JÜLICH FORSCHUNGSZENTRUM

EDMs of Light Nuclei
in Chiral Effective Field Theory

Promotionskolloquium

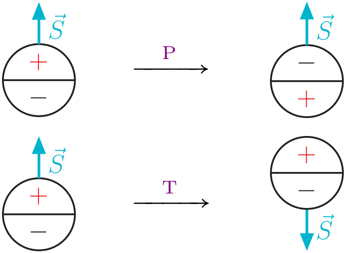
25.04.2014 | Jan Bsaisou

Why Electric Dipole Moments (EDMs)?

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

(polar) (axial)

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



$$\mathcal{H} \xrightarrow{\mathrm{P}} \mathcal{H}' = +\,d\frac{\vec{S}}{S}\cdot\vec{E}$$

$$\mathcal{H} \xrightarrow{\mathrm{T}} \mathcal{H}' = +\,d\frac{\vec{S}}{S}\cdot\vec{E}$$

$\longrightarrow$ Permanent EDMs of subatomic particles violate parity (P) and time-reversal (T) symmetry

CPT theorem: T violation $\leftrightarrow$ CP violation

EDMs are a measure of flavor-diagonal CP violation in fundamental particle interactions!

JÜLICH FORSCHUNGSZENTRUM

Why is CP violation interesting?

One example: baryon-antibaryon asymmetry $\mathcal{A}_{B\bar{B}}$ in the universe

Cosmic background radiation (photon freeze-out point)

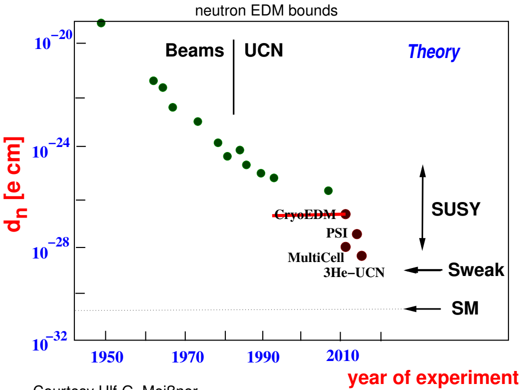
WMAP+COBE (2012):	?	SM with CKM matrix:
$\mathcal{A}_{B\bar{B}} = (n_B - n_{\bar{B}})/n_\gamma \sim 10^{-10}$		$\mathcal{A}_{B\bar{B}} = (n_B - n_{\bar{B}})/n_\gamma \sim 10^{-18}$

Sakharov conditions for dynamically generated $\mathcal{A}_{B\bar{B}}$ (1967):

1. Baryon number violation
2. C and CP violation
3. Interactions outside thermal equilibrium

What could be the sources of CP violation
within and/or beyond the SM ?

Hadronic EDMs



Courtesy Ulf-G. Meißner

Current bounds:

$|d_n| < 3 \cdot 10^{-26}\ e\,\mathrm{cm}$
Baker et al. (2006)

$|d_p| < 8 \cdot 10^{-25}\ e\,\mathrm{cm}$
(from ^{199}Hg)
Griffith et al. (2009),
Dimitri & Sen'kov (2003)

SM (CKM matrix):
$d_n \sim 10^{-31}\ e\,\mathrm{cm}$

Planned storage ring experiments with sensitivity $\sim 10^{-29}\ e\,\mathrm{cm}$:

p @ BNL or FNAL,   p, D, ^{3}He @ FZ Jülich

Hadronic EDMs

Hypothesis: EDM measurement $\longrightarrow$ $\not{CP}$ beyond SM (CKM-matrix)

$\downarrow$

different $\not{CP}$ sources induce different hierarchies of light nuclei EDMs!

