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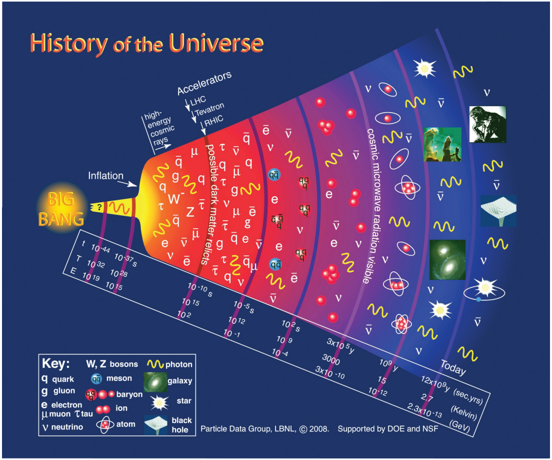
JÜLICH FORSCHUNGSZENTRUM

Electric dipole moment of the nucleon and light nuclei

Hirschegg | January 14, 2014 | Andreas Wirzba

Matter Excess in the Universe



1 End of inflation: $n_B = n_{\bar{B}}$

2 Cosmic Microwave Bkgr.

- SM(s) *prediction:* $(n_B - n_{\bar{B}})/n_\gamma|_{\rm CMB} \sim 10^{-18}$
- WMAP+COBE (2012): $n_B/n_\gamma|_{\rm CMB} = (6.08 \pm 0.09)10^{-10}$

Sakaharov conditions ('67)
for dyn. generation of net B:

1 B violation to depart from initial B=0

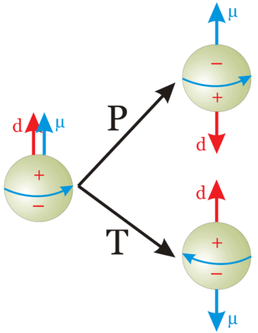
2 C & CP violation

to distinguish B and $\bar{B}$ production rates

3 non-equilibrium

to escape $\langle B \rangle$=0 if CPT holds

The Electric Dipole Moment (EDM)



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 some subatomic particle violates P & T

- Assuming CPT to hold, CP is violated as well
  ↪ subatomic EDMs: “rear window” to CP violation in early universe
- Strongly suppressed in SM (CKM-matrix): $d_n \sim 10^{-31}\, e\,\mathrm{cm}$, $d_e \sim 10^{-38}\, e\,\mathrm{cm}$
- Current bounds: $d_n < 3 \cdot 10^{-26}\, e\,\mathrm{cm}$, $d_p < 8 \cdot 10^{-25}\, e\,\mathrm{cm}$, $d_e < 1 \cdot 10^{-28}\, e\,\mathrm{cm}$

n: Baker et al. (2006), p prediction: Dimitriev & Sen’kov (2003)*, e: Baron et al. (2013)†

* input from ^{199}Hg atom EDM measurement of Griffith et al. (2009) † from ThO molecule measurement

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

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

- CP & P conserving magnetic moment $\sim$ 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 $\sim 10^{-7}$

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

  and 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: $\boxed{d_N \sim 10^{-7} \times 10^{-3} \times \mu_N \sim 10^{-24}\, e\,\mathrm{cm}}$

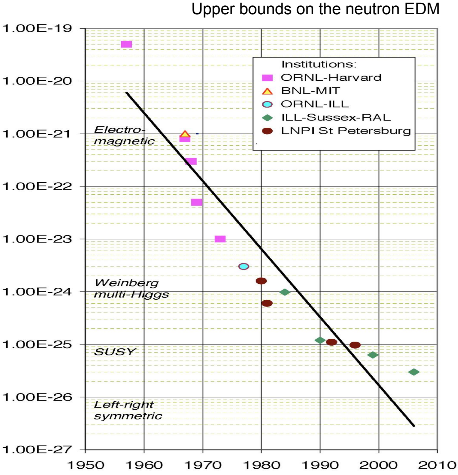
- In SM (without θ term): extra $G_F m_\pi^2$ factor to undo flavor change

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

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

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

Chronology of upper bounds on the neutron EDM



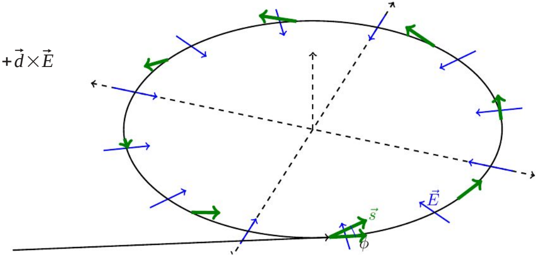
Smith, Purcell, Ramsey (1957) .... Baker et al. (2006)

$\hookrightarrow$ 5 to 6 orders above SM predictions which are out of reach !

