A}}_{\hookrightarrow d_A}$$

θ-Term Induced Nucleon EDM

Baluni, *PRD* (1979); Crewther et al., *PLB* (1979); ... Pich & de Rafael, *NPB* (1991); ... Ottnad et al., *PLB* (2010)

Isospin-conserving πNN coupling:

$$g_0^\theta = \frac{(m_n - m_p)^{\text{strong}}(1-\epsilon^2)}{4F_\pi \epsilon}\bar\theta \approx (-15.5 \pm 1.9)\cdot 10^{-3}\bar\theta \quad (\text{where } \epsilon \equiv \frac{m_u - m_d}{m_u + m_d})$$

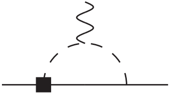
$$\hookrightarrow d_N|^{\text{isovector}}_{\text{loop}} \sim (1.8 \pm 0.3)\cdot 10^{-16}\,\bar\theta\,\mathrm{e\,cm}$$

Bsaisou et al., *EPJA* **49** (2013), *JHEP* **03** (2015)

Note also: $g_1^\theta = 8c_1 m_N \Delta^\theta + (0.6 \pm 1.1)\cdot 10^{-3}\bar\theta = (3.4 \pm 1.5)\cdot 10^{-3}\bar\theta$ with the

3-pion coupling: $\Delta^\theta = \frac{\epsilon(1-\epsilon^2)}{16F_\pi m_N}\frac{M_\pi^4}{M_K^2 - M_\pi^2}\bar\theta + \cdots = (-0.37 \pm 0.09)\cdot 10^{-3}\bar\theta$

single nucleon EDM:

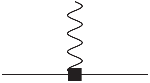


isovector

$\approx$

$\ll$

isoscalar



$g_0^\theta/\bar\theta$ known $\rightsquigarrow$ “controlled” “unknown” coefficients

$\longrightarrow$ lattice QCD required

Guo & Meißner, *JHEP* **12** (2012)

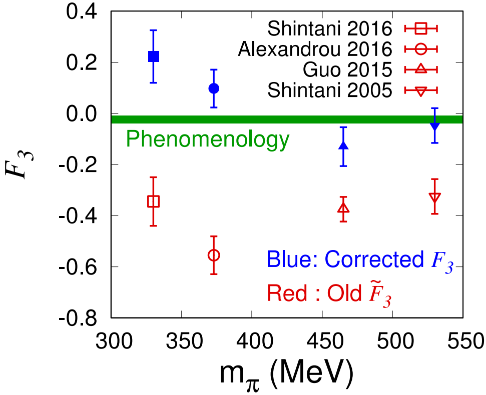
Unfortunately, all recent lattice results for the θ-induced nEDM are affected by a mixing of $F_3(q^2)$ with $F_2(q^2)$ and compatible with zero

M. Abramczyk et al., *Phys. Rev. D* **96** (2017)

Lattice Parity Mixing of F_3 and F_2 Form Factors
for the θ-induced nEDM results

M. Abramcyk et al., *Phys. Rev. D* **96** (2018) 014501

θ-term induced CP-violating interaction
$\hookrightarrow$ neutron mass term $m \to \tilde{m} = e^{-2i\alpha\gamma_5} m$
$\hookrightarrow$ Rotate neutron spinor $\tilde{u} = e^{i\alpha\gamma_5} u$
such that γ_4 remains the parity operator



$\Longrightarrow$ mixing of F_2 and F_3:

$$F_2 = \cos(2\alpha)\tilde{F}_2 - \sin(2\alpha)\tilde{F}_3$$
$$F_3 = \sin(2\alpha)\tilde{F}_2 + \cos(2\alpha)\tilde{F}_3$$

Corrections include some assumptions due to limited information on the parity induced rotation in the original calculations.

Corrected lattice results for F_3 are small and consistent with zero.

This holds also for the qCEDM data.