$\downarrow$

Several EDM measurements required to disentangle sources

Outline:

1. Compile list of SM and BSM $\not{CP}$ sources
2. Derive induced $\not{CP}$ hadronic operators
3. Compute EDMs of n, p, D, ^3He

$\not{CP}$ sources of dim 4: SM beyond CKM-mechanism

Topological non-trivial field configurations $\longrightarrow$ $\not{CP}$ term in $\mathcal{L}_{QCD}$

$$\mathcal{L}_{QCD} = \mathcal{L}_{QCD}^{\text{CP}} + \underbrace{\theta \frac{g_s^2}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}}_{\text{QCD } \theta\text{-term}} \quad \text{(dim 4)}$$

$U(1)_A$-anomaly: $\theta \frac{g_s^2}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma} \overset{U(1)_A}{\longleftrightarrow} -\bar{\theta} m_q^* i\bar{q}\gamma_5 q$

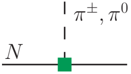
$\bar{\theta} = \theta + \arg\mathrm{Det}(\mathcal{M})$, $\mathcal{M}$: quark mass matrix, $m_q^* = m_u m_d / (m_u + m_d)$

Current $\bar{\theta}$-bound from d_n: $|\bar{\theta}| \lesssim 10^{-10}$ Baker et al. (2006) + Ottnad et al. (2010)

$\not{CP}$ sources at the hadronic level: θ-term

$SU(2)$ ChPT (π, N, γ, ...): symmetries of QCD preserved by EFT

$\not{CP}, \mathrm{I}$		$\mathrm{CP}, \not{\mathrm{I}}$
$-\bar{\theta} m_q^* i\bar{q}\gamma_5 q$	$\xleftrightarrow{SU(2)_L \times SU(2)_R}$	$\bar{m}_q \epsilon \bar{q}\tau_3 q$
$\downarrow$		$\downarrow$
$\underbrace{c_5\,(\bar{\theta} 2B m_q^*/F_\pi)}_{\longrightarrow g_0} N^\dagger \vec{\pi}\cdot\vec{\tau} N$	$\xleftrightarrow{SU(2)_L \times SU(2)_R}$	$\underbrace{c_5\, 4B\bar{m}_q\epsilon}_{\delta m_{np}^{str}/2 = (2.6\pm0.85)\,\mathrm{MeV}/2^*} N^\dagger \tau_3 N$



$$\longrightarrow \quad g_0 = \bar{\theta}\frac{\delta m_{np}^{str}}{4F_\pi}\frac{1-\epsilon^2}{\epsilon} + \cdots = (-0.018 \pm 0.007)\bar{\theta}$$

Mereghetti et al. (2010), JB et al. (2013)

* Gasser & Leutwyler (1984) + Walker-Loud et al. (2012)

$\bar{m}_q = (m_u + m_d)/2, \quad m_q^* = m_u m_d/(m_u+m_d), \quad \epsilon = (m_u - m_d)/(m_u+m_d)$

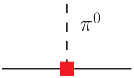
$\not{CP}$ sources at the hadronic level: θ-term induced $\not{I}$ πNN-vertex

$\not{CP}$ terms break $SU(2)_L \times SU(2)_R$ symmetry $\longrightarrow$ ground state shifted!

Shift defined by angle $\beta = \beta(\underbrace{(M^2_{\pi_\pm} - M^2_{\pi^0})_{str}}_{(\delta M^2_\pi)_{str}})$:

Mereghetti et al. (2010)
JB et al. (2013)

$$\underset{\longrightarrow \Delta m_N}{\underbrace{c_1\, 8B\bar{m}_q}}\; N^\dagger N \quad (\mathrm{CP}, \mathrm{I}) \qquad \xrightarrow[\text{shift}]{SU(2)_L \times SU(2)_R} \qquad \underset{\longrightarrow g_1}{\underbrace{c_1\, 8B\bar{m}_q\, 2\beta}}\; N^\dagger \pi_3 N \quad (\not{\mathrm{CP}}, \not{\mathrm{I}})$$



$$\longrightarrow g_1 = c_1 \frac{2\bar{\theta}(\delta M^2_\pi)_{str}}{F_\pi} \frac{1-\epsilon^2}{\epsilon} + \cdots = (0.003 \pm 0.002)\bar{\theta}$$

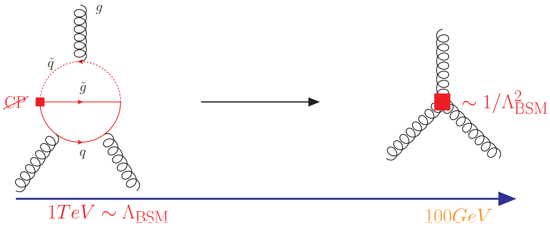
c_1: Baru et al. (2011), $(\delta M^2_\pi)_{str}$: Gasser & Leutwyler (1984)