Search for EDMs of charged particles in storage rings

General idea:

$$\frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$



Initially longitudinally polarized particles interact with radial $\vec{E}$ field
$\hookrightarrow$ build-up of vertical polarization (measured with a polarimeter)

The spin precession relative to the momentum direction is given by the Thomas-BMT equation (for $\vec{\beta} \cdot \vec{B} = 0,\ \vec{\beta} \cdot \vec{E} = 0,\ \vec{E} \cdot \vec{B} = 0$):

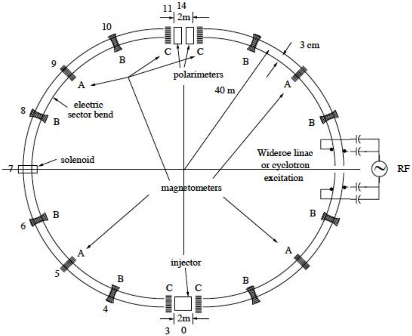
$$\frac{d\vec{S}^*}{dt} = \vec{\Omega} \times \vec{S}^* \quad \text{with} \quad \vec{\Omega} = -\frac{e}{m}\left(a\vec{B} + \left(\beta^{-2} - 1 - a\right)\vec{\beta} \times \vec{E} + \eta(\vec{E} + \vec{\beta} \times \vec{B})\right)$$

$$\text{and} \quad \vec{\mu} = (1 + a)\frac{e}{2m}\vec{S}/S \quad \text{and} \quad \vec{d} = \eta\frac{e}{2m}\vec{S}/S$$

Method 1: pure electrostatic ring

$$\vec{\Omega} = -\frac{e}{m}\left(\cancel{a\vec{B}} + \underbrace{\left(\beta^{-2} - 1 - a\right)\vec{\beta}\times\vec{E}}_{:=0,\ \text{“Frozen spin method”}} + \eta\left(\vec{E} + \cancel{\vec{\beta}\times\vec{B}}\right)\right) \longrightarrow -\frac{e}{m}\eta\vec{E}$$

only possible for $a > 0$, *i.e.* for p and ^{3}H, but not for d or ^{3}He



Advantages:

– no magnetic field

– counter rotating beams possible

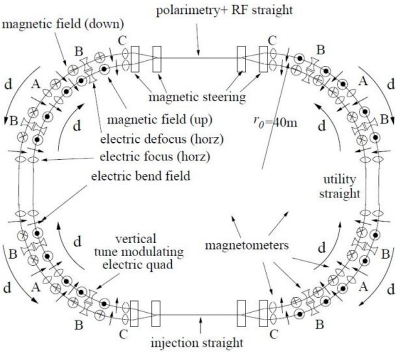
Disadvantage:

– not possible for deuterons ($a_D < 0$)

BNL or Fermilab?

Method 2: combined electric & magnetic ring

$$\vec{\Omega} = -\frac{e}{m}\left(\underbrace{a\vec{B} + \left(\beta^{-2} - 1 - a\right)\vec{\beta}\times\vec{E}}_{:=0,\ \text{“Frozen spin method”}} + \eta(\vec{E} + \vec{\beta}\times\vec{B}) \right) \rightarrow -\frac{e}{m}\eta(\vec{E} + \vec{\beta}\times\vec{B})$$



Advantage:

– works for p, deuterons and ^{3}He

Disadvantages:

– requires also magnetic fields

– two beam pipes

– magnetic coils made of copper

Jülich ?

