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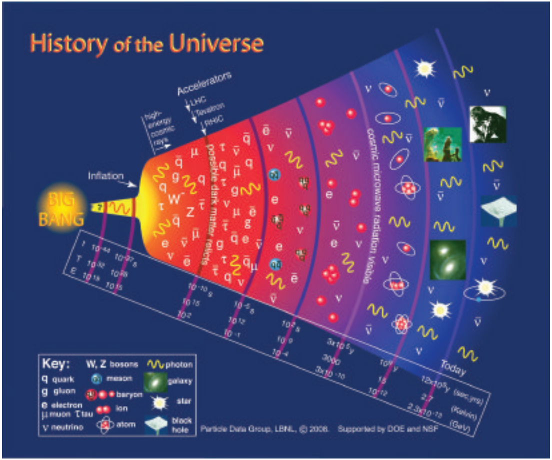
JÜLICH FORSCHUNGSZENTRUM

Electric dipole moment of the nucleon and light nuclei

A Tribute to Gerry Brown

Stony Brook | November 25, 2013 | 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 (2003): $n_B/n_\gamma|_{\rm CMB} = (6.1 \pm 0.3) 10^{-10}$

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

1 B violation to depart from initial B=0

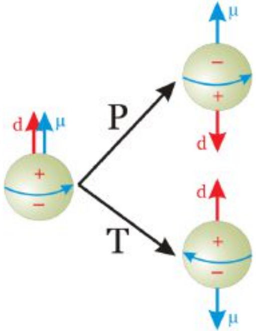
2 C & CP violation

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
  $\hookrightarrow$ 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)†

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

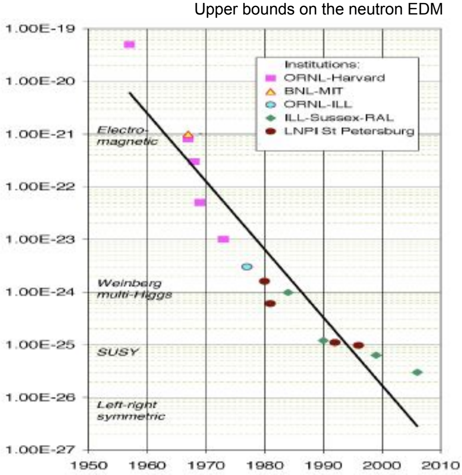
- In SM (without θ term): extra $G_F m_\pi^2$ factor to undo flavor change

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

$\hookrightarrow$ *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



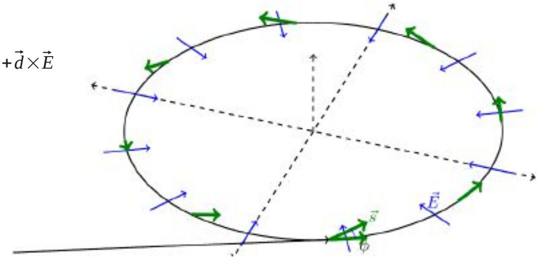
Smith, Purcell, Ramsey (1957) . . . . Baker et al. (2006)

↪ 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 transversal $\vec{E}$
$\hookrightarrow$ 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 $\vec{\beta} \cdot \vec{B} = \vec{\beta} \cdot \vec{E} = 0$):

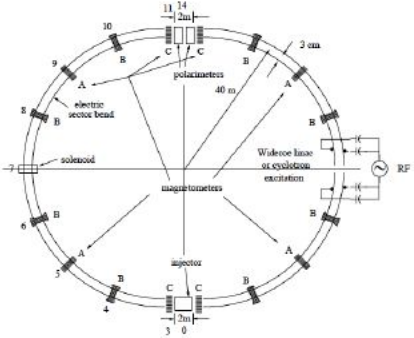
$$\frac{d\vec{S}^*}{dt} = \vec{\Omega} \times \vec{S}^* \quad \text{with} \quad \vec{\Omega} = -\frac{e}{m}\left(a\vec{B} + \left(\frac{1}{\gamma^2-1} - a\right)\vec{\beta} \times \vec{E} + \eta(\vec{E} + \vec{\beta} \times \vec{B})\right)$$