$|g_0| \gg |g_1|$ $\qquad$ $g_1/g_0 = -0.2 \pm 0.1 \sim \mathcal{O}(M_\pi/m_N)$ $\qquad$ JB et al. (2013)

$\not{CP}$ sources of dim > 4: BSM physics

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

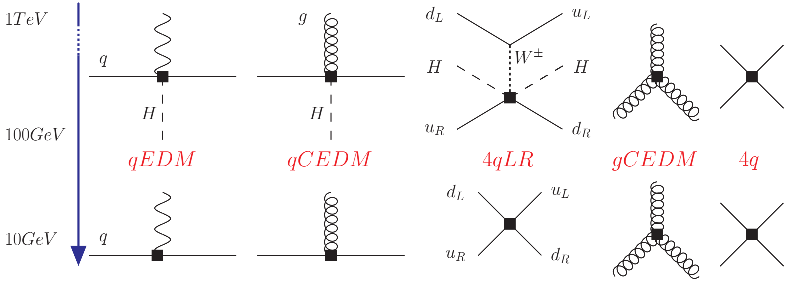
Effective field theory approach:



- All degrees of freedom beyond Λ_{BSM} are integrated out
  $\hookrightarrow$ Only SM degrees of freedom remain: q, g, H, $W^{\pm}$,...
- BSM d.o.f. encoded in effective coupling constants
- $\mathcal{L}_{eff}$ expansion in powers of $1/\Lambda_{\mathrm{BSM}}$
  $\longrightarrow$ eff. operators of dim. 5, 6, ...

$\not{CP}$ sources of dim > 4: BSM physics

Add to SM all $\not{CP}$ effective dim $\leq$ 6 sources: Buchmüller et al. (1986), Grzadkowski et al. (2010), Ng et al. (2012), de Vries et al. (2013), ...

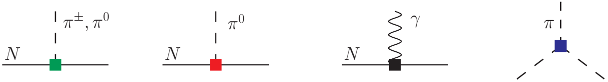


$\longrightarrow$ Effective dim-6 sources: new, independent operators

$\not{CP}$ sources in ChPT: effective dim-6 sources de Vries et al. (2012), JB et al. (in prep)

New, independent operators $\longrightarrow$ new LECs (Lattice QCD, NDA, ...)

	$g_0: \not{CP}, \mathrm{I}$	$g_1: \not{CP}, \not{\mathrm{I}}$	$d_0, d_1: \not{CP}, \mathrm{I}+\not{\mathrm{I}}$	$\Delta: \not{CP}, \not{\mathrm{I}}$
$\mathcal{L}^{\not{CP}}_{\text{EFT}}$:				
θ-term:	$\bar{\theta}\,\dfrac{M_\pi^2}{m_N^2}$	$\bar{\theta}\,\dfrac{M_\pi^3}{m_N^3}$	$e\,\bar{\theta}\,\dfrac{M_\pi^2}{m_N^2}\,\dfrac{1}{m_N}$	$\bar{\theta}\,\dfrac{M_\pi^4}{m_N^4}$
qCEDM:	$\propto \dfrac{M_\pi^2}{F_\pi m_N}$	$\propto \dfrac{M_\pi^2}{F_\pi m_N}$	$\propto e\,\dfrac{M_\pi^2}{m_N^2}\,\dfrac{1}{m_N}$	$\propto \dfrac{M_\pi^4}{F_\pi m_N^3}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$

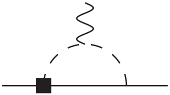


$\not{CP}$ sources $\longrightarrow$ different hierarchies of coupling constants

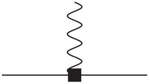
θ-term induced EDMs: nucleons

Leading one-loop contribution:

Crewther et al.(1979), Pich et al. (1991)
Ottnad et al. (2010)

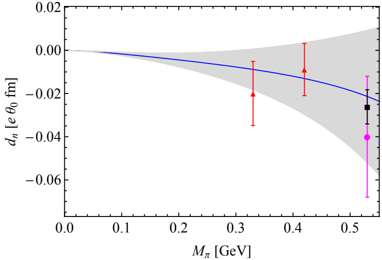


$\approx$



two counter terms

Lattice QCD input required to quantify counter terms!