Method 3: pure magnetic ring

$$\vec{\Omega} = -\frac{e}{m}\left(\underbrace{a\vec{B}}_{\text{precession in beam plane}} + \cancel{\left(\frac{1}{\beta^2} - 1 - a\right)\vec{\beta}\times\vec{E}} + \eta(\cancel{\vec{E}} + \underbrace{\vec{\beta}\times\vec{B}}_{\text{+ Wien filter: accumulation of vertical spin}}) \right)$$

→ "rigged roulette route"

Advantage:

– existing COSY accelerator

↪ precursor experiment:

First *direct* measurement of an EDM of a charged hadron

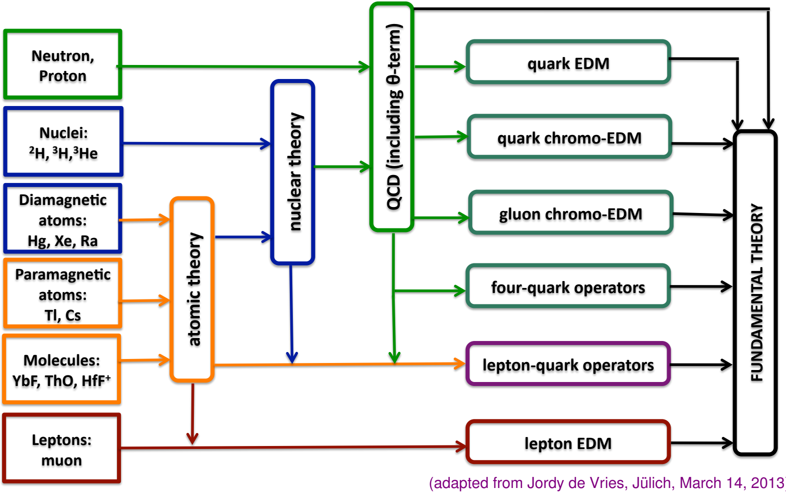
Disadvantage:

– low sensitivity $\gtrsim 10^{-25}\, e\,\mathrm{cm}$

JEDI@Jülich !

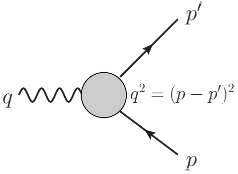
Road map from EDM Measurements to EDM Sources

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



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

EDMs of nucleons and light nuclei



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

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

Dirac $F_1(q^2)$, Pauli $F_2(q^2)$, electric dipole $F_3(q^2)$, anapole $F_a(q^2)$ FFs (here s=1/2 fermion)

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

Outline:

- CP-violation beyond CKM matrix of the SM: $\mathcal{L}_{QCD}$ θ-term (dim. 4):
  $\rightsquigarrow$ testing the $\bar\theta$-term with EDMs of the nucleon, deuteron and He-3
- CP-violation from physics beyond SM: SUSY, multi-Higgs $\cdots$ (dim. 6):
  $\rightsquigarrow$ disentangling $\not{CP}$ sources

Jülich-Bonn Collaboration (JBC):

Eur. Phys. J. A 49 (2013) 31 [arXiv:1209.6306]

J. Bsaisou, C. Hanhart, S. Liebig, U.-G. Meißner, D. Minossi, A. Nogga, J. de Vries, A.W

The $\mathcal{L}_{\text{QCD}}$ θ-term in the SM

topologically non-trivial vacuum $\rightarrow$ $\cancel{CP}$ term in $\mathcal{L}_{QCD}$:

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

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

with $\bar{\theta} = \theta + \arg \operatorname{Det} \mathcal{M}$, $\mathcal{M}$: quark mass matrix, $m_q^* \equiv \frac{m_u m_d}{m_u + m_d}$

$$d_n^{\bar{\theta}} \sim \bar{\theta} \cdot \frac{m_q^*}{\Lambda_{QCD}} \cdot \frac{e}{2m_n} \sim \bar{\theta} \cdot 10^{-2} \cdot 10^{-14}\, e\,\text{cm} \sim \bar{\theta} \cdot 10^{-16}\, e\,\text{cm} \quad \text{with } \bar{\theta} \overset{\text{NDA}}{\sim} \mathcal{O}(1).$$

