EDM of the Deuteron from the QCD θ-Term

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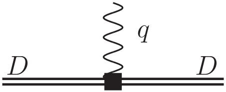
arXiv:1209.6306

Deuteron EDM (d_D) from Formfactor F_3:



$$\langle J=1, J_z'=\pm 1 | J^0_{\not{CP}} | J=1, J_z=\pm 1\rangle = \mp i q^3 \frac{F_3(\vec{q})}{2m_N} \quad \rightarrow \quad d_D = \lim_{\vec{q}\to 0} \frac{F_3(\vec{q})}{2m_N}$$

- CP-violation in the SM:
  - complex phase of CKM Matrix → insufficient
  - $\mathcal{L}_{QCD}$ θ-term
- CP-violation from extensions of the SM: SUSY, multi-Higgs,$\cdots$

assumption in this talk : θ-term sole $\not{CP}$-mechanism

The $\mathcal{L}_{QCD}$ θ-Term

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

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

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

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

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

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

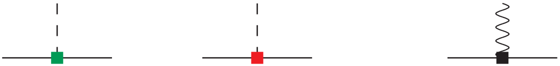
see talks of U. van Kolck and J. de Vries

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

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

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

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



...

dominating
see later

Lebedev et al. (2004)

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

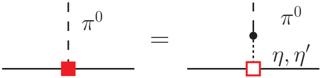
Crewther et al. (1979); Ottnad et al. (2010); Mereghetti et al. (2011); de Vries et al. (2011); J.B. et al. arXiv:1209.6306

$$\mathcal{M} \to \mathcal{M} + \bar{\theta} m^* i\gamma_5$$

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

$$+ \; c_1 4BN^\dagger \left((m_u + m_d) + \frac{2m^*\bar{\theta}}{F_\pi} \tilde{\eta} \right) N$$

$\tilde{\eta}$: U(2) remnant of η, η'



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

$\tilde{\eta}\pi^0$-mixing ampl. $\quad \epsilon_{\tilde{\eta}\pi^0} \approx \epsilon M_\pi^2/(M_{\tilde{\eta}}^2 - M_\pi^2) \quad \to \quad g_1^\theta = \bar{\theta} c_1 \epsilon_{\tilde{\eta}\pi^0}(1-\epsilon^2)\frac{2}{F_\pi}$

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

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

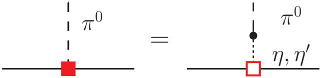
Calculating the Coupling Constants:

- $\delta M_{np}^{em} \quad \rightarrow \quad \delta M_{np}^{str} = (2.6 \pm 0.5)\text{MeV}$ — Walker-Loud et al. (2012)

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

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

  2 $\epsilon_{\tilde{\eta}\pi^0} \sim M_\pi^4/(M_{\tilde{\eta}}{}^2 - M_\pi^2) \quad \leftarrow \quad m_{\bar{u}u+\bar{d}d} \sim 711\text{MeV} < M_{\tilde{\eta}} < M_{\eta'}$



$$\longrightarrow g_1^\theta = (0.0035 \pm 0.0018)\bar{\theta}$$

J.B. et al. arXiv:1209.6306

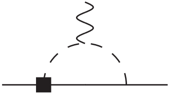
$$\text{NDA: } \frac{g_1^\theta}{g_0^\theta} \sim \epsilon \frac{M_\pi^2}{m_N^2} \sim -0.01 \quad \longleftrightarrow \quad \boxed{\frac{g_1^\theta}{g_0^\theta} = -0.20 \pm 0.13 \sim \frac{M_\pi}{m_N}}$$

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

θ-Term Induced Nucleon EDM:

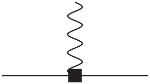
single nucleon EDM:

Ottnad et al. (2010)



"controlled"

isovector $\approx$ $\ll$ isoscalar

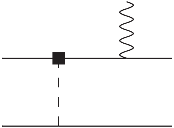


undetermined

$\longrightarrow$ lattice QCD required

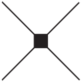
two nucleon EDM:

Sushkov, Flambaum, Khriplovich (1984)



controlled

$\gg$

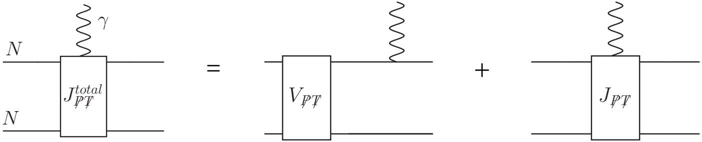


unknown coefficient

EDM of the Deuteron:

note:  $= \frac{ie}{2}(1+\tau_3)$

2N-system: $I + S + L$=odd



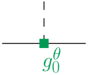
total current	irred. potential	irred. current
${}^3S_1 \longrightarrow {}^3S_1$	${}^3S_1 \rightarrow {}^3P_1 \rightarrow {}^3S_1$	${}^3S_1 \longrightarrow {}^3S_1$
$\mathrm{I}=0 \qquad \mathrm{I}=0$	$\mathrm{I}=0 \rightarrow \mathrm{I}=1 \rightarrow \mathrm{I}=0$	$\mathrm{I}=0 \qquad \mathrm{I}=0$

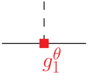
non vanishing contributions to the deuteron EDM from:

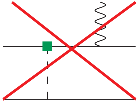
- isospin anti-symmetric and spin symmetric irreducible potentials
- isospin symmetric and spin symmetric irreducible currents

Power Counting: Deuteron

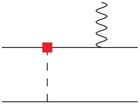
Note: $4\pi F_\pi \sim m_N$





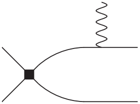


$$\frac{g_0^\theta}{F_\pi M_\pi}\,\frac{m_N}{M_\pi^2}\,e = g_0^\theta\,\frac{e m_N}{M_\pi^3 F_\pi}$$



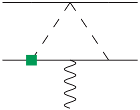
$$\frac{g_1^\theta}{F_\pi M_\pi}\,\frac{m_N}{M_\pi^2}\,e = g_0^\theta\,\frac{e}{M_\pi^2 F_\pi}$$

$\sim LO$



$$[g_0^\theta]\,\frac{M_\pi}{F_\pi m_N^2}\,\frac{m_N}{M_\pi^2}\,e$$

$\sim NLO$



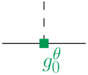
$$\frac{g_0^\theta e}{M_\pi^5}\,\frac{M_\pi^4}{(4\pi)^2} = g_0^\theta\,\frac{e}{M_\pi m_N F_\pi}$$

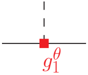
$\sim N^2LO$

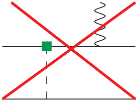
J.B. et al.:1209.6306

Power Counting: Deuteron

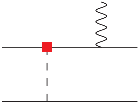
Note: $4\pi F_\pi \sim m_N$







$$\frac{g_0^\theta}{F_\pi M_\pi}\,\frac{m_N}{M_\pi^2}\,e = g_0^\theta\,\frac{e m_N}{M_\pi^3 F_\pi}$$



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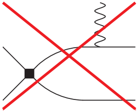
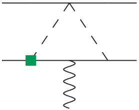
$\sim LO$



$$[g_0^\theta]\,\frac{M_\pi}{F_\pi m_N^2}\,\frac{m_N}{M_\pi^2}\,e$$

$\sim$ ~~NLO~~ $\rightarrow N^3LO$



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$\sim N^2LO$

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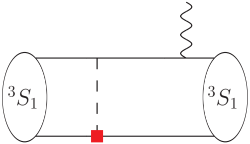
EDM of the Deuteron at LO:



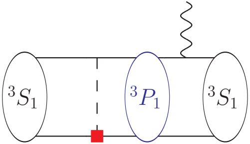
$g_1^\theta N^\dagger \pi_3 N$: $\not{C}\not{P}$, $\not{I}$

in g_1^θ e · fm · $(g_A\, m_N/F_\pi)$

State	CDBonn [U] (3)	Reid93 [U] (3)	AV18 [U] (2)	ZRA [U] (1)
$^3S_1$	$-1.46\cdot 10^{-2}$			
$^3D_1$-adm.	$-0.48\cdot 10^{-2}$			
Total	$-1.94\cdot 10^{-2}$	$-1.92\cdot 10^{-2}$		$-1.8\cdot 10^{-2}$