Courtesy Guo & Meißner (preliminary)

Fitting to Lattice QCD data
@ $M_\pi = 320$ MeV, $M_\pi = 420$ MeV

Shintani (2014, preliminary)

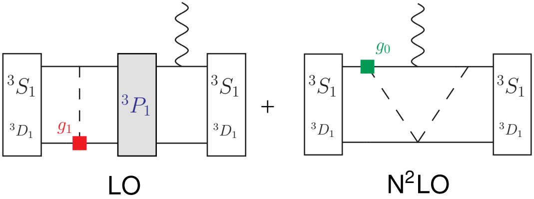
$$d_p = +(2.1 \pm 1.2) \cdot 10^{-16} \bar{\theta}\, e\,\text{cm}$$
$$d_n = -(2.7 \pm 1.2) \cdot 10^{-16} \bar{\theta}\, e\,\text{cm}$$

Guo, Meißner (2012) & (in prep)

θ-term induced EDMs: deuteron

Leading *NN* tree-level contribution $\longrightarrow$ $\not{C}\not{P}$ $4N$ vertices suppressed!

Flambaum et al. (1984)

$d_D = d_n + d_p +$  $+ \cdots$

$$d_D^{LO}(2N) = (\ 0.55 \pm \underbrace{0.36}_{\text{hadronic}} \pm \underbrace{0.05}_{\text{nuclear}}) \cdot 10^{-16}\,\bar{\theta}\,e\,\text{cm}$$

(ChPT)

JB et al. (inprep)

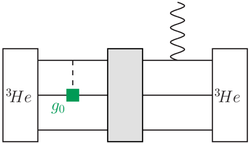
$$d_D^{N^2LO}(2N) = (-0.05 \pm \underbrace{0.02}_{\text{hadronic}}) \cdot 10^{-16}\,\bar{\theta}\,e\,\text{cm}$$

JB et al. (2013)

θ-term induced EDMs: helion

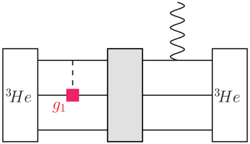
$d_{^3He} = \underbrace{\tilde{d}_n}_{=0.88 d_n - 0.047 d_p} +$

de Vries et al. (2011)



LO

$+$



NLO

$+ \cdots$

$$d^{LO}_{^3He}(2N) = (-1.78 \pm \underbrace{0.70}_{\text{hadronic}} \pm \underbrace{0.46}_{\text{nuclear}}) \cdot 10^{-16}\, \bar{\theta}\, e\,\text{cm}$$

$$d^{NLO}_{^3He}(2N) = (\ 0.43 \pm \underbrace{0.28}_{\text{hadronic}} \pm \underbrace{0.08}_{\text{nuclear}}) \cdot 10^{-16}\, \bar{\theta}\, e\,\text{cm}$$

(ChPT)

JB et al. (in prep)

Stetcu et al. (2008), Song et al. (2013): d_D, $d_{^3He}$ from phen. potentials

→ functions of $g_{0,1}$, no controlled uncertainty, discrepancies now resolved

Testing Strategies for the θ-term

EDM results:

$$d_D = d_n + d_p + (0.55 \pm 0.37) \cdot 10^{-16}\,\bar{\theta}\,e\,\mathrm{cm} \quad \text{JB et al. (in prep)}$$

$$d_{^3He} = \underbrace{\tilde{d}_n}_{= 0.88\,d_n - 0.047\,d_p} - (1.35 \pm 0.88) \cdot 10^{-16}\,\bar{\theta}\,e\,\mathrm{cm} \quad \text{JB et al. (in prep)}$$

$= 0.88\,d_n - 0.047\,d_p$ de Vries et al. (2011)

Testing strategies:

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

If $\bar{\theta}$-term tests fail: effective BSM dim-6 sources

de Vries et al. (2011), JB et al. (in prep)

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

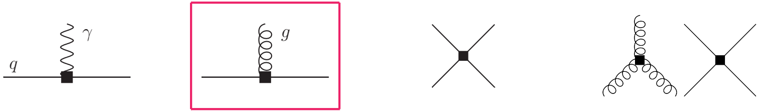
$\longrightarrow \quad g_0,\, g_1 \propto \alpha_{em}/(4\pi)$ (from photon loop)

$2N$ contribution suppressed!

here: only absolute values considered

If $\bar{\theta}$-term tests fail: effective BSM dim-6 sources

de Vries et al. (2011), JB et al. (in prep)



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

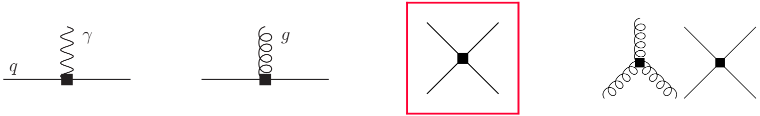
$\longrightarrow$ $g_0 \sim g_1$ dominant!