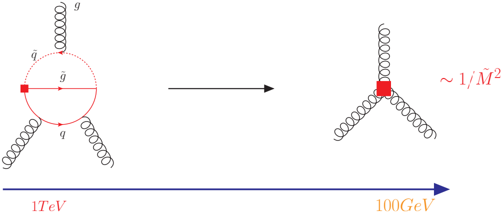
$$d_n^{emp} < 2.9 \cdot 10^{-26}\, e\,\text{cm} \rightsquigarrow \boxed{|\bar{\theta}| \lesssim 10^{-10}} \text{ strong CP problem}$$

New Physics Beyond Standard Model (BSM)

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

Effective field theory approach:

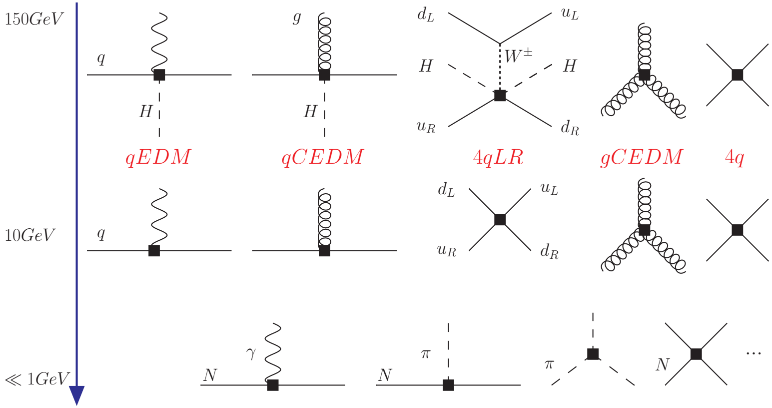
- All degrees of freedom beyond specified scale are integrated out:
  $\hookrightarrow$ Only SM degrees of freedom remain: q, g, H, $W^{\pm}$,...
- Write down *all* interactions among these degrees of freedom that respect the SM + Lorentz symmetries: here dim. 6 or higher order
- Relics of eliminated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



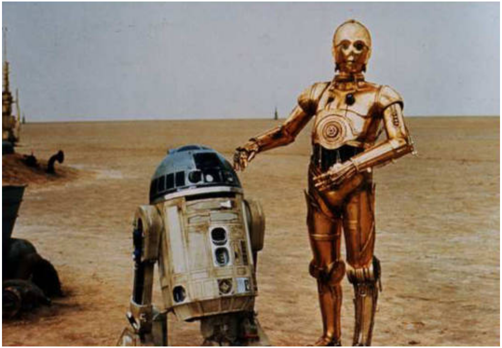
- Need a power-counting scheme to order these infinite # interactions

SM plus all possible T- and P-odd *contact* interactions

Removal of Higgs & $W^{\pm}$ bosons, then transition to hadronic fields (+ mixing):



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



$\hookrightarrow$

Symmetries (esp. chiral one) and Goldstone Theorem
Low-Energy Effective Field Theory with External Sources
i.e. Chiral Perturbation Theory (suitably extended)

Scalings of $\cancel{CP}$ hadronic vertices (from θ and BSM sources)

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

$\mathcal{L}^{\cancel{CP}}_{\text{EFT}}$:

	g_0: $\cancel{CP}$, I	g_1: $\cancel{CP}$, $\cancel{I}$	d_0, d_1: $\cancel{CP}$, I + $\cancel{I}$	$C_{3\pi}$: $\cancel{CP}$, $\cancel{I}$
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 on the Hadronic Level

hadronic level: non perturbative techniques required: *e.g.* 2-flavor *ChPT*

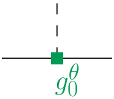
- Symmetries of QCD preserved by the effective field theory (EFT)

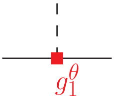
$$\mathcal{L}^{\theta}_{QCD} = -\bar\theta m_q^* \sum_f \bar q_f i\gamma_5 q_f : \quad \cancel{CP},\ \mathrm{I} \quad \Leftrightarrow \quad \mathcal{M} \to \mathcal{M} + \bar\theta m_q^* i\gamma_5 \qquad m_q^* = \frac{m_u m_d}{m_u+m_d}$$

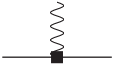
$$\cancel{CP},\ \mathrm{I} \qquad\qquad \cancel{CP},\ \cancel{\mathrm{I}} \qquad\qquad \cancel{CP},\ \mathrm{I} + \cancel{\mathrm{I}}$$

