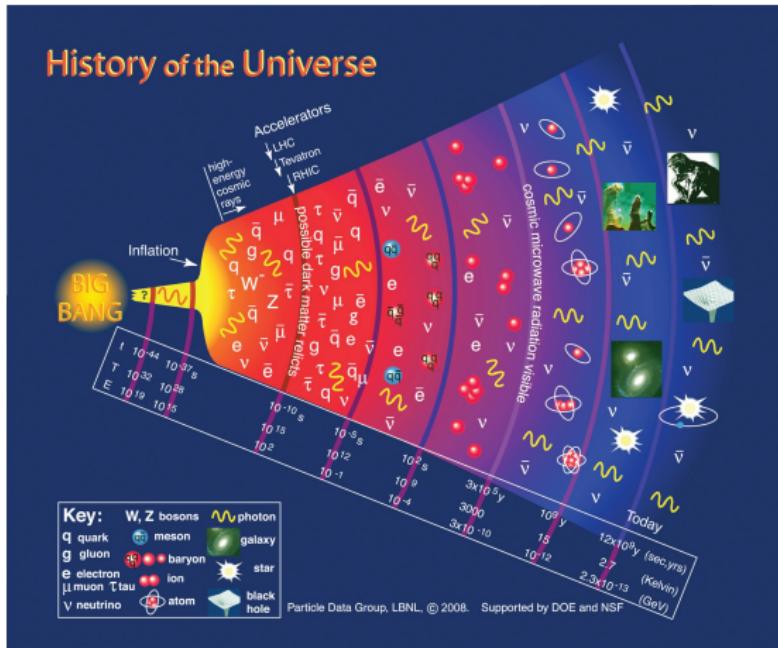


Electric dipole moment of the nucleon and light nuclei



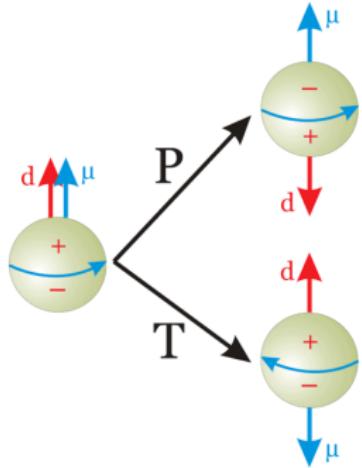
A Tribute to Gerry Brown

Matter Excess in the Universe



- 1 End of inflation: $n_B = n_{\bar{B}}$
 - 2 Cosmic Microwave Bkgr.
 - SM(s) prediction: $(n_B - n_{\bar{B}})/n_\gamma|_{CMB} \sim 10^{-18}$
 - WMAP+COBE (2003): $n_B/n_\gamma|_{CMB} = (6.1 \pm 0.3) 10^{-10}$
- Sakharov 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)



$$\text{EDM: } \vec{d} = \sum_i \vec{r}_i e_i \xrightarrow[\text{(polar)}]{\substack{\text{subatomic} \\ \text{particles}}} d \cdot \vec{S}/|\vec{S}| \xrightarrow[\text{(axial)}]{} d \cdot \vec{S}/|\vec{S}|$$

$$\mathcal{H} = -\mu \frac{\vec{S}}{S} \cdot \vec{B} - d \frac{\vec{S}}{S} \cdot \vec{E}$$

$$P: \quad \mathcal{H} = -\mu \frac{\vec{S}}{S} \cdot \vec{B} + d \frac{\vec{S}}{S} \cdot \vec{E}$$

$$T: \quad \mathcal{H} = -\mu \frac{\vec{S}}{S} \cdot \vec{B} + d \frac{\vec{S}}{S} \cdot \vec{E}$$

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): $d_n \sim 10^{-31} \text{ ecm}$, $d_e \sim 10^{-38} \text{ ecm}$
- Current bounds: $d_n < 3 \cdot 10^{-26} \text{ ecm}$, $d_p < 8 \cdot 10^{-25} \text{ ecm}$, $d_e < 1 \cdot 10^{-28} \text{ ecm}$