(1): Khriplovich,Korkin (2000),de Vries et al.(2011); (2): Liu,Timmermans (2004)
(3): Afnan,Gibson (2004); (4): J.B. et al. arXiv:1209.6306

EDM of the Deuteron at LO:



$g_1^\theta N^\dagger \pi_3 N$: $\not{CP}$, $\not{I}$

in $g_1^\theta\, \mathrm{e} \cdot \mathrm{fm} \cdot (g_A\, m_N / F_\pi)$

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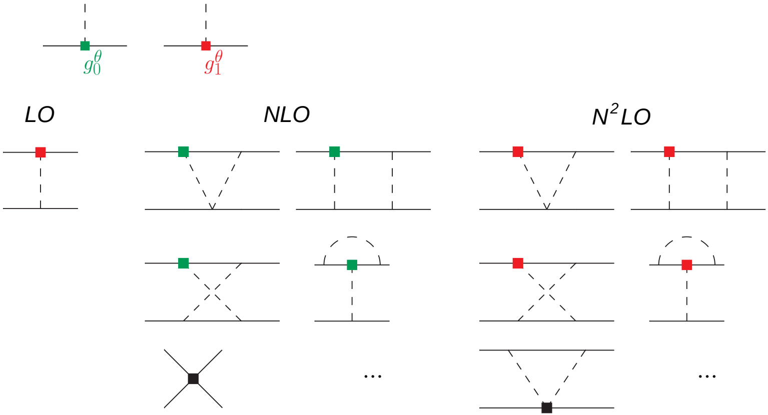
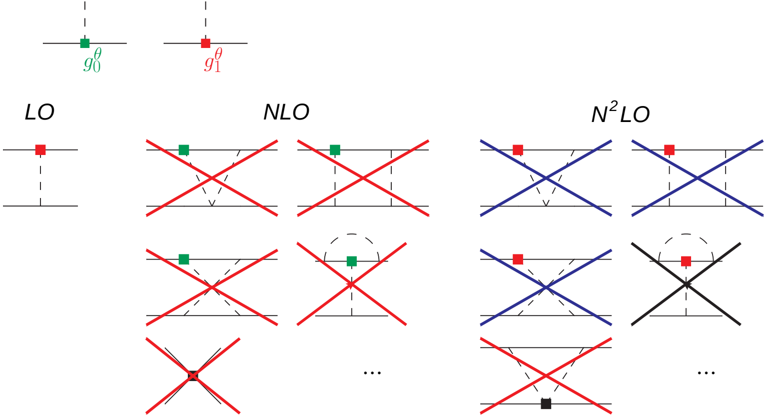
$^3D_1$-adm.	$-0.48 \cdot 10^{-2}$			
Total	$-1.94 \cdot 10^{-2}$	$-1.92 \cdot 10^{-2}$		$-1.8 \cdot 10^{-2}$
$^3P_1$-int.	$0.43 \cdot 10^{-2}$	$0.39 \cdot 10^{-2}$		
Total	$-1.51 \cdot 10^{-2}$	$-1.52 \cdot 10^{-2}$	$-1.43 \cdot 10^{-2}$	

(1): Khriplovich,Korkin (2000),de Vries et al.(2011); (2): Liu,Timmermans (2004)
(3): Afnan,Gibson (2004); (4): J.B. et al. arXiv:1209.6306