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

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







...

dominating for n, p & ^3He

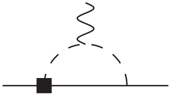
dominating for D

important for n, p

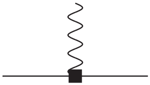
Lebedev et al. (2004), Mereghetti et al. (2010), Bsaisou et al. (2013)

θ-Term Induced Nucleon EDM

single nucleon EDM:



isovector $\approx$ $\ll$ isoscalar



"controlled"

two "unknown" coefficients

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

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

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

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

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

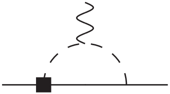
Ottnad et al. (2010); Bsaisou et al. (2013)

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

θ-Term Induced Nucleon EDM:

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

single nucleon EDM:



isovector

$\approx$

$\ll$

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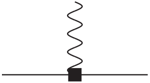
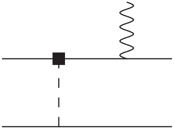


"controlled" "unknown" coefficients

$\longrightarrow$ lattice QCD required $\longrightarrow$ see *Eigo Shintani*'s talk

two nucleon EDM:

Sushkov, Flambaum, Khriplovich (1984)



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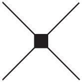

controlled unknown coefficient

θ-Term Induced Nucleon EDM:

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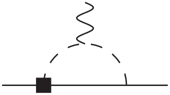
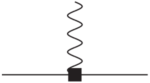


isovector $\approx$ $\ll$ isoscalar



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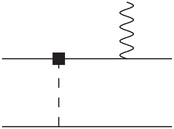

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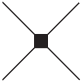
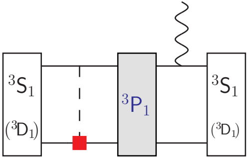


controlled unknown coefficient

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



LO: $\cancel{g_0^\theta N^\dagger \vec{\pi}\cdot\vec{\tau} N}$ $(\cancel{CP}, \mathrm{I}) \rightarrow 0$ (Isospin filter!)

NLO: $g_1^\theta N^\dagger \pi_3 N$ $(\cancel{CP}, \cancel{\mathrm{I}})$ $\rightarrow$ "LO" in D case

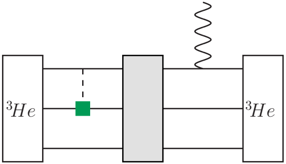
in units of $g_1^\theta\ \mathrm{e}\cdot\mathrm{fm}\cdot(g_A\, m_N/F_\pi)$

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 $(N^2LO)^\dagger$	-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: g_1 πNN term is the *LO vertex* in qCEDM or 4qLR case

^3He EDM: quantitative results for g_0 exchange



$g_0 N^\dagger \vec{\pi} \cdot \vec{\tau} N \quad (\cancel{CP}, \mathrm{I})$

θ-term, qCEDM $\rightarrow$ LO

4qLR $\rightarrow$ N^{2}LO

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

author	potential	no int.	with int.	total
JBC (2013)*	Av_{18}UIX	-0.45×10^{-2}	-0.12×10^{-2}	-0.57×10^{-2}
JBC (2013)*	CD BONN TM	-0.56×10^{-2}	-0.12×10^{-2}	-0.68×10^{-2}
JBC (2013)*	ChPT (N^2LO)†	-0.56×10^{-2}	-0.19×10^{-2}	-0.76×10^{-2}
Song (2013)	Av_{18}UIX	-	-	-0.55×10^{-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 !

Quantitative EDM results in the θ-term scenario

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

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

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

Deuteron:

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

Helium-3:

$$d_{^3He} = \tilde{d}_n + \left[(1.78 \pm 0.83) - (0.43 \pm 0.30)\right] \cdot 10^{-16}\,\bar{\theta}\,e\,\text{cm}$$
$$= \tilde{d}_n + (1.35 \pm 0.88) \cdot 10^{-16}\,\bar{\theta}\,e\,\text{cm} \qquad \text{(JBC (2013))}$$