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

$$\mu_N = \frac{e}{2m_p} \sim 10^{-14} \text{ ecm}.$$

- A nonzero EDM requires

parity P violation: the price to pay is $\sim 10^{-7}$

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

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

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

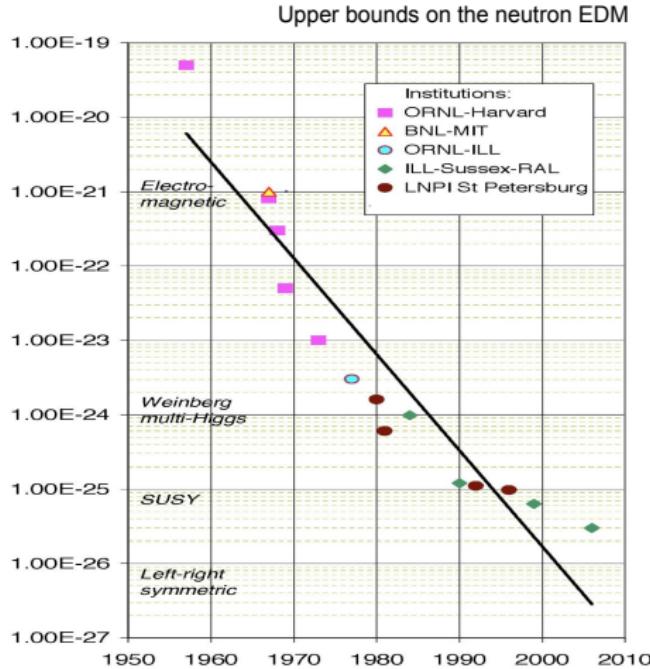
- In summary: $d_N \sim 10^{-7} \times 10^{-3} \times \mu_N \sim 10^{-24} \text{ ecm}$
- In SM (without θ term): extra $G_F m_\pi^2$ factor to undo flavor change

$$\rightarrow d_N^{\text{SM}} \sim 10^{-7} \times 10^{-24} \text{ ecm} \sim 10^{-31} \text{ ecm}$$

→ The empirical window for search of physics BSM($\theta=0$) is

$$10^{-24} \text{ ecm} > d_N > 10^{-30} \text{ ecm.}$$

Chronology of upper bounds on the neutron EDM

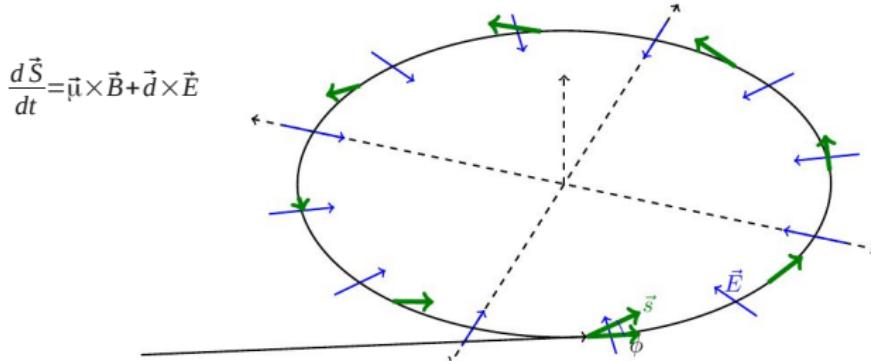


Smith, Purcell, Ramsey (1957) Baker et al. (2006)

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

Search for EDMs of charged particles in storage rings

General idea:



Initially **longitudinally polarized** particles interact with **transversal \vec{E}**
 ↳ 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 $\vec{\beta} \cdot \vec{B} = \vec{\beta} \cdot \vec{E} = 0$):