$2N$ contribution enhanced!

here: only absolute values considered

If $\bar{\theta}$-term tests fail: effective BSM dim-6 sources

de Vries et al. (2011), JB et al. (in prep)



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

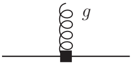
$\longrightarrow g_1 \gg g_0$, 3π-coupling (unsuppressed)

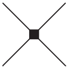
Isospin-breaking $2N$ contribution enhanced!

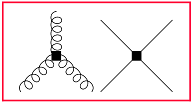
here: only absolute values considered

If $\bar{\theta}$-term tests fail: effective BSM dim-6 sources

de Vries et al. (2011), JB et al. (in prep)







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

$\longrightarrow g_1 \sim g_0 \sim 4N-$coupling

$2N$ contribution difficult to quantify!

here: only absolute values considered

Conclusions

- (Hadronic) EDMs play a key role in hunting new sources of $\not{C}\not{P}$
- Measurements of hadronic EDMs are low-energy measurements
  $\hookrightarrow$ Predictions have to be given in the *language of hadrons*
  $\hookrightarrow$ only reliable systematic methods: *ChPT/EFT* and/or *Lattice QCD*
- Deuteron and ^{3}*He* nucleus provide independent information for EDMs (different isospin filters)

> EDM measurements of *p*, *n*, *D*, and ^{3}He
> (combined with Lattice QCD results)
> required
> to disentangle the underlying physics

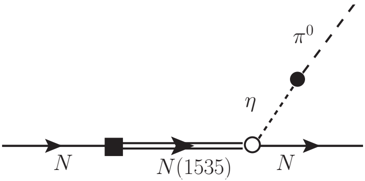
Backup Slides

Another contribution to g_1^θ

Mereghetti et al. (2010), JB et al. (2013)

$$\mathcal{L}_{\pi N} = \ldots + c_1^{(3)} \frac{B^2 m^* (m_u - m_d)}{F_\pi} \bar{\theta} N^\dagger \pi_3 N + \ldots \quad \longrightarrow \quad c_1^{(3)} \text{ unkown!}$$

estimate $c_1^{(3)}$ by resonance saturation: JB et al. (2013)



$\Gamma_{N_{1535} \to N\eta}$

+

$\eta - \pi_0$-mixing amplitude

$\Downarrow$

$\not{CP}$ $N^* \to N\pi_0$ coupling

$$\delta g_1^\theta = (0.0006 \pm 0.0003)\bar{\theta} \quad \ll \quad g_1^\theta = (0.003 \pm 0.002)\bar{\theta}$$

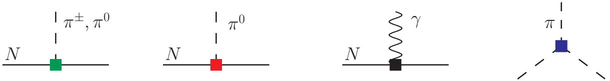
incorporated into increased uncertainty

$\not{CP}$ sources in ChPT: effective dim-6 sources de Vries et al. (2012), JB et al. (in prep)

New, independent operators $\longrightarrow$ new LECs (Lattice QCD, NDA)

	g_0: $\not{CP}$, I	g_1: $\not{CP}$, $\not{I}$	d_0, d_1: $\not{CP}$, I+$\not{I}$	Δ: $\not{CP}$, $\not{I}$