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

Testing Strategies in the θ EDM scenario

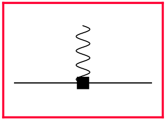
Remember:

$$
\begin{aligned}
d_D &= d_n + d_p - (0.54 \pm 0.39) \cdot 10^{-16}\, \bar{\theta}\, e\,\mathrm{cm} && \text{(Bsaisou et al. (2013))} \\
d_{^3He} &= \tilde{d}_n + (1.35 \pm 0.88) \cdot 10^{-16}\, \bar{\theta}\, e\,\mathrm{cm} && \text{(JBC (2013))}
\end{aligned}
$$

$\boxed{\text{Testing strategies:}}$

- 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)

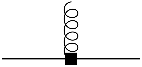
If $\bar{\theta}$-term tests fail: use effective BSM dim. 6 sources de Vries et al. (2011)



qEDM

$d_D \approx d_p + d_n$

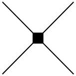
$d_{^3He} \approx d_n$



qCEDM

$d_D > d_p + d_n$

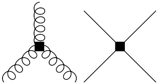
$d_{^3He} > d_n$



4qLR

$d_D > d_p + d_n$

$d_{^3He} > d_n$



gCEDM + 4qEDM

$d_D \sim d_p + d_n$

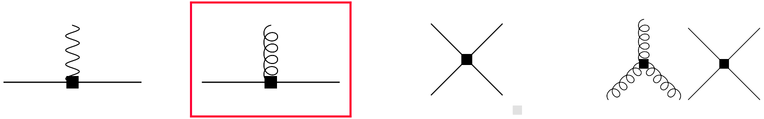
$d_{^3He} \sim d_n$

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

2N 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)



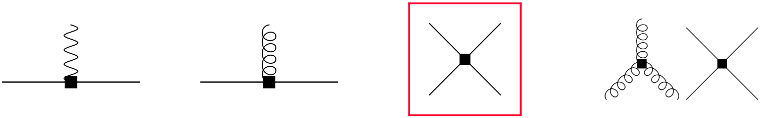
qEDM	qCEDM	4qLR	gCEDM + 4qEDM
$d_D \approx d_p + d_n$	$d_D > d_p + d_n$	$d_D > d_p + d_n$	$d_D \sim d_p + d_n$
$d_{^3He} \approx d_n$	$d_{^3He} > d_n$	$d_{^3He} > d_n$	$d_{^3He} \sim d_n$

$\longrightarrow$ g_0, g_1 dominant and of same order

2N contributions enhanced!

here: only absolute values considered

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



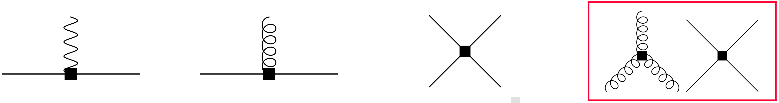
qEDM	*qCEDM*	*4qLR*	*gCEDM + 4qEDM*
$d_D \approx d_p + d_n$	$d_D > d_p + d_n$	$d_D > d_p + d_n$	$d_D \sim d_p + d_n$
$d_{^3He} \approx d_n$	$d_{^3He} > d_n$	$d_{^3He} > d_n$	$d_{^3He} \sim d_n$

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

$\not{I}$ $2N$ contribution enhanced!

here: only absolute values considered

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



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

$\longrightarrow$ g_1, g_0, $4N$ – coupling

$2N$ contribution difficult to asses!

here: only absolute values considered

Conclusions

- First non-vanishing EDM might be observed in charge-neutral systems: *neutrons* or *dia-/ paramagnetic atoms* or *molecules* $\cdots$
- However, measurements of light ion EDMs will play a key role in disentangling the sources of $\cancel{CP}$
- EDM measurements are characteristically of *low-energy nature:*
  $\hookrightarrow$ Predictions have to be in the empirical *language of hadrons*
  $\hookrightarrow$ only reliable methods: $\boxed{\textit{ChPT/EFT}}$ and (ultimately) $\boxed{\textit{Lattice QCD}}$ because the pertinent uncertainty estimates are inherent
- EDMs of light nuclei provide independent information to nucleon EDMs and may be even larger and, moreover, even simpler
- Deuteron & He-3 nuclei work as independent isospin filters of EDMs

> At least the EDMs of p, n, d, and ^{3}He are needed to disentangle the underlying physics

Many thanks to my colleagues

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in Bonn: Feng-Kun Guo, Bastian Kubis, Ulf-G. Meißner