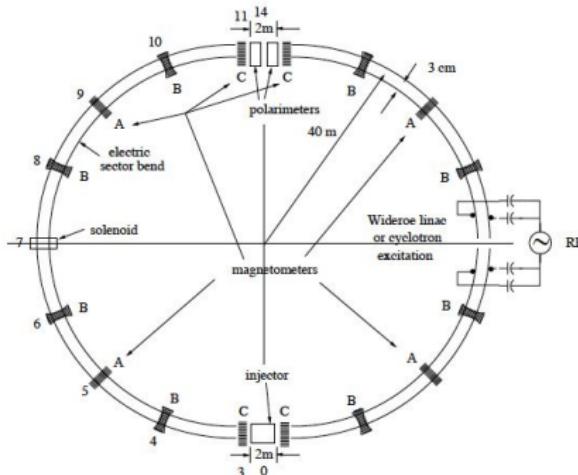
$$\frac{d\vec{S}^*}{dt} = \vec{\Omega} \times \vec{S}^* \quad \text{with} \quad \vec{\Omega} = -\frac{e}{m} \left(a\vec{B} + \left(\frac{1}{\gamma^2 - 1} - a \right) \vec{\beta} \times \vec{E} + \eta(\vec{E} + \vec{\beta} \times \vec{B}) \right)$$

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

Method 1: pure electric ring

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

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



Advantages:

- no magnetic field
- counter rotating beams

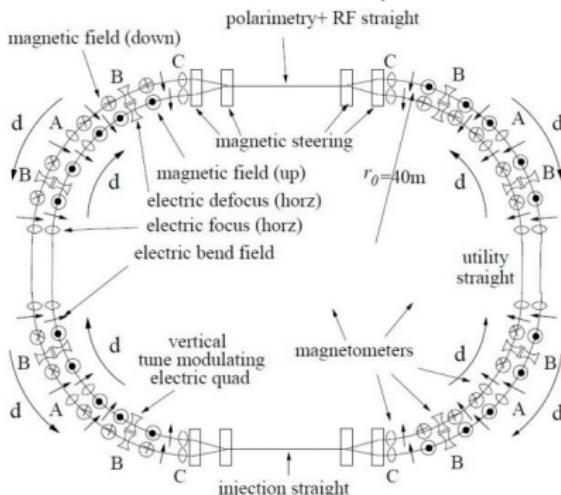
Disadvantage:

- 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 ${}^3\text{He}$

Disadvantages:

- requires magnetic field
- two beam pipes
- magnetic coils made of copper

Jülich ?

Method 3: pure magnetic ring

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



Advantage:

- existing COSY accelerator
- precursor experiment:

First *direct* measurement of charged hadron EDMs

Disadvantage:

- lower sensitivity

EDMs of the nucleon and especially light nuclei



Outline:

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

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

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

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

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

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

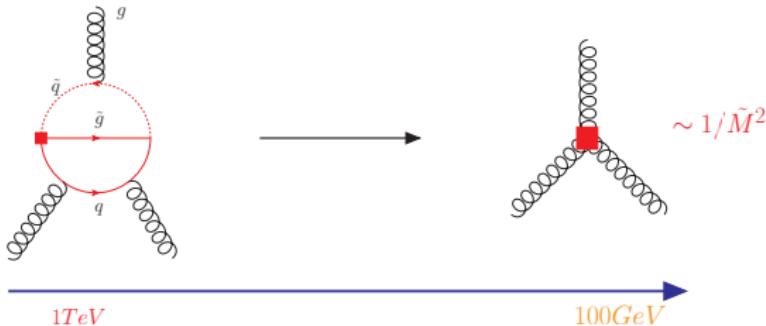
$$d_n^{\text{emp}} < 2.9 \cdot 10^{-26} \text{ ecm} \sim |\bar{\theta}| < 10^{-10} \quad \text{strong CP problem}$$

New Physics Beyond Standard Model (BSM)

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

Effective field theory approach:

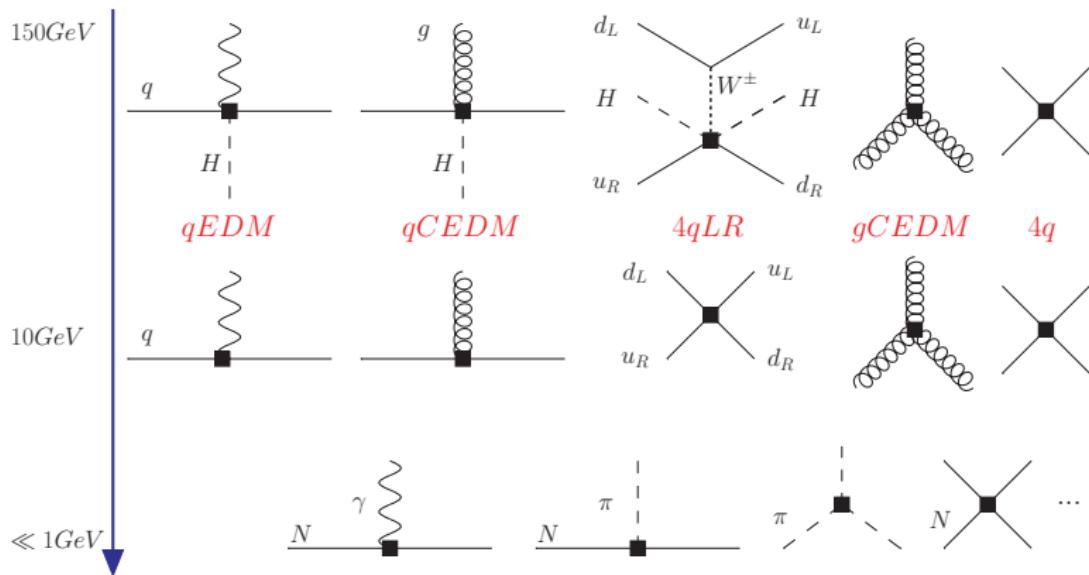
- All degrees of freedom beyond a specified scale are integrated out:
 ↳ Only SM degrees of freedom remain: q, g, H, W^\pm, \dots
- Relics of eliminated BSM physics ‘remembered’ by the values of the low-energy constants (LECs) of the CP-violating contact terms, e.g.



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

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

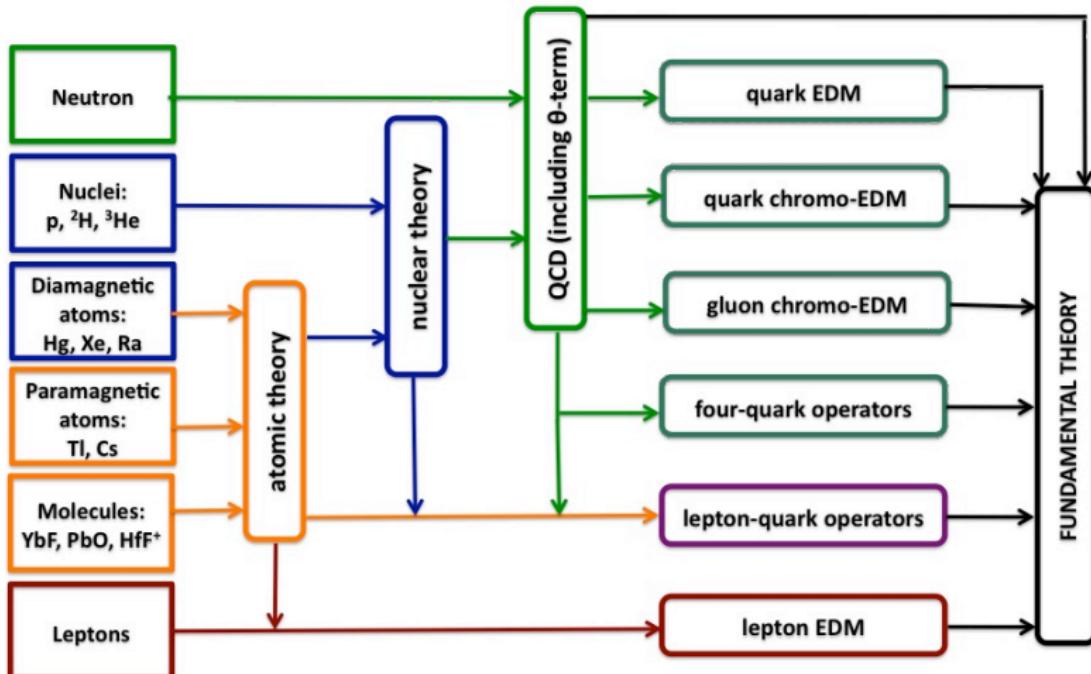
Order the interactions by power counting