So far, reliable lattice data only for the qEDM case:

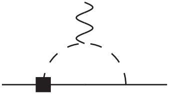
$$d^{\text{qEDM}}_{\text{n, lattice}} \approx (3/5) \times d^{\text{qEDM}}_{\text{n, quark model}}$$
$$d_n = g^{\text{u}}_{\text{T}} d_{\text{u}} + g^{\text{d}}_{\text{T}} d_{\text{d}} + g^{\text{s}}_{\text{T}} d_{\text{s}}$$
$$g^{\text{u}}_{\text{T}} = -0.211(16),\ g^{\text{d}}_{\text{T}} = 0.811(31),\ g^{\text{s}}_{\text{T}} = -0.0023(23)$$

Figure and references:
B. Yoon, T. Bhattacharya, R. Gupta, *EPJ Web Conf.* **175** (2018);
Rajan Gupta, EDM Workshop, CERN, 26-March-2018

Single Nucleon Versus Nuclear EDM

Baluni, *PRD* (1979); Crewther et al., *PLB* (1979); ... Pich & de Rafael, *NPB* (1991); ... Ottnad et al., *PLB* (2010)

single nucleon EDM:



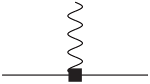
“controlled”

isovector

$\approx$

$\ll$

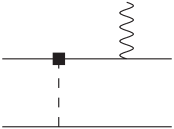
isoscalar



“unknown” coefficients

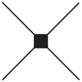
two nucleon EDM:

Sushkov, Flambaum, Khriplovich *Sov.Phys. JETP*’84



controlled

$\gg$



unknown coefficient

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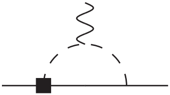
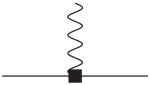


“controlled”

isovector $\approx$ $\ll$ isoscalar



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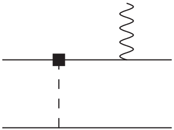
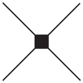


controlled

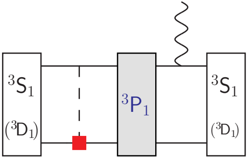
$\gg$



unknown coefficient

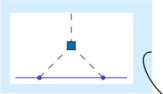
EDM of the Deuteron at LO: CP-violating π exchange

$$\mathcal{L}^{\pi N}_{\not{CP}} = -d_n N^\dagger(1-\tau^3)S^\mu v^\nu N F_{\mu\nu} - d_p N^\dagger(1+\tau_3)S^\mu v^\nu N F_{\mu\nu}$$
$$+ (m_N \Delta)\pi^2\pi_3 + \cancel{g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N} + g_1 N^\dagger \pi_3 N$$
$$+ \cancel{C_1 N^\dagger N \mathcal{D}_\mu (N^\dagger S^\mu N)} + \cancel{C_2 N^\dagger \vec{\tau} N \cdot \mathcal{D}_\mu (N^\dagger \vec{\tau} S^\mu N)} + \cdots .$$



LO: $\cancel{g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N}$ ($\not{CP}$,I) $\to$ 0 (Isospin filter!)

NLO: $g_1 N^\dagger \pi_3 N$ ($\not{CP}, \not{I}$) $\to$ *"LO"* in D case



term	N^{2}LO χPT	N^{4}LO$^+$ χPT	Av_{18}	CD-Bonn	units
d_n^D	0.939(9)	0.929(8)	0.914	0.927	d_n
d_p^D	0.939(9)	0.929(8)	0.914	0.927	d_p
g_1	0.183(17)	0.188(3)	0.186	0.186	$g_1\, e$ fm
Δf_{g_1}	−0.748(138)	−0.722(12)	−0.703	−0.719	$\Delta\, e$ fm

Bsaisou et al., *JHEP* **03** (2015); A.W., Bsaisou, Nogga, *IJMP E* **26** (2017)

