Electric Dipole Moments of Light Nuclei

Spin Physics Workshop 2012

26.06.2012 | Jan Bsaisou

Motivation:

Matter-Antimatter Asymmetry

- Sakharov Conditions:

  JETP Lett.5 (1967) 24

  1. baryon number violation
  2. *C*- and *CP*(*T*)-symmetry violation
  3. no thermal equilibrium

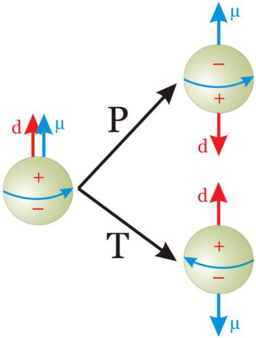
- observed asymmetry: $(n_B - n_{\bar{B}})/n_\gamma = 6 \cdot 10^{-10}$
  Standard Model prediction: $(n_B - n_{\bar{B}})/n_\gamma = 10^{-18}$
- Investigation of *CP*-violation from SM extensions required
- Complementary approaches:

  high energy ↔ high precision

Outline:

1. The EDM
2. CP-Violating Sources beyond the Standard Model
3. CP-Violating Sources on the Nuclear Level
4. Electric Dipole Moments of Nucleons
5. Electric Dipole Moments of the Deuteron at Leading and Sub-leading Order
6. Conclusions

The Electric Dipole Moment (EDM)



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

$$H = \mu\vec{\sigma} \cdot \vec{B} + d\vec{\sigma} \cdot \vec{E}$$

T: $H = \mu\vec{\sigma} \cdot \vec{B} - d\vec{\sigma} \cdot \vec{E}$

P: $H = \mu\vec{\sigma} \cdot \vec{B} - d\vec{\sigma} \cdot \vec{E}$

non vanishing EDM is
P- and T-violating

- Strongly suppressed in SM (CKM-matrix): $d_n \sim 10^{-31}$ e cm
- Current bounds: $d_n < 3 \cdot 10^{-26}$ e cm, $d_p < 8 \cdot 10^{-25}$ e cm

n: Baker et al.(2006), p: Dimitriev and Sen'kov (2005)*

* derived from Hg measurement

Griffith et al. (2009)

CP-violating sources beyond SM: dim. 4

Strong CP-violation

- Topologically non trivial structure of the vacuum

$$|\theta\rangle = \sum_{n=-\infty}^{\infty} e^{in\theta}|n\rangle$$

$\Rightarrow$ Vacuum characterised by fixed value of θ

- Leads to CP-violating term in QCD Lagrangian

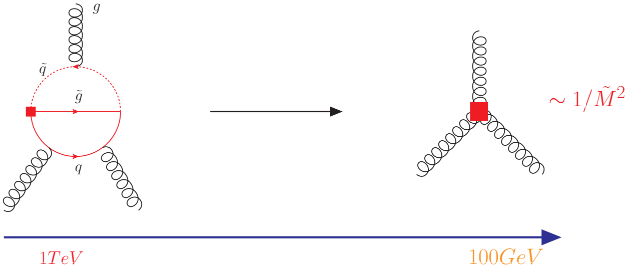
$$\mathcal{L} = \quad \ldots \quad + \theta \frac{g_S^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \quad \xrightarrow{U_A(1)} \quad \ldots + \bar{\theta} m^* \bar{q} i\gamma_5 q$$

$\Rightarrow$ θEDM:  $\qquad m^* = \frac{m_u m_d}{m_u + m_d}$

NDA: $\bar{\theta} \sim \mathcal{O}(1)$

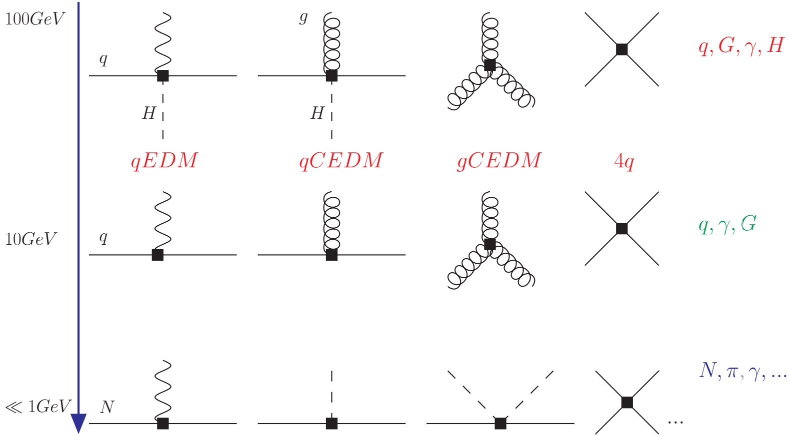
CP-violating sources beyond SM: dim. 6

- *CP*-violation from extensions of the standard model
  $\Rightarrow$ SUSY, multi-Higgs,...
- Treatment of SM as an effective field theory
  - Theory contains only relevant information at energies considered
  - Independence of a particular extension of the SM



