Mitglied der Helmholtz-Gemeinschaft

JÜLICH FORSCHUNGSZENTRUM

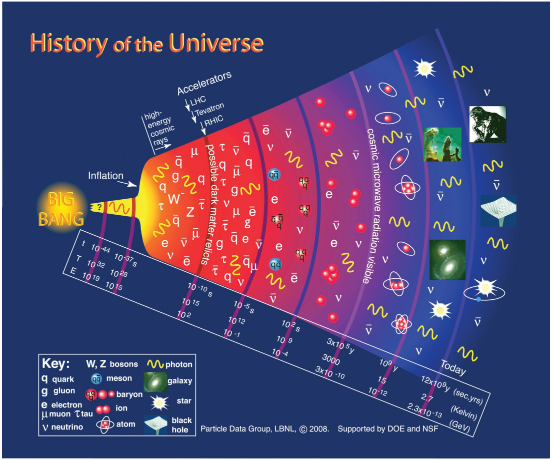
Electric dipole moments of the nucleon and light nuclei

Jülich-Bonn Collaboration (JBC)

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

Schleching | February 20, 2014 | Andreas Wirzba

Matter Excess in the Universe



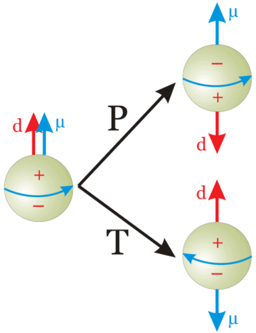
1. End of inflation: $n_B = n_{\bar{B}}$
2. Cosmic Microwave Bkgr.
   - SM(s) *prediction:* *
     $(n_B - n_{\bar{B}})/n_\gamma|_{\rm CMB} \sim 10^{-18}$
   - WMAP+COBE (2012):
     $n_B/n_\gamma|_{\rm CMB} = (6.08 \pm 0.09) 10^{-10}$

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

(*) $2J^{\rm CKM}_{\rm Jarlskog}(m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2) \sim 10^{-18} M_{\rm EW}^{12}$

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 a non-deg. (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): $|d_n| \sim 10^{-31} e\,\text{cm}$, $|d_e| \sim 10^{-38} e\,\text{cm}$
- Current bounds: $|d_n| < 3 \cdot 10^{-26} e\,\text{cm}$, $|d_p| < 8 \cdot 10^{-25} e\,\text{cm}$, $|d_e| < 1 \cdot 10^{-28} e\,\text{cm}$

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

* from $|d_{^{199}\text{Hg}}| < 3.1 \cdot 10^{-29} e\,\text{cm}$ bound of Griffith et al. (2009) † from polar ThO: $|d_{ThO}| \lesssim 10^{-21} e\,\text{cm}$

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

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

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

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

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

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

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

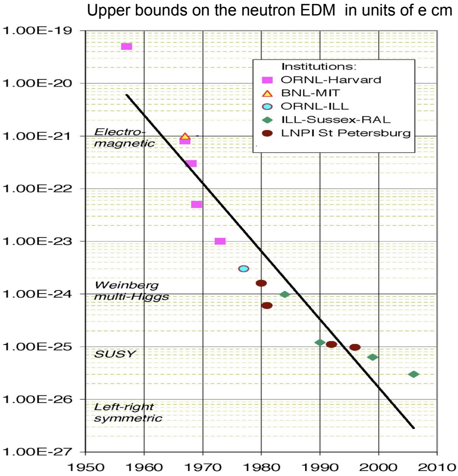
- In SM (without θ term): extra $G_F F_\pi^2$ factor to undo flavor change

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

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

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

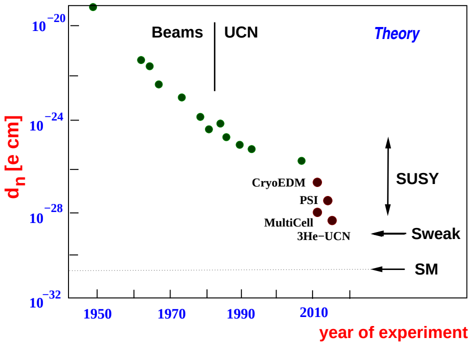
Chronology of upper bounds on the neutron EDM



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

↪ 5 to 6 orders above SM predictions which are out of reach !