BSM $\not{CP}$ sources: g_1 πNN vertex is of LO in qCEDM and 4qLR case

$(\Lambda_{LS}, \Lambda_{SFR}) = \{(0.45, 0.5); (0.6, 0.5); (0.55, 0.6); (0.45, 0.7); (0.6, 0.7)\}$ GeV

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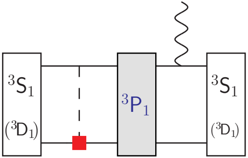

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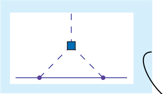
NLO: $g_1 N^\dagger\pi_3 N$ ($\not{CP}$, $\not{I}$) $\rightarrow$ *"LO"* in D case

Yamanaka & Hiyama, *PRC* **91** (2015): $d_N^D = \left(1 - \frac{3}{2}P_{^3D_1}\right)d_N$



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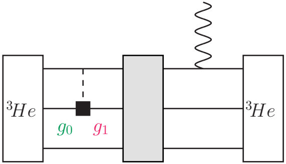
^3He EDM: results for CP-violating π exchange



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

LO: θ-term, qCEDM

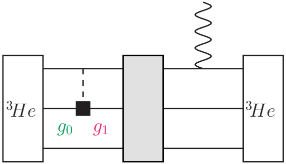
N^2LO: 4qLR

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

LO: qCEDM, 4qLR

NLO: θ term

^3He EDM: results for CP-violating π exchange



$g_0 N^\dagger \vec{\pi} \cdot \vec{\tau} N$ ($\not{CP}$, I)
LO: θ-term, qCEDM
N^{2}LO: 4qLR

$g_1 N^\dagger \pi_3 N$ ($\not{CP}$, $\not{I}$)
LO: qCEDM, 4qLR
NLO: θ term

term	A	N^{2}LO ChPT	Av$_{18}$+UIX	CD-Bonn+TM	units
d_n	^{3}He	0.904 ± 0.013	0.875	0.902	d_n
	^{3}H	-0.030 ± 0.007	−0.051	−0.038	
d_p	^{3}He	-0.029 ± 0.006	−0.050	−0.037	d_p
	^{3}H	0.918 ± 0.013	0.902	0.876	
Δ	^{3}He	-0.017 ± 0.006	−0.015	−0.019	$\Delta\, e$ fm
	^{3}H	-0.017 ± 0.006	−0.015	−0.018	
g_0	^{3}He	0.111 ± 0.013	0.073	0.087	$g_0\, e$ fm
	^{3}H	-0.108 ± 0.013	−0.073	−0.085	
g_1	^{3}He	0.142 ± 0.019	0.142	0.146	$g_1\, e$ fm
	^{3}H	0.139 ± 0.019	0.142	0.144	
Δf_{g_1}	^{3}He	-0.608 ± 0.142	−0.556	−0.586	$\Delta\, e$ fm
	^{3}H	-0.598 ± 0.141	−0.564	−0.576	
C_1	^{3}He	-0.042 ± 0.017	−0.0014	−0.016	$C_1\, e\,\mathrm{fm}^{-2}$
	^{3}H	0.041 ± 0.016	0.0014	0.016	
C_2	^{3}He	0.089 ± 0.022	0.0042	0.033	$C_2\, e\,\mathrm{fm}^{-2}$
	^{3}H	-0.087 ± 0.022	−0.0044	−0.032	

Bsaisou, dissertation, Univ. Bonn (2014); Bsaisou et al., *JHEP* **03** (2015)

^3He EDM: results for CP-violating π exchange

$$
\begin{aligned}
\mathcal{L}^{\pi N}_{\not{CP}} \quad = \quad & - d_n N^\dagger (1-\tau^3) S^\mu v^\nu N F_{\mu\nu} - d_p N^\dagger (1+\tau_3) S^\mu v^\nu N F_{\mu\nu} \\
& + (m_N \Delta) \pi^2 \pi_3 + g_0 N^\dagger \vec{\pi} \cdot \vec{\tau} N + g_1 N^\dagger \pi_3 N \\
& + C_1 N^\dagger N \mathcal{D}_\mu (N^\dagger S^\mu N) + C_2 N^\dagger \vec{\tau} N \cdot \mathcal{D}_\mu (N^\dagger \vec{\tau} S^\mu N) + \cdots .
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$(\Lambda_{LS}, \Lambda_{SFR}) = \{(0.45, 0.5); (0.6, 0.5); (0.55, 0.6); (0.45, 0.7); (0.6, 0.7)\}$ GeV