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

- J. Bsaisou, C. Hanhart, S. Liebig, U.-G. Meißner, A. Nogga and A. Wirzba, *The electric dipole moment of the deuteron from the QCD θ-term,* Eur. Phys. J. A **49** (2013) 31 [arXiv:1209.6306 [hep-ph]].
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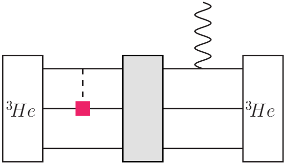
- F.-K. Guo and U.-G. Meißner, *Baryon electric dipole moments from strong CP violation,* JHEP **1212** (2012) 097 [arXiv:1210.5887 [hep-ph]].
- W. Dekens and J. de Vries, *Renormalization Group Running of Dimension-Six Sources ...,* JHEP **1305** (2013) 149 [arXiv:1303.3156 [hep-ph]].
- J. de Vries, R. Higa, C.-P. Liu, E. Mereghetti, I. Stetcu, R. Timmermans, U. van Kolck, *Electric Dipole Moments of Light Nuclei From Chiral Effective Field Theory,* Phys. Rev. C **84** (2011) 065501 [arXiv:1109.3604 [hep-ph]].

Backup slides

^3He EDM: quantitative results for g_1 exchange



$g_1 N^\dagger \pi_3 N$ $(\cancel{CP}, \cancel{I})$

θ-term $\rightarrow$ NLO

qCEDM, 4qLR $\rightarrow$ LO !

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

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 $(N^2LO)^\dagger$	-1.09×10^{-2}	$+0.14 \times 10^{-2}$	-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: $\cancel{CP}$ 3π-vertex contribution (4qLR: LO)

θ-term: $\cancel{CP}$ 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)

$$\boxed{g_0^\theta: \quad N^\dagger \vec{\pi}\cdot\vec{\tau} N\text{-vertex}}$$

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

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

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

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)

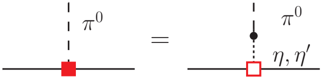
$\boxed{g_1^\theta: \quad \pi_3 NN\text{-vertex}}$

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

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

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

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



$$\longrightarrow \boxed{g_1^\theta = (0.003 \pm 0.002)\bar\theta}$$

Bsaisou et al. (2013)

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

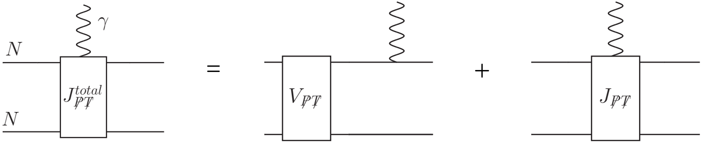
Bsaisou et al. (2013) de Vries et al. (2011)

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

EDM of the Deuteron:

Deuteron (D) as Isospin Filter

note:  $= \frac{ie}{2}(1+\tau_3)$ 2N-system: $I+S+L$=odd



total current irred. potential irred. current

I = 0 I = 0 I = 0 → I = 1 → I = 0 I = 0 I = 0

isospin selection rules!

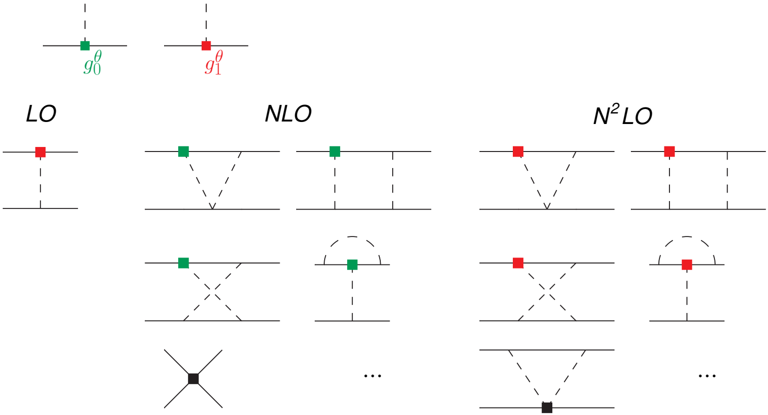
$\Downarrow$

$\cancel{g_0^\theta N^\dagger \vec{\pi}\cdot\vec{\tau} N}$ at leading order (LO)