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

Method 1: pure electric ring

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

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



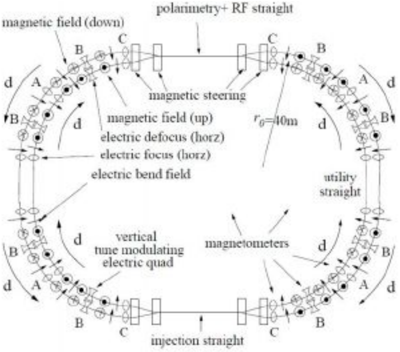
Advantages:
– no magnetic field
– counter rotating beams

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

BNL or Fermilab?

Method 2: combined electric & magnetic ring

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



Advantage:
– works for p, deuterons and ^{3}He

Disadvantages:
– requires magnetic field
– two beam pipes
– magnetic coils made of copper

Jülich ?

Method 3: pure magnetic ring

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

$\rightarrow$ rigged roulette

Advantage:

– existing COSY accelerator

$\hookrightarrow$ precursor experiment:

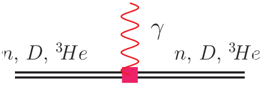
First *direct* measurement of charged hadron EDMs

Disadvantage:

– lower sensitivity

JEDI@Jülich !

EDMs of the nucleon and especially light nuclei



Outline:

- CP-violation beyond CKM matrix in the SM: $\mathcal{L}_{QCD}$ θ-term (dim. 4)
  - EDM of the nucleon
  - EDM of the deuteron / EDM of helium-3
  - strategies of testing the $\bar{\theta}$-term
- CP-violation from physics beyond the SM: SUSY, multi-Higgs,$\cdots$

  $\longrightarrow$ dim. 6 sources: qEDM, qCEDM, gCEDM, 4qEDMs
  - EDM of the deuteron / EDM of helium-3
  - disentangling dim. 6 sources

Jülich-Bonn Collaboration (JBC):

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

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

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

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

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

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

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

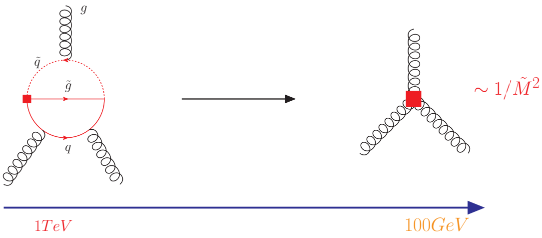
$$d_n^{emp} < 2.9 \cdot 10^{-26}\, e\,\mathrm{cm} \rightsquigarrow \boxed{|\bar{\theta}| < 10^{-10}} \text{ strong CP problem}$$

New Physics Beyond Standard Model (BSM)

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

Effective field theory approach:

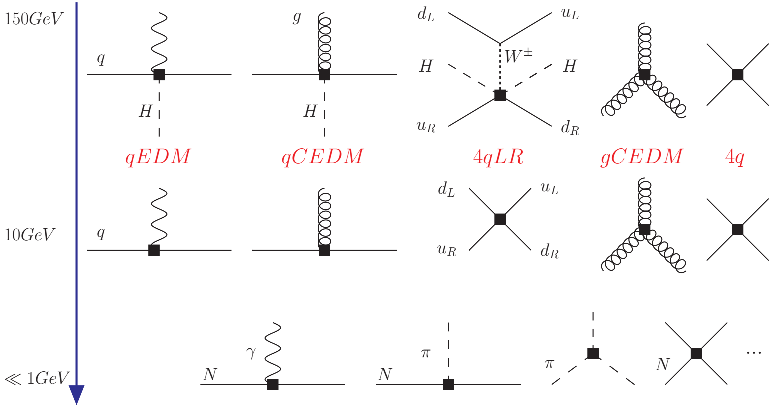
- All degrees of freedom beyond a specified scale are integrated out:
  $\hookrightarrow$ Only SM degrees of freedom remain: q, g, H, $W^{\pm}$,...
- Relics of eliminated BSM physics 'remembered' by the values of the low-energy constants (LECs) of the CP-violating contact terms, e.g.