Discriminating between three scenarios at 1 GeV

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

1. The Standard Model + $\bar{\theta}$

$$\mathcal{L}_{\mathrm{SM}}^{\theta} = \mathcal{L}_{\mathrm{SM}} + \bar{\theta} m_q^* \bar{q} i \gamma_5 q$$

2. The left-right symmetric model — with two 4-quark operators:

$$\mathcal{L}_{LR} = -\mathrm{i}\,\Xi \left[1.1 (\bar{u}_R \gamma_\mu u_R)(\bar{d}_L \gamma^\mu d_L) + 1.4 (\bar{u}_R t^a \gamma_\mu u_R)(\bar{d}_L t^a \gamma^\mu d_L) \right] + \mathrm{h.c.}$$

3. The aligned two-Higgs-doublet model — with the dipole operators:

$$\mathcal{L}_{a2HM} = -e \frac{d_d}{2} \bar{d}\, \mathrm{i} \sigma_{\mu\nu} \gamma_5 d\, F^{\mu\nu} - \frac{\tilde{d}_d}{4} \bar{d}\, \mathrm{i} \sigma_{\mu\nu} \gamma_5 \lambda^a d\, G^{a\,\mu\nu} + \frac{d_W}{3} f_{abc} \tilde{G}^{a\,\mu\nu} G^b_{\mu\rho} G^{c\rho}_{\nu}$$

— with the hierarchy $\tilde{d}_d \simeq 4 d_d \simeq 20 d_W$

matched on

$$\begin{aligned} \mathcal{L}^{\pi N}_{\not{CP}\,\mathrm{EFT}} \quad = \quad & - d_n N^\dagger (1 - \tau^3) S^\mu v^\nu N F_{\mu\nu} - d_p N^\dagger (1 + \tau_3) S^\mu v^\nu N F_{\mu\nu} \\ & + (m_N \Delta) \pi^2 \pi_3 + g_0 N^\dagger \vec{\pi} \cdot \vec{\tau} N + g_1 N^\dagger \pi_3 N \\ & + C_1 N^\dagger N \mathcal{D}_\mu (N^\dagger S^\mu N) + C_2 N^\dagger \vec{\tau} N \cdot \mathcal{D}_\mu (N^\dagger \vec{\tau} S^\mu N) + \cdots . \end{aligned}$$

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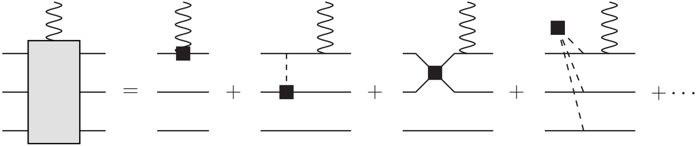

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Testing strategies: SM + $\bar{\theta}$

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

Measurement of the helion and neutron EDMs

Testing strategies: SM + $\bar{\theta}$

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

Measurement of the helion and neutron EDMs

→

Extraction of $\bar{\theta}$

$$d_{^3\text{He}} - 0.9 d_n = -\bar{\theta}\left(1.01 \pm 0.31_{\text{had}} \pm 0.29^{\star}_{\text{nucl}}\right) \cdot 10^{-16}\, e\,\text{cm}$$

* includes ± 0.20 uncertainty from 2N contact terms

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Extraction of $\bar{\theta}$

$$d_D - 0.94(d_n + d_p) = \bar{\theta}\left(0.89 \pm 0.29_{\mathrm{had}} \pm 0.08_{\mathrm{nucl}}\right) \cdot 10^{-16}\, e\,\mathrm{cm}$$