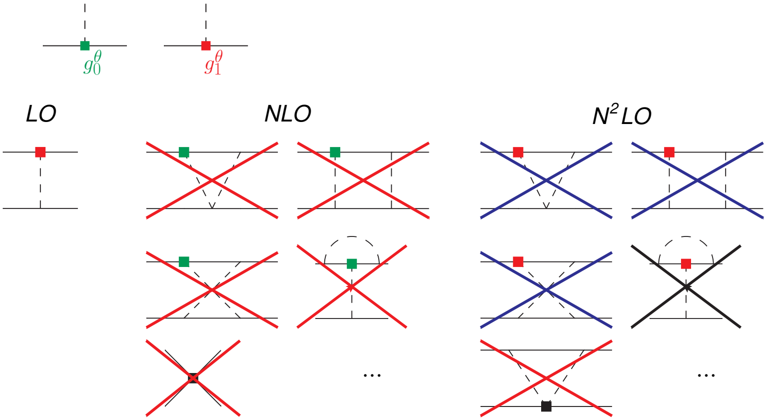
$\Downarrow$

subleading (NLO) $g_1^\theta N^\dagger \pi_3 N$ acts as *'new'* leading order (LO) for D

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

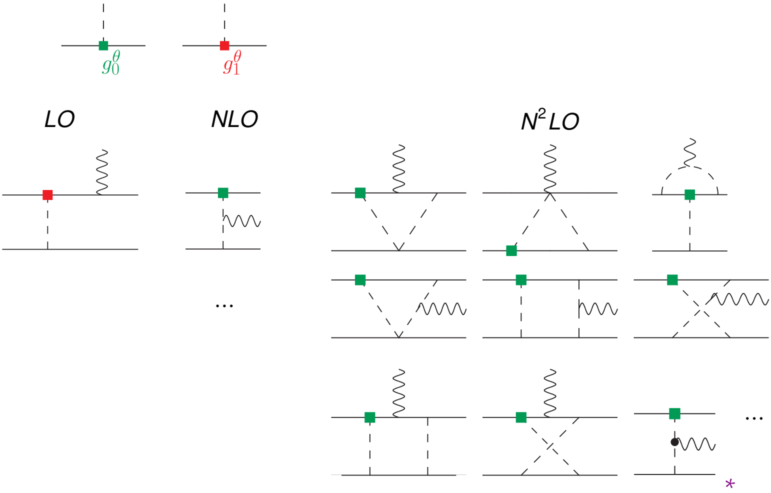


EDM of the Deuteron: *NLO*- and *N²LO*-Potentials



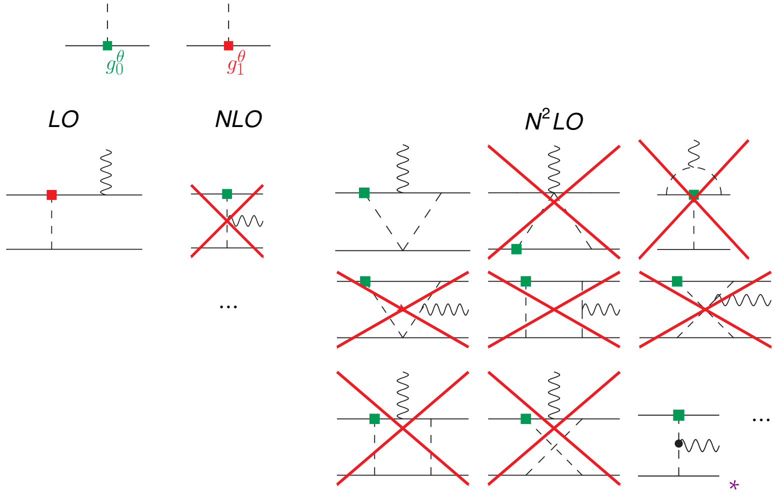
- ×: vanishing by selection rules, ×: sum of diagrams vanishes
  ×: vertex correction

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



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

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



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

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

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 $\cancel{CP}$ $NN\pi$ couplings may be accessible even for dim-6 sources

  $\hookrightarrow$ then *quantifiable* d_D ($d_{^3He}$) EFT predictions feasible in BSM case