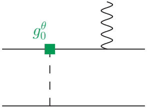
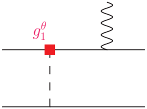
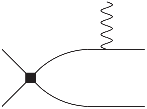
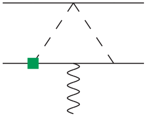
$\mathcal{L}^{\not{CP}}_{\text{EFT}}$:



	g_0	g_1	d_0, d_1	Δ
θ-term:	$\bar{\theta}\,\frac{M_\pi^2}{m_N^2}$	$\bar{\theta}\,\frac{M_\pi^3}{m_N^3}$	$e\,\bar{\theta}\,\frac{M_\pi^2}{m_N^3}$	$\bar{\theta}\,\frac{M_\pi^4}{m_N^4}$
qEDM:	$c\,\frac{\alpha_{em}}{4\pi}\,\frac{M_\pi^2}{F_\pi m_N}$	$c\,\frac{\alpha_{em}}{4\pi}\,\frac{M_\pi^2}{F_\pi m_N}$	$e\,c\,\frac{M_\pi^2}{m_N^3}$	$c\,\frac{\alpha_{em}}{4\pi}\,\frac{M_\pi^4}{F_\pi m_N^3}$
qCEDM:	$c\,\frac{M_\pi^2}{F_\pi m_N}$	$c\,\frac{M_\pi^2}{F_\pi m_N}$	$e\,c\,\frac{M_\pi^2}{m_N^3}$	$c\,\frac{M_\pi^4}{F_\pi m_N^3}$
4qLR:	$c\,\frac{M_\pi^2}{F_\pi m_N}$	$c\,\frac{m_N}{F_\pi}$	$e\,c\,\frac{1}{m_N}$	$c\,\frac{m_N}{F_\pi}$
gCEDM, 4q:	$c\,\frac{M_\pi^2}{F_\pi m_N}$	$c\,\frac{\epsilon M_\pi^2}{F_\pi m_N}$	$e\,c\,\frac{1}{m_N}$	$c\,\frac{\epsilon M_\pi^4}{F_\pi m_N^3}$

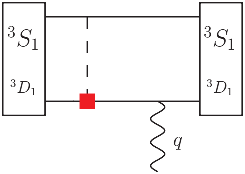
$\not{CP}$ sources $\longrightarrow$ different hierarchies of couplings

D EDM: Power Counting

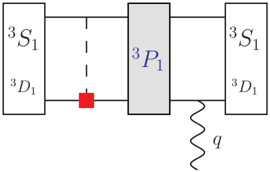
	θ-term	qCEDM	4qLR
	A_θ (~~LO~~)	A_{qC} (LO)	A_{4q} (N^2LO)
	$A_\theta \times \frac{M_\pi}{m_N}$ (~~NLO~~ → LO)	A_{qC} (LO)	$A_{4q} \times \frac{M_\pi^2}{m_N^2}$ (LO)
	$A_\theta \times \frac{M_\pi^2}{m_N^2}$ (N^2LO → ~~NLO~~ → N^3LO)	$A_{qC} \times \frac{M_\pi^2}{m_N^2}$ (N^2LO)	A_{4q} (N^2LO)
	$A_\theta \times \frac{M_\pi^3}{m_N^3}$ (N^3LO → N^2LO)	$A_{qC} \times \frac{M_\pi^3}{m_N^3}$ (N^3LO)	$A_{4q} \times \frac{M_\pi^3}{m_N^3}$ (N^5LO)

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

plane wave: multiple rescatterings:



$+$



$+$ perm.

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

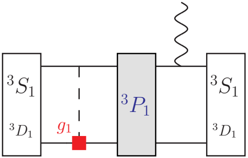
$$G = G_0 + G_0\, t_{12}\, G_0 \qquad\qquad t_{12} = (1 - V_{12}\, G_0)^{-1}\, V_{12}$$

Note:

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

JÜLICH
FORSCHUNGSZENTRUM

EDM of the Deuteron at LO: θ-term



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

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

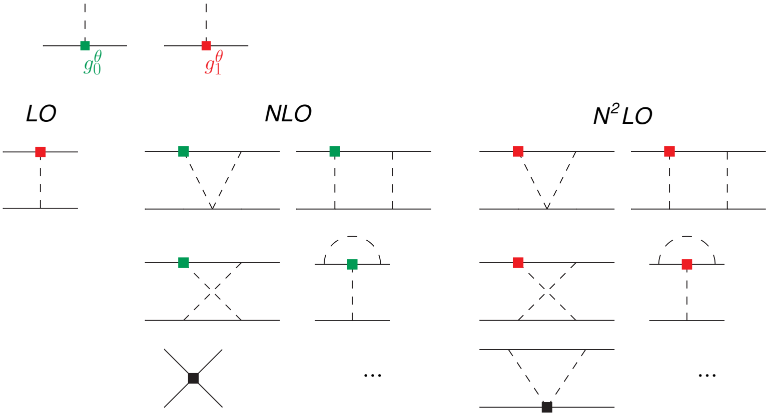
in units of g_1^θ e $\cdot$ fm $\cdot$ $(g_A\, m_N / F_\pi)$