Prediction for $d_D - 0.94(d_n + d_p)$
(& triton EDM): $d_D^{\mathrm{Nucl}} \approx -d_{^3\mathrm{He}}^{\mathrm{Nucl}} \approx \frac{1}{2} d_{^3\mathrm{H}}^{\mathrm{Nucl}}$

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Testing strategies: SM + $\bar\theta$

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

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Extraction of $\bar\theta$

$$d_D - 0.94(d_n + d_p) = \bar\theta \left(0.89 \pm 0.29_{\rm had} \pm 0.08_{\rm nucl}\right) \cdot 10^{-16}\, e\,\mathrm{cm}$$

Prediction for $d_D - 0.94(d_n + d_p)$

(& triton EDM): $d_D^{\rm Nucl} \approx -d_{^3\mathrm{He}}^{\rm Nucl} \approx \frac{1}{2} d_{^3\mathrm{H}}^{\rm Nucl}$

$$g_0^\theta = \frac{(m_n - m_p)^{\rm strong}(1-\epsilon^2)}{4F_\pi\,\epsilon}\,\bar\theta = (-16\pm2)10^{-3}\,\bar\theta$$

$$\frac{g_1^\theta}{g_0^\theta} \approx \frac{8c_1\,(M^2_{\pi^\pm} - M^2_{\pi^0})^{\rm strong}}{(m_n - m_p)^{\rm strong}}\,, \quad \epsilon \equiv \frac{m_u - m_d}{m_u + m_d}$$

$g_1^\theta / g_0^\theta \approx -0.2$

* includes ± 0.20 uncertainty from 2N contact terms

Testing strategies: minimal LR symmetric Model

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

Measurement of the deuteron and nucleon EDMs

Testing strategies: minimal LR symmetric Model

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

Measurement of the deuteron and nucleon EDMs

↓

Extraction of Δ^{LR}

$$d_D - 0.94(d_n + d_p) \simeq d_D = -\left(2.1 \pm 0.5^{\star}\right)\Delta^{LR} e\,\text{fm}$$

*includes ± 0.1 uncertainty from 2N contact terms

Testing strategies: minimal LR symmetric Model

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

Measurement of the deuteron and nucleon EDMs

↓

Extraction of Δ^{LR}

↓

Prediction for the helion EDM
(& triton EDM): $d_D \approx d_{^3\mathrm{He}} \approx d_{^3\mathrm{H}}$

$$d_D - 0.94(d_n + d_p) \simeq d_D = -\big(2.1 \pm 0.5^{\star}\big)\Delta^{LR}\, e\,\mathrm{fm}$$

$$d_{^3\mathrm{He}} - 0.9 d_n \simeq d_{^3\mathrm{He}} = -(1.7 \pm 0.5^{\star})\Delta^{LR}\, e\,\mathrm{fm}$$

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Testing strategies: minimal LR symmetric Model

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

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Prediction for the helion EDM
(& triton EDM): $d_D \approx d_{^3\text{He}} \approx d_{^3\text{H}}$

$$g_1^{LR} = 8 c_1 m_N \Delta^{LR} = (-7.5 \pm 2.3)\Delta^{LR},$$
$$g_0^{LR} = \frac{(m_n - m_p)^{\text{str}} m_N}{M_\pi^2}\Delta^{LR} = (0.12 \pm 0.02)\Delta^{LR}$$

$-g_1^{LR}/g_0^{LR} \gg 1$ (!)