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

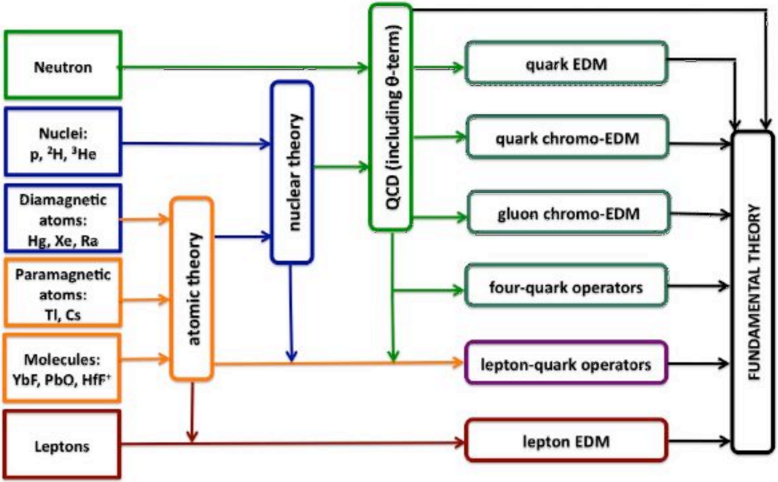
Removal of Higgs and $W^{\pm}$ bosons & transition to hadronic fields (plus mixing):

Order the interactions by power counting



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)

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

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

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

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

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

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

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

dominating for *n*, *p* & ^3He

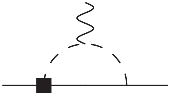
dominating for *D*

important for *n*, *p*

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

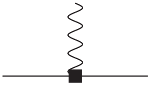
θ-Term Induced Nucleon EDM

single nucleon EDM:



“controlled”

isovector
$\approx$
$\ll$
isoscalar



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)

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

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

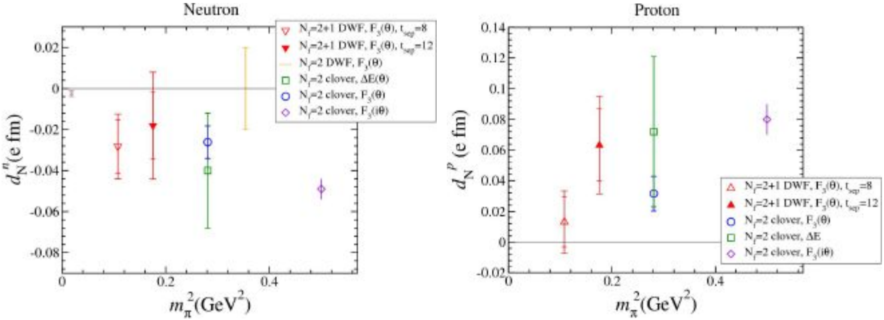
Ottnad et al. (2010); Bsaisou et al. (2013)

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

We'll always have ... the lattice

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

Preliminary EDM results from lattice QCD (no systematical errors!):



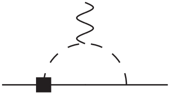
$\theta = 1$ (adapted from Eigo Shintani (Mainz & RBRC), *MITP Workshop, Mainz, Oct. 10, 2013*)

Don't mention the ... light nuclei

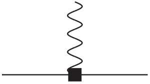
θ-Term Induced Nucleon EDM:

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

single nucleon EDM:



isovector $\approx$ $\ll$ isoscalar



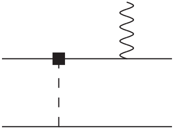
“controlled” “unknown" coefficients

$\longrightarrow$ lattice QCD required

Guo, Meißner (2012)

two nucleon EDM:

Sushkov, Flambaum, Khriplovich (1984)