Chronology of upper bounds on the neutron EDM



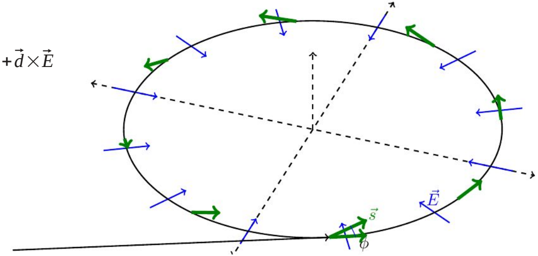
Smith, Purcell, Ramsey (1957) .... Baker et al. (2006)

↪ 5 to 6 orders above SM predictions which are out of reach !

Search for EDMs of charged particles in storage rings

General idea:

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



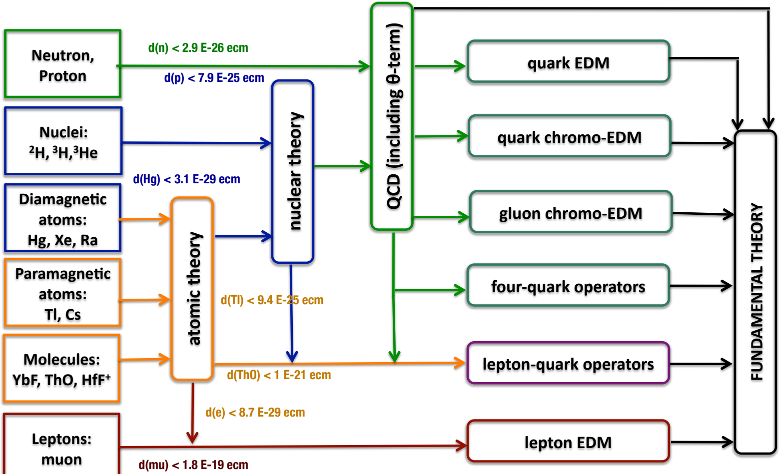
Initially longitudinally polarized particles interact with radial $\vec{E}$ field
↪ build-up of vertical polarization (measured with a polarimeter)

Proposed storage ring experiments ($\sim 10^{-29}\, e\,\text{cm}$):

- Counter-circling proton ring at Brookhaven (srEDM) or Fermilab (Project X) ?
- All-purpose ring for proton, deuteron (and helion) in Jülich (JEDI) ?
- ↪ Precursor experiment ($\gtrsim 10^{-25}\, e\,\text{cm}$) for p or D at COSY@Jülich !

Road map from EDM Measurements to EDM Sources

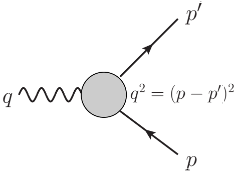
Experimentalist's point of view → ← Theorist's point of view



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

CP-conserving and -violating form factors and EDMs

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



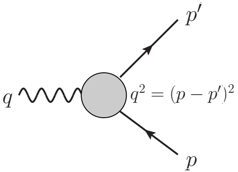
$$\Gamma^{\mu}(q^2) = \gamma^{\mu}F_1(q^2) - i\sigma^{\mu\nu}q_{\nu}\frac{F_2(q^2)}{2m_f} + \sigma^{\mu\nu}q_{\nu}\gamma_5\frac{F_3(q^2)}{2m_f} + (\not{q}\,q^{\mu} - q^2\gamma^{\mu})\gamma_5\frac{F_a(q^2)}{m_f^2}$$

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

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

CP-conserving and -violating form factors and EDMs

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



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

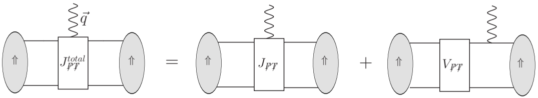
Dirac FF — Pauli FF — electric dipole FF ($\not{CP}$) — anapole FF ($\not{P}$)

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

Nucleus A

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

in Breit frame



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

EDM sources: QCD θ-term of the SM

QCD has topologically non-trivial vacuum $\rightarrow$ $\not{P}$ & $\not{T}$ term in $\mathcal{L}_{QCD}$:

$$\mathcal{L} = \mathcal{L}^{\mathrm{CP}}_{\mathrm{QCD}} + \theta \frac{g_S^2}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma} \qquad (\text{of dimension } 4)$$