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

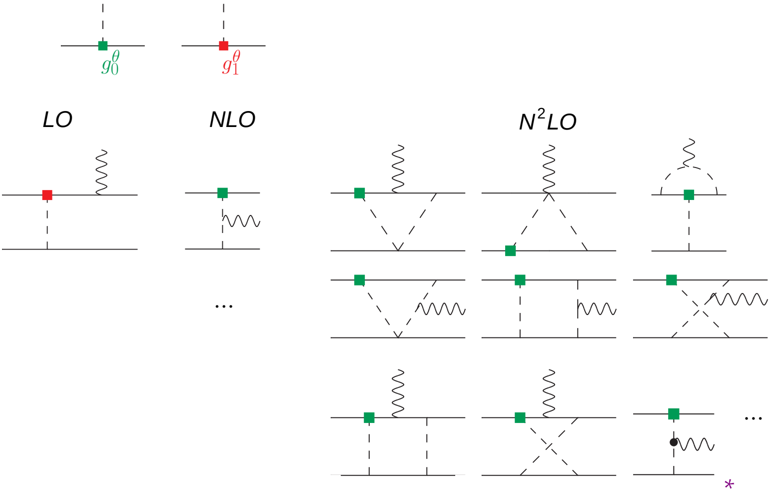


EDM of the Deuteron: *NLO*- and N^2LO-Potentials



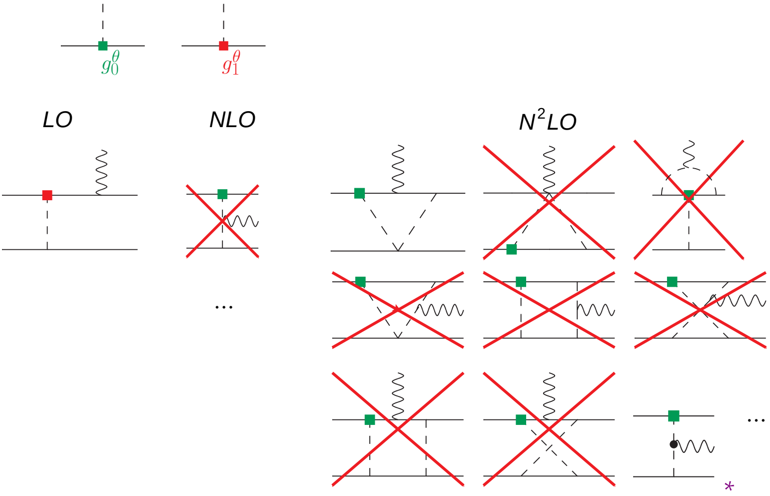
- ×: vanishing by selection rules, ×: sum of diagrams vanishes
  ×: vertex correction

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



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

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



*: de Vries et al. (2011)

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

assumption: $\bar{\theta}$-term dominating $\not{CP}$-mechanism

total deuteron EDM d_D:

$$d_D = d_n + d_p + d_D(2N)$$

- single-nucleon contribution: EFT has no predictive power
  $\longrightarrow$ experiment or lattice QCD needed

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

$$d_D(2N) = \underbrace{-(6.9 \pm 3.7) \cdot 10^{-4} \bar{\theta}\, e\, fm}_{\text{LO}} + \underbrace{(0.6 \pm 0.3) \cdot 10^{-4} \bar{\theta}\, e\, fm}_{\text{N}^2\text{LO}}$$

testing procedures:

- strategy 1: measure d_D, d_n, d_p $\rightarrow$ $d_D(2N) : \bar{\theta}$ $\leftrightarrow$ $d_{^3He}$
- strategy 2: measure d_n or d_p + Lattice-QCD $\rightarrow \bar{\theta} \rightarrow d_D$

If $\bar{\theta}$-term tests fail:

see talks of U. van Kolck and J. de Vries

effective dim. 6 sources:

qEDM *qCEDM* *gCEDM* 4 – *quark*

- $d_D - d_n - d_p$ is much larger than $\bar{\theta}$-test

  → *qCEDM* dominates (NDA)

- $d_D - d_n - d_p$ much smaller than $\bar{\theta}$-test

  → ~~$\bar{\theta}$*EDM*~~, ~~*qCEDM*~~

- $d_D \approx d_n + d_p$ → *qEDM*

measurements of d_n- ,d_p- ,d_D- and $d_{^3He}$ required
to further disentangle ~~*CP*~~ sources