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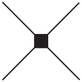

controlled unknown coefficient

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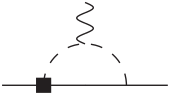
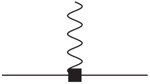


isovector

$\approx$

$\ll$

isoscalar



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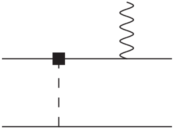
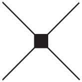
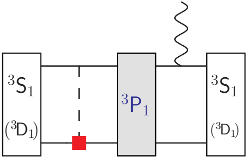


$\gg$



controlled | unknown coefficient

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



LO: $\cancel{g_0^\theta N^\dagger \vec{\pi}\cdot\vec{\tau} N}$ ($\cancel{CP}$,I) $\rightarrow$ Isospin excl.

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

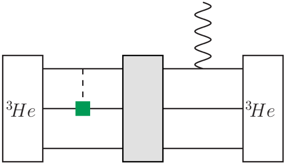
in units of $g_1^\theta\, e\cdot \mathrm{fm}\cdot (g_A\, m_N/F_\pi)$

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)†	-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 $\dagger$: cutoffs at 600 MeV (LS) and 700 MeV (SFR)

$\boxed{\text{BSM } \cancel{CP} \text{ sources:}}$ LO g_1 πNN-vertex also exists in qCEDM and 4qLR cases

^3He EDM: quantitative results for g_0 exchange



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

θ-term, qCEDM $\rightarrow$ LO

4qLR $\rightarrow$ N^2LO

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

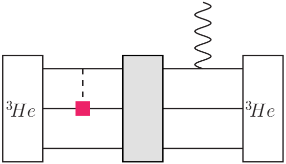
author	potential	no int.	with int.	total
JBC (2013)*	Av_{18}UIX	-0.45×10^{-2}	-0.13×10^{-2}	-0.57×10^{-2}
JBC (2013)*	CD BONN TM	-0.56×10^{-2}	-0.12×10^{-2}	-0.67×10^{-2}
JBC (2013)*	ChPT $(N^2LO)^\dagger$	-0.56×10^{-2}	-0.19×10^{-2}	-0.76×10^{-2}
Song (2013)	Av_{18}UIX	-	-	-0.59×10^{-2}
Stetcu (2008)	Av_{18} UIX	-	-	-1.21×10^{-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



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

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)†	-1.09×10^{-2}	-0.14×10^{-2}	-0.96×10^{-2}
Song (2013)	Av_{18}UIX	-	-	-1.08×10^{-2}
Stetcu (2008)	Av_{18} UIX	-	-	-2.20×10^{-2}

*: in preparation $\quad$ †: 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)

Quantitative EDM results in the θ-term scenario

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

$$
\begin{aligned}
-d_1^{\text{loop}} &\equiv \tfrac{1}{2}(d_n - d_p)^{\text{loop}} \\
&= (2.1 \pm 0.9) \cdot 10^{-16}\,\bar{\theta}\,e\,\text{cm} && \text{(Bsaisou et al. (2013))} \\
d_n &= +(2.9 \pm 0.9) \cdot 10^{-16}\,\bar{\theta}\,e\,\text{cm} && \text{(Guo \& Meißner (2012))} \\
d_p &= -(1.1 \pm 1.1) \cdot 0^{-16}\,\bar{\theta}\,e\,\text{cm} && \text{(Guo \& Meißner (2012))}
\end{aligned}
$$

Deuteron:

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

Helium-3:

$$
\begin{aligned}
d_{^3He} &= \tilde{d}_n + \left[(1.52 \pm 0.60) - (0.46 \pm 0.30)\right] \cdot 10^{-16}\,\bar{\theta}\,e\,\text{cm} \\
&= \tilde{d}_n + (1.06 \pm 0.67) \cdot 10^{-16}\,\bar{\theta}\,e\,\text{cm} && \text{(JBC (2013))}
\end{aligned}
$$