refs.	potential	no $^3P_1$-int	with $^3P_1$-int	total
JB et al. (2014)*	Av_{18}	1.93×10^{-2}	-0.48×10^{-2}	1.45×10^{-2}
JB et al. (2014)*	CD BONN	1.95×10^{-2}	-0.51×10^{-2}	1.45×10^{-2}
JB et al. (2014)*	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}	1.53×10^{-2}

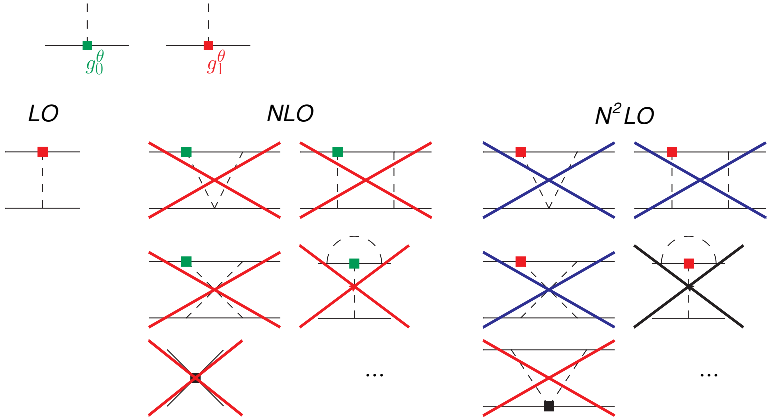
*: in preparation †: cutoffs at 600 MeV (LS) and 700 MeV (SFR)

BSM $\not{CP}$ sources: g_1 πNN-vertex induces also LO NN contribution

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

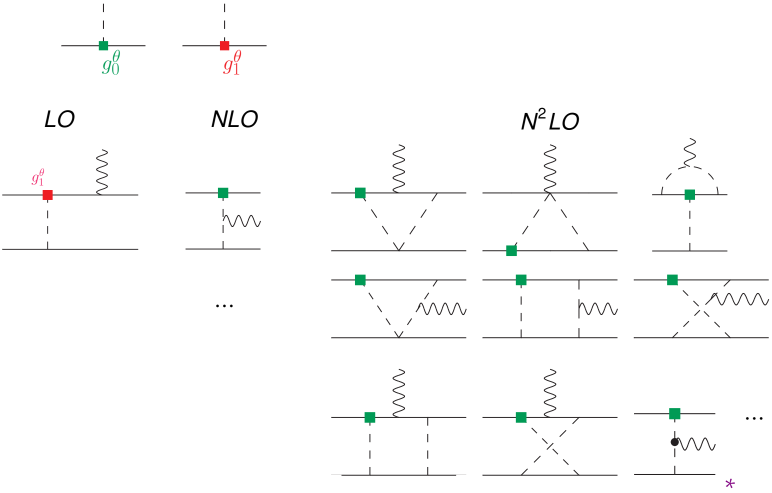


EDM of the Deuteron: *NLO*- and N^2LO-Potentials



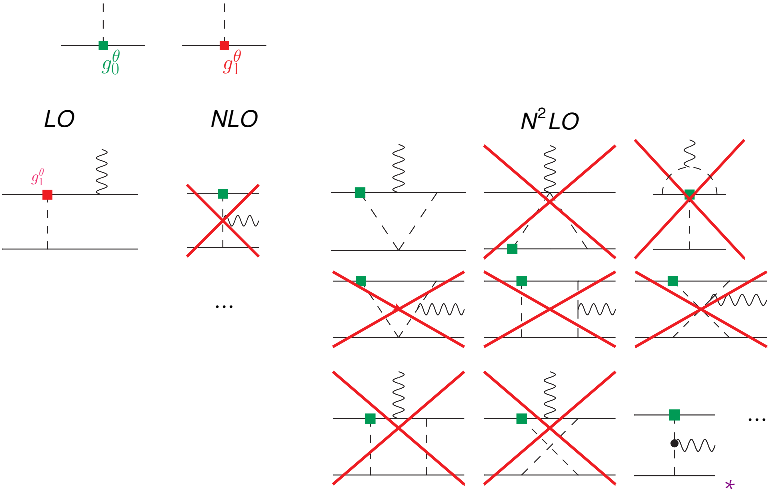
- ✕: vanishing by selection rules, ✕: sum of diagrams vanishes
  ✕: vertex correction