*includes ± 0.1 uncertainty from 2N contact terms

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Testing strategies: aligned 2-Higgs Doublet Model

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

Measurement of the deuteron and nucleon EDMs

Testing strategies: aligned 2-Higgs Doublet Model

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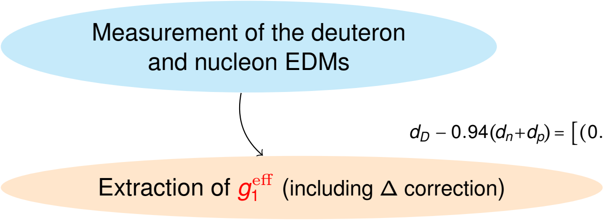

$$d_D - 0.94(d_n + d_p) = \left[(0.18 \pm 0.02) g_1 - (0.75 \pm 0.14)\Delta\right] e\,\mathrm{fm}$$

Testing strategies: aligned 2-Higgs Doublet Model

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Extraction of g_1^{eff} (including Δ correction)

+ Measurement of $d_{^3\mathrm{He}}$ (or $d_{^3\mathrm{H}}$)

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+ Measurement of $d_{^3\mathrm{He}}$ (or $d_{^3\mathrm{H}}$)

$$d_{^3\mathrm{He}} - 0.9 d_n$$
$$= \left[(0.11\pm0.02^{\star})g_0 + (0.14\pm0.02^{\star})g_1 - (0.61 \pm 0.14)\Delta\right] e\,\mathrm{fm}$$

Extraction of g_0

*includes ±0.01 uncertainty from 2N contact terms

Testing strategies: aligned 2-Higgs Doublet Model

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

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Extraction of g_0

Prediction of $d_{^3\mathrm{H}}$ (or $d_{^3\mathrm{He}}$)

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Summary

- *D* EDM might **distinguish** between $\bar{\theta}$ and other scenarios and allows **extraction** of the g_1 coupling constant via $d_D - 0.94(d_n{+}d_p)$.
  (The prefactor of $(d_n{+}d_p)$ stands for a 4% probability of the $^3D_1$ state.)
- ^3He (or ^3H) EDM necessary for a **proper test** of $\bar{\theta}$ and LR scenarios:
- Deuteron & helion work as complementary isospin filters of EDMs
- 2N contact terms **cannot be neglected** for nuclei beyond *D*
- a2HDM case: ^3He *and* ^3H EDMs would be needed for a proper test
- pure qCEDM: similar to a2HDM scenario
- pure qEDM: $d_D = 0.94(d_n + d_p)$ and $d_{^3He/^3H} = 0.9 d_{n/p}$
- gCEDM, 4quark χ singlet: controlled calculation difficult (lattice ?)

- Ultimate progress may eventually come from **Lattice QCD**
  $\hookrightarrow$ $\not{C}\not{P}$ $N\pi$ couplings g_0 & g_1 may be accessible even for dim-6 case

Many thanks to my colleagues

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and: Werner Bernreuther, Bira van Kolck, and Kolya Nikolaev

References:

1. A.W., J. Bsaisou, A. Nogga,
Permanent Electric Dipole Moments in Single-, Two- and Three-Nucleon Systems, Int. J. Mod. Phys. E **26**, 1740031 (2017), arXiv:1610.00794.

2. J. Bsaisou, U.-G. Meißner, A. Nogga and A.W.,
P- and T-Violating Lagrangians in Chiral Effective Field Theory and Nuclear Electric Dipole Moments, Annals of Physics **359**, 317-370 (2015), arXiv:1412.5471 [hep-ph].

3. J. Bsaisou, C. Hanhart, S. Liebig, D. Minossi, U.-G. Meißner, A. Nogga and A.W.,
Electric dipole moments of light nuclei, JHEP **03**, 104 (**05**, 083) (2015), arXiv:1411.5804.

4. W. Dekens, J. de Vries, J. Bsaisou, W. Bernreuther, C. Hanhart, U.-G. Meißner, A. Nogga and A.W., JHEP **07**, 069 (2014), arXiv:1404.6082 [hep-ph].

5. J. Bsaisou, C. Hanhart, S. Liebig, U.-G. Meißner, A. Nogga and A.W.,
The electric dipole moment of the deuteron from the QCD θ-term,
Eur. Phys. J. A **49**, 31 (2013), arXiv:1209.6306 [hep-ph].