CP-violating sources beyond SM: dim. 6

effective dimension-6 sources



Effective *CP*-violating sources on the hadronic level:

Non perturbative techniques required: e.g. 2-flavour-ChPT

J.DeVries et.al. (2010,2011)

C.Hanhart, A.Wirzba, J.B. (2012,in preparation)

- Symmetries of QCD preserved by the effective field theory
- Association of terms by chiral transformation properties

hadronic operator	θ	qEDM 1	qEDM τ_3	qCEDM 1	qCEDM τ_3	gCEDM 4q
$N^\dagger \vec{\tau} \cdot \vec{\pi} N$	$\surd$	–	–	$\surd$	–	($\surd$)
$N^\dagger \pi_3 N$	–	–	–	–	$\surd$	($\surd$)
$N^\dagger S^\mu v^\nu N F_{\mu\nu}$	$\surd$	$\surd$	–	$\surd$	$\surd$	$\surd$
$N^\dagger S^\mu v^\nu \tau_3 N F_{\mu\nu}$	$\surd$	–	$\surd$	$\surd$	$\surd$	$\surd$

($\surd$): Suppresed by Goldstone theorem

All sources contribute to nucleon EDMs

Measurement of nuclear EDMs required for disentanglement!

θ-term on the hadronic level:

θ-term related to chiral symmetry breaking mass term:

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

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

$$\frac{m_u - m_d}{2}\bar{q}\tau_3 q \quad \longleftrightarrow \quad m^*\bar{\theta}\bar{q}i\gamma_5 q$$

$$\downarrow \qquad\qquad \downarrow$$

$$\frac{\delta M_{str}}{2} N^\dagger \left(\tau_3 - \frac{1}{2F_\pi^2}\vec{\tau}\cdot\vec{\pi}\pi_3\right) N \quad \longleftrightarrow \quad \frac{\delta M_{str}}{2}\frac{(1-\epsilon^2)\bar{\theta}}{2F_\pi^2\epsilon} N^\dagger \vec{\tau}\cdot\vec{\pi} N$$

$$\delta M_{str} = (M_n - M_p)_{str}$$

Non-perturbative part of πNN-vertex fixed by CSB studies:

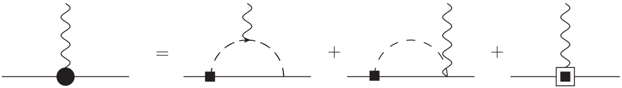
$$\delta M_{str} = (2.0 \pm 0.3)\text{MeV}^*$$

*Gasser, Leutwyler (1982)

Nucleon EDM: θ-term

Complete 1-loop calculation

Ottnad, Kubis, Meißner & Guo, PLB **687** (2010) 42



$$d_n = d_n^{\text{tree}} + d_n^{\text{loop}} = ([2.9 \pm 1.1] + [(-3 \cdots -5) \pm 2]) \times 10^{-16} \bar{\theta}\, e\,\text{cm}$$

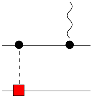
$\Rightarrow \quad \bar{\theta} < 3 \times 10^{-10}$ (using $d_n < 3 \times 10^{-26}\, e\,\text{cm}$)

- EDM of p and n not related by isovector symmetry
- Counter term at LO: estimate is model dependent
  $\Rightarrow$ Lattice calculation required for reliable prediction

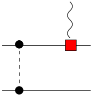
Nuclear EDMs might be larger

Nuclear EDM

for gCEDM and 4q; changes for θ-term and qCEDM in [..];

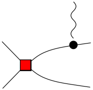


$\frac{e\delta q}{f_\pi}\frac{1}{m_\pi^2}\frac{1}{E}\frac{m_\pi^2}{\Lambda f_\pi}\,[\times 1]$ $\quad\sim 1\ [1]$

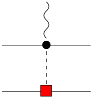


$\frac{e\delta q}{\Lambda}\frac{1}{E}\frac{1}{f_\pi^2}\left[\times\frac{m_\pi^2}{\Lambda^2}\right]$ $\quad\sim 1\ \left[\ln\left(\frac{m_\pi^2}{\mu^2}\right)\frac{m_\pi^2}{\Lambda^2}+C\right]$

Sushkov, Flambaum, Khriplovich (1984)



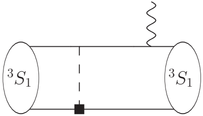
$\frac{e\delta q}{\Lambda}\frac{1}{E}\frac{1}{f_\pi^2}\left[\times\frac{m_\pi^2}{\Lambda^2}\right]$ $\quad\sim 1\ \left[\frac{m_\pi^2}{\Lambda^2}\right]$