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

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

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

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

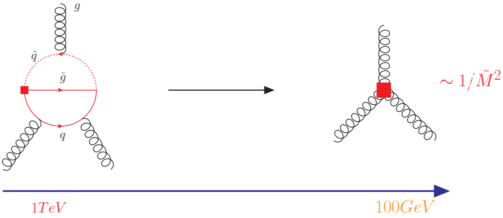
Note: $\not{P} \cdot \not{T}|_{emp} \overset{CPT}{:=} \not{P} \cdot \not{CP}|_{emp} \sim 10^{-10}$ (??)

More sources: New Physics (Beyond the Standard Model)

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

Evaluated in Effective Field Theory (EFT) approach:

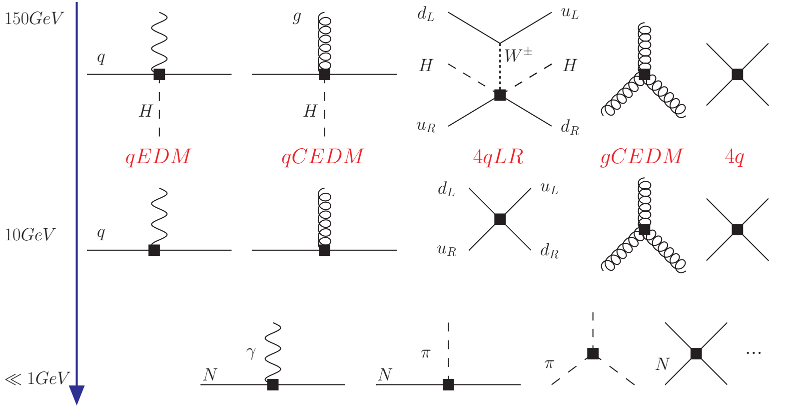
- All degrees of freedom *beyond NP (EW) scale* are integrated out:
  $\hookrightarrow$ Only SM degrees of freedom remain: q, g, (H, $W^{\pm}$, ...)
- Write down *all interactions* for these *active* degrees of freedom that *respect the* SM + Lorentz *symmetries*: here dim. 6 or higher order
- Need a *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.



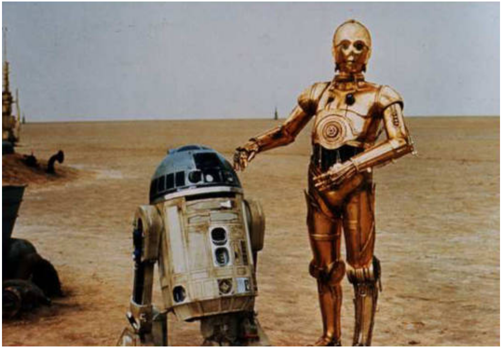
All possible (BSM) $\not{T}$ and $\not{P}$ *contact* interactions

of dimension 6 above/below the EW scale and their $\not{CP}$ hadronic equivalents

W. Dekens & J. de Vries (2013)



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

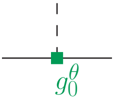
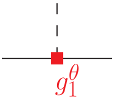
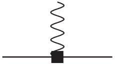


↪ Symmetries (esp. chiral one) and Goldstone Theorem
Low-Energy Effective Field Theory with External Sources
i.e. Chiral Perturbation Theory (suitably extended)

θ-Term on the Hadronic Level (non-perturbative QCD regime!)

$\mathcal{L}^{\theta}_{QCD} = -\bar\theta m_q^* \sum_f \bar q_f i\gamma_5 q_f$: $\;\not{CP}$, I $\quad\Leftrightarrow\quad \mathcal{M} \to \mathcal{M} + \bar\theta m_q^* i\gamma_5 \qquad m_q^* = \frac{m_u m_d}{m_u+m_d}$

$\hookrightarrow$ $\bar\theta$ source breaks chiral symmetry ($\propto m_q^*$) but *conserves* the isospin one:

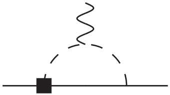
	$\not{CP}$, I		$\not{CP}$, $\not{I}$		$\not{CP}$, I + $\not{I}$	
$\mathcal{L}^{ChPT}_{\theta} =$	$g_0^\theta N^\dagger \vec\pi\cdot\vec\tau N$	$+$	$g_1^\theta N^\dagger \pi_3 N$	$+$	$N^\dagger(b_0^\theta + b_1^\theta\tau_3) S^\mu v^\nu F_{\mu\nu} N$	$+\cdots$
	$\Downarrow$		$\Downarrow$		$\Downarrow$	
						$\cdots$
	dominating for *n*, *p* & ^{3}*He*		suppressed but imp. for *D*		important for *n*, *p*	

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

$|g_0^\theta| \gg |g_1^\theta|$: NDA estimate predicts: $g_1^\theta/g_0^\theta \sim \mathcal{O}(m_\pi^2/m_n^2)$ — de Vries et al. (2011)

ChPT LECs predict: $g_1^\theta/g_0^\theta \sim \mathcal{O}(m_\pi/m_n)$! — Bsaisou et al. (2013)

θ-Term Induced EDM of a Single Nucleon

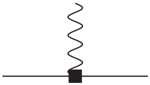


isovector

$\approx$

$\ll$

isoscalar



"controlled"

two "unknown" coefficients

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

$$d_N\Big|^{\text{isovector}}_{\text{loop}} = -e\frac{g_{\pi NN}\, g_0^\theta}{4\pi^2}\frac{\ln(M_N^2/m_\pi^2)}{2M_N} \sim \bar\theta\, m_\pi^2 \ln m_\pi^2 \qquad (e>0)$$

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

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

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

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

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

We'll always have ... the lattice

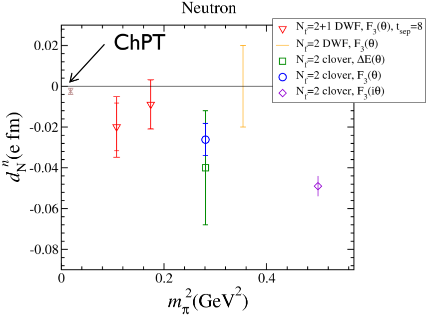
Don't mention the ... light nuclei

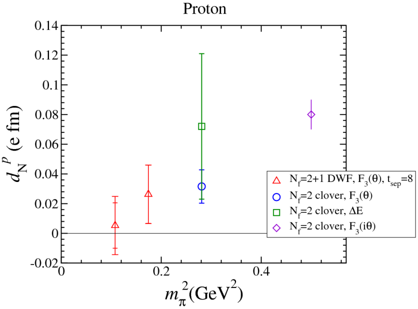
We'll always have ... the lattice

However, *It's a long way to Tipperary ...*

Results from *full* QCD calculations (no systematical errors!) for the

neutron EDM and proton EDM





$\theta \equiv 1$! (adapted from Eigo Shintani (Mainz), *Lattice calculation of nucleon EDM*, Hirschegg, Jan. 14, 2014)

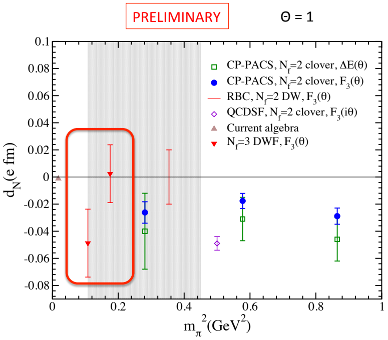
Don't mention the ... light nuclei

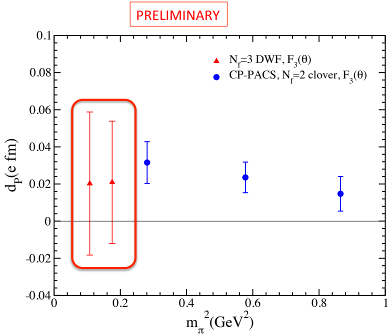
We'll always have ... the lattice

However, *It's a long way to Tipperary ...*

Results from *full* QCD calculations (no systematical errors!) for the

neutron EDM and proton EDM





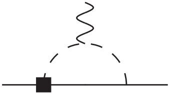
(adapted from Taku Izubuchi (BNL), *Lattice-QCD calculations for EDMs*, Fermilab, Feb. 14, 2013)