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

Testing Strategies in the θ EDM scenario

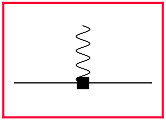
Remember:

$$d_D = d_n + d_p - (0.54 \pm 0.39) \cdot 10^{-16}\, \bar{\theta}\, e\,\mathrm{cm} \quad \text{(Bsaisou et al. (2013))}$$
$$d_{^3He} = \tilde{d}_n + (1.06 \pm 0.67) \cdot 10^{-16}\, \bar{\theta}\, e\,\mathrm{cm} \quad \text{(JBC (2013))}$$

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

- 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)

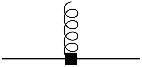
If $\bar{\theta}$-term tests fail: use effective BSM dim. 6 sources   de Vries et al. (2011)



qEDM

$d_D \approx d_p + d_n$

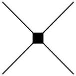
$d_{^3He} \approx d_n$



qCEDM

$d_D > d_p + d_n$

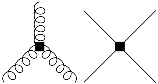
$d_{^3He} > d_n$



4qLR

$d_D > d_p + d_n$

$d_{^3He} > d_n$



gCEDM + 4qEDM

$d_D \sim d_p + d_n$

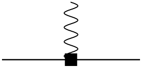
$d_{^3He} \sim d_n$

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

2N contribution suppressed by photon loop!

here: only absolute values considered

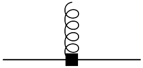
If $\bar{\theta}$-term tests fail: use effective BSM dim. 6 sources de Vries et al. (2011)



qEDM

$d_D \approx d_p + d_n$

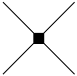
$d_{^3He} \approx d_n$



qCEDM

$d_D > d_p + d_n$

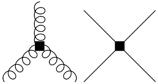
$d_{^3He} > d_n$



4qLR

$d_D > d_p + d_n$

$d_{^3He} > d_n$



gCEDM + 4qEDM

$d_D \sim d_p + d_n$

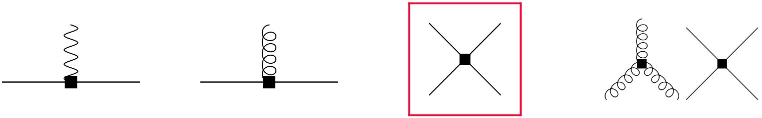
$d_{^3He} \sim d_n$

$\longrightarrow \quad g_0, \; g_1$

$2N$ contribution enhanced!

here: only absolute values considered

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



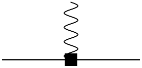
qEDM	*qCEDM*	*4qLR*	*gCEDM + 4qEDM*
$d_D \approx d_p + d_n$	$d_D > d_p + d_n$	$d_D > d_p + d_n$	$d_D \sim d_p + d_n$
$d_{^3He} \approx d_n$	$d_{^3He} > d_n$	$d_{^3He} > d_n$	$d_{^3He} \sim d_n$

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

$2N$ contribution enhanced!

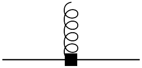
here: only absolute values considered

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



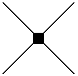
qEDM

$d_D \approx d_p + d_n$
$d_{^3He} \approx d_n$



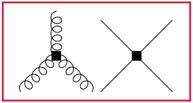
qCEDM

$d_D > d_p + d_n$
$d_{^3He} > d_n$



4qLR

$d_D > d_p + d_n$
$d_{^3He} > d_n$



gCEDM + 4*qEDM*

$d_D \sim d_p + d_n$
$d_{^3He} \sim d_n$

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

2*N* contribution difficult to asses!

here: only absolute values considered

Conclusions

- (Hadronic) EDMs play a key role in probing new sources of $\cancel{CP}$
- Measurements of hadronic EDMs are low-energy measurements
  $\hookrightarrow$ Predictions have to be given in the *empirical language of hadrons*
  $\hookrightarrow$ only reliable methods predicting *uncertainties* as well:
  ChPT/EFT and/(or ultimately) *Lattice QCD*
- EDMs of light nuclei provide independent information to nucleon EDMs and may be even larger and even simpler
- Deuteron and helium-3 nuclei serve as isospin filters for EDMs

At least the EDMs of p, n, d, and ^{3}He
have to be measured
to disentangle the underlying physics
by applying methods of EFT and lattice QCD

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