$\frac{e\delta q}{f_\pi M}\frac{1}{m_\pi^2}\frac{m_\pi^2}{\Lambda f_\pi}\,[\times 1]$ $\quad\sim \frac{E}{\Lambda}\ \left[\frac{E}{\Lambda}\right]$

pion ranged operators enhanced for θ-term and qCEDM

EDM of the Deuteron at LO:



 $= ie(1+\tau_3)$

$N^\dagger \vec{\pi}\cdot\vec{\tau}N: \quad {}^3S_1 \xrightarrow{\not{CP}} {}^1P_1 \xrightarrow{\gamma} {}^3\not{S}_1$

$N^\dagger \pi_3 N \quad : \quad {}^3S_1 \xrightarrow{\not{CP}} {}^3P_1 \xrightarrow{\gamma} {}^3S_1$

$\Rightarrow$ No θEDM contribution to ^2H at LO
θEDM contribution to ^3He at LO

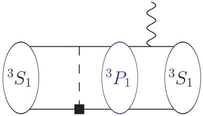
in e fm $G_\pi^{(1)}$

State	CDBonn [U] (3)	AV18 [U] (3)	Reid93 [U] (2)	ZRA [U] (1)
$^3S_1$	$-1.46\cdot10^{-2}$	$-1.41\cdot10^{-2}$		
$^3D_1$-adm.	$-0.48\cdot10^{-2}$	$-0.49\cdot10^{-2}$		
Total	$-1.94\cdot10^{-2}$	$-1.91\cdot10^{-2}$	$-1.92\cdot10^{-2}$	$-1.8\cdot10^{-2}$

(1): Khriplovich,Korkin (2000), J. de Vries et al.(2011)

(2): Afnan,Gibson (2010) (3): Hanhart,Wirzba,Nogga,Liebig,J.B. (2012,in prep.)

EDM of the Deuteron at LO:



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$N^\dagger \vec{\pi} \cdot \vec{\tau} N$: $\quad {}^3S_1 \xrightarrow{\not{CP}} {}^1P_1 \xrightarrow{\gamma} {}^3\not{S}_1$

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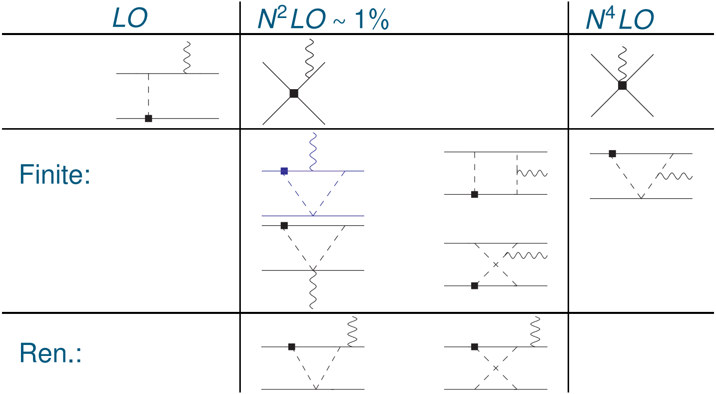
Total	$-1.94 \cdot 10^{-2}$	$-1.91 \cdot 10^{-2}$	$-1.92 \cdot 10^{-2}$	$-1.8 \cdot 10^{-2}$
$^3P_1$-int.	$0.43 \cdot 10^{-2}$		$0.39 \cdot 10^{-2}$	
Total	$-1.51 \cdot 10^{-2}$		$-1.52 \cdot 10^{-2}$	

(1): Khriplovich,Korkin (2000), J. de Vries et al.(2011)
(2): Afnan,Gibson (2010) (3): Hanhart,Wirzba,Nogga,Liebig,J.B. (2012,in prep.)

EDM of the Deuteron at NLO:


$=N^\dagger \pi_3 N$ (qCEDM)

Hanhart,Wirzba,J.B. (2012,in prep.)



- All other topologies yield no EDM contribution, blue: also θEDM contr.
- Consistent power counting scheme

Conclusions:

source	θ	*qEDM* 1	*qEDM* τ_3	*qCEDM* 1	*qCEDM* τ_3	*gCEDM* 4q
p	√	√	√	√	√	√
n	√	√	√	√	√	√
^2H					√	√
^3He	√			√	√	√

- EDMs are ideal probes for CP violation in the hadronic sector
- EDMs of light nuclei provide independent information to p and n
- EDMs of light nuclei may be larger than nucleon EDMs
- qEDM dominates if nuclear EDM is sum of nucleon EDMs
- Nuclear calculation possible up to accuracy of a few %
- θEDM: $^3He \Leftrightarrow \bar{\theta} \Leftrightarrow$ p-,n-EDM

A measurement of *p*, *n*, *d*, and ^{3}He EDM is necessary to learn about the underlying physics