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



*: de Vries et al. (2011), JB et al. (2013)

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

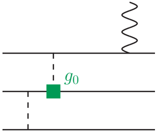
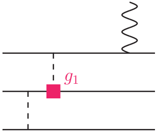
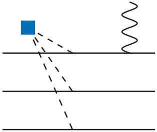


*: de Vries et al. (2011), JB et al. (2013)

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

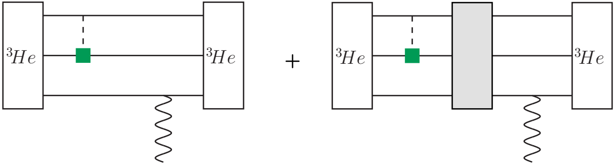
${}^{3}He$ EDM: Power Counting

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.

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

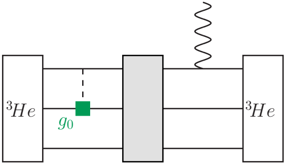
$\Rightarrow$ Faddeev equation: $(1+P)|U_{(3)}\rangle \equiv V\,G\,(1+P)\mathcal{O}_3(\vec{q})\,|{}^3He\rangle$

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

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

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

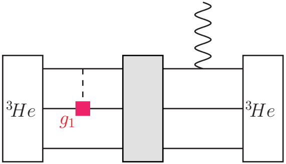
author	potential	no int.	with int.	total
JB et al. (2014)*	Av_{18}UIX	0.45×10^{-2}	0.13×10^{-2}	0.57×10^{-2}
JB et al. (2014)*	CD BONN TM	0.56×10^{-2}	0.12×10^{-2}	0.67×10^{-2}
JB et al. (2014)*	ChPT $(N^2LO)^\dagger$	0.56×10^{-2}	0.19×10^{-2}	0.76×10^{-2}
Song (2013)	Av_{18}UIX	-	-	0.55×10^{-2}
Stetcu (2008)	Av_{18} UIX	-	-	1.20×10^{-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



$g_1 N^\dagger \pi_3 N$ (CP̸, I̸)

θ-term → NLO

qCEDM, 4qLR → LO !

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

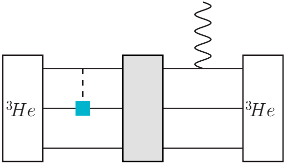
Ref.	potential	no int.	with int.	total
JB et al. (2014)*	Av_{18}UIX	1.09×10^{-2}	0.02×10^{-2}	1.11×10^{-2}
JB et al.(2014)*	CD BONN TM	1.11×10^{-2}	0.03×10^{-2}	1.14×10^{-2}
JB et al. (2014)*	ChPT (N^2LO)†	1.09×10^{-2}	0.14×10^{-2}	0.96×10^{-2}
Song (2013)	Av_{18}UIX	-	-	1.06×10^{-2}
Stetcu (2008)	Av_{18} 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: CP̸ 3π-vertex contribution (4qLR: LO)

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

Ref.	potential	no int.	with int.	total
JB et al. (2014)*	Av_{18}UIX	1.36×10^{-2}	0.35×10^{-2}	1.71×10^{-2}
JB et al.(2014)*	CD BONN TM	1.46×10^{-2}	0.37×10^{-2}	1.83×10^{-2}
JB et al. (2014)*	ChPT $(N^2LO)^\dagger$	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: JB et al. (2013)* ~ Stetcu (2008) / 2

Quantitative EDM results in the θ-term scenario

Single Nucleon:

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

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

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

Deuteron:

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

Helium-3:

$$d_{^3He} = \tilde{d}_n - \big[(1.52 \pm 0.60) - (0.46 \pm 0.30)\big] \cdot 10^{-16}\,\bar{\theta}\,e\,\text{cm}$$
$$= \tilde{d}_n - (1.06 \pm 0.67) \cdot 10^{-16}\,\bar{\theta}\,e\,\text{cm}$$ (JB et al. (in prep))

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