Don't mention the ... light nuclei

Single Nucleon Versus Nuclear EDM of the θ-Term

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

single nucleon EDM:

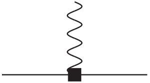


isovector

$\approx$

$\ll$

isoscalar



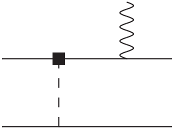
“controlled” “unknown" coefficients

$\longrightarrow$ lattice QCD required

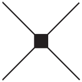
Guo, Meißner (2012)

two nucleon EDM:

Sushkov, Flambaum, Khriplovich (1984)



$\gg$

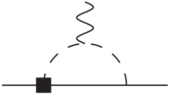


controlled unknown coefficient

Single Nucleon Versus Nuclear EDM of the θ-Term

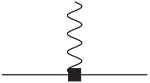
Crewther, di Vecchia, Veneziano & Witten (1979); Pich & de Rafael (1991); Ottnad et al. (2010)

single nucleon EDM:



isovector
$\approx$

$\ll$
isoscalar



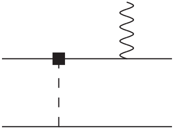
“controlled” | “unknown" coefficients

$\longrightarrow$ lattice QCD required

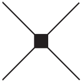
Guo, Meißner (2012)

two nucleon EDM:

Sushkov, Flambaum, Khriplovich (1984)

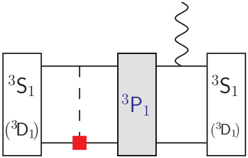


$\gg$



controlled | unknown coefficient

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



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

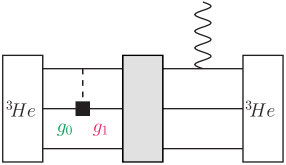
NLO: $g_1^\theta N^\dagger \pi_3 N$ $(\not{CP}, \not{I})$ $\to$ *"LO"* in D case

Reference	potential	result [$g_1 \, g_{\pi NN} \, e\,\text{fm}$]
Liu & Timmermans (2004)	Av_{18}	1.43×10^{-2}
Afnan & Gibson (2010)	Reid 93	1.53×10^{-2}
Song et al. (2013)	Av_{18}	1.45×10^{-2}
JBC (2014)*	Av_{18}	1.45×10^{-2}
Bsaisou et al. (2013)$^\diamond$	CD Bonn	1.52×10^{-2}
JBC (2014)*	ChPT (N^2LO)	$(1.43 \pm 0.13) \times 10^{-2}$

* unpublished, $^\diamond$ Eur. Phys. J. A **49** (2013) 31 [arXiv:1209.6306]

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

^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

Reference	potential	result [$g_0 g_{\pi NN}\, e$ fm]	result [$g_1 g_{\pi NN}\, e$ fm]
Stetcu et al.(2008)	Av_{18} UIX	$1.20\times10^{-2}/2^\diamond$	$2.20\times10^{-2}/2^\diamond$
Song et al.(2013)	Av_{18}UIX	0.55×10^{-2}	1.06×10^{-2}
JBC (2014)$^\diamond$	Av_{18}UIX	0.57×10^{-2}	1.11×10^{-2}
JBC (2014)$^\diamond$	CD BONN TM	0.68×10^{-2}	1.14×10^{-2}
JBC (2014)$^\diamond$	ChPT (N^2LO)	$(0.86\pm0.11)\times10^{-2}$	$(1.11\pm0.14)\times10^{-2}$

$^\diamond$ unpublished

Results for $^3H(g_i) \approx (-1)^{1+i} \times {}^3He(g_i)$ ones

Testing Strategies in the θ EDM scenario

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

$$d_D = d_n + d_p + (0.54 \pm 0.39) \cdot 10^{-16}\, \bar{\theta}\, e\,\mathrm{cm} \quad \text{(Bsaisou et al. (2013))}$$

$$d_{^3He} = \tilde{d}_n - (1.35 \pm 0.88) \cdot 10^{-16}\, \bar{\theta}\, e\,\mathrm{cm} \quad \text{(JBC (2014))}$$

Uncertainties dominated by the *hadronic* ones:

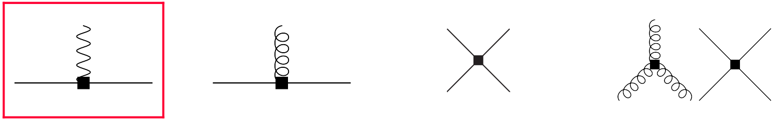
$$g_0^\theta = \frac{(m_n - m_p)^{\text{strong}}(1-\epsilon^2)}{4F_\pi \epsilon}\bar{\theta} \quad \text{and} \quad \frac{g_1^\theta}{g_0^\theta} \approx \frac{8c_1(M^2_{\pi^\pm} - M^2_{\pi^0})^{\text{strong}}}{(m_n - m_p)^{\text{strong}}} \quad \text{with} \quad \epsilon = \frac{m_u - m_d}{m_u + m_d}$$

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, then effective BSM dim. 6 sources

de Vries et al.(2011)



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

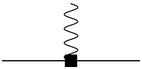
$\longrightarrow \quad g_0,\, g_1 \propto \alpha/(4\pi)$

$2N$ contribution suppressed by photon loop!

here: only absolute values considered

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

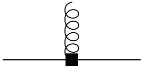
de Vries et al.(2011)



$qEDM$

$d_D \approx d_p + d_n$

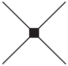
$d_{^3He} \approx d_n$



$qCEDM$

$d_D > d_p + d_n$

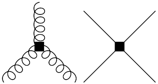
$d_{^3He} > d_n$



$4qLR$

$d_D > d_p + d_n$

$d_{^3He} > d_n$



$gCEDM + 4qEDM$

$d_D \sim d_p + d_n$

$d_{^3He} \sim d_n$

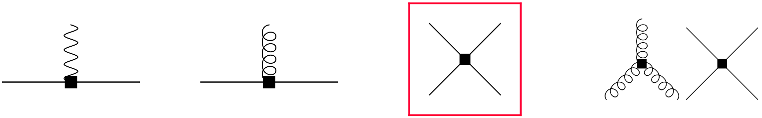
$\longrightarrow$ g_0, g_1 dominant and of the same order

$2N$ contribution enhanced!

here: only absolute values considered

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

de Vries et al.(2011)



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

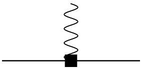
$\longrightarrow$ $g_1 \gg g_0$; 3π-coupling (unsuppressed in ^{3}He)

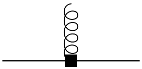
isospin-breaking $2N$ contribution enhanced!

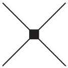
here: only absolute values considered

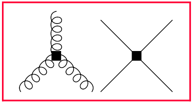
If $\bar{\theta}$-term tests fail, then effective BSM dim. 6 sources

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 on the same footing

$2N$ contribution difficult to asses!

here: only absolute values considered

Conclusions

- The first non-vanishing EDM might be detected in a charge-neutral case: *neutrons* or *dia-/ paramagnetic atoms* or *molecules* ⋯
- However, measurements of light ion EDMs will play a key role in disentangling the *sources* of $\not{C}\not{P}$
- EDM measurements are characteristically of *low-energy nature:*
  ↪ non-leptonic predictions have to be in the *language of hadrons*
  ↪ only reliable methods: *ChPT/EFT* and *Lattice QCD*
  because of their *inherent & systematical* uncertainty estimates
- EDMs of light nuclei provide independent information to nucleon ones and may be even larger and, moreover, even simpler
- Deuteron & helion work as independent isospin filters of EDMs

At least the EDMs of *p*, *n*, *d*, and ^{3}He are needed
to have a realistic chance
to disentangle the underlying physics

JÜLICH
FORSCHUNGSZENTRUM

Many thanks to my colleagues

in Jülich: Jan Bsaisou, Christoph Hanhart, Susanna Liebig, Ulf-G. Meißner, David Minossi, Andreas Nogga, and Jordy de Vries

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]].
- K. Ottnad, B. Kubis, U.-G. Meißner and F.-K. Guo,
  New insights into the neutron electric dipole moment,
  Phys. Lett. B **687** (2010) 42 [arXiv:0911.3981 [hep-ph]].
- 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]].