Road map from EDM Measurements to EDM Sources

Experimentalist's point of view →

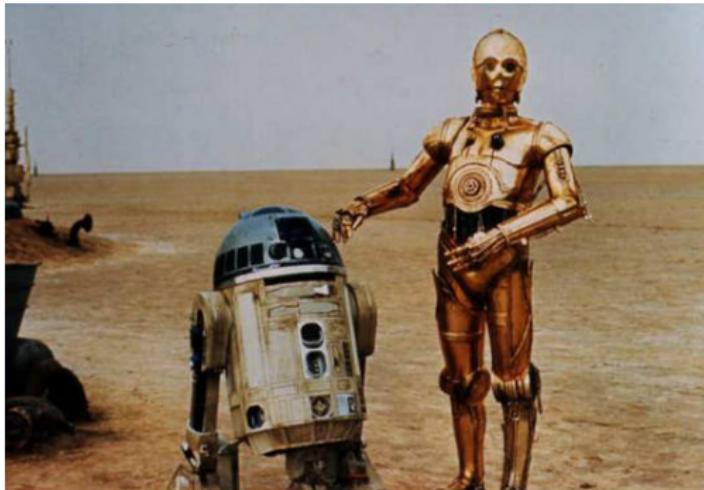
← Theorist's point of view



(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)

$$\mathcal{L}_{QCD}^{\theta} = -\bar{\theta} m_q^* \sum_f \bar{q}_f i\gamma_5 q_f : \mathcal{OP}, I : \Leftrightarrow \mathcal{M} \rightarrow \mathcal{M} + \bar{\theta} m_q^* i\gamma_5 \quad m_q^* = \frac{m_u m_d}{m_u + m_d}$$

\mathcal{OP}, I

\mathcal{OP}, I

$\mathcal{OP}, I + I'$

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



dominating
for n, p & 3He

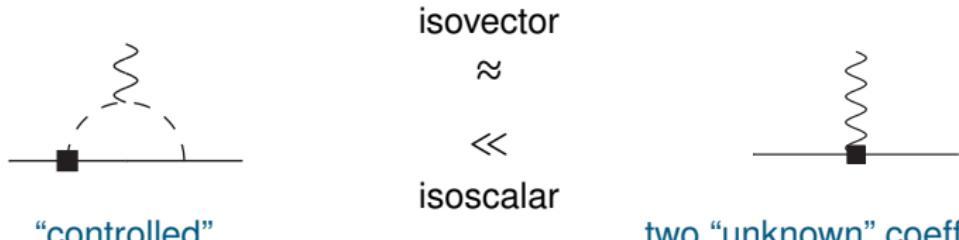
dominating
for D

important for
 n, p

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

θ -Term Induced Nucleon EDM

single nucleon EDM:



two “unknown” coefficients

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

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

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

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

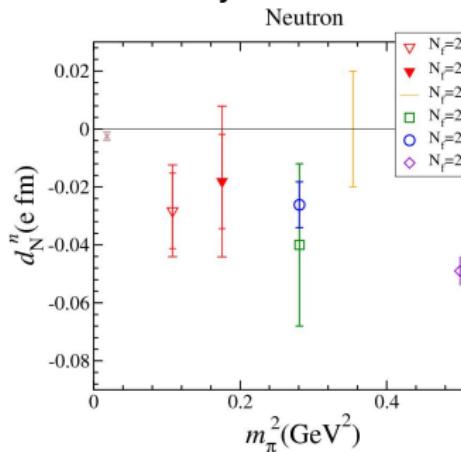
$$\hookrightarrow d_n|_{\text{loop}}^{\text{isovector}} \sim -(2.1 \pm 0.9) \cdot 10^{-16} \bar{\theta} \text{ e cm} \quad \text{Otnad et al. (2010); Bsaisou et al. (2013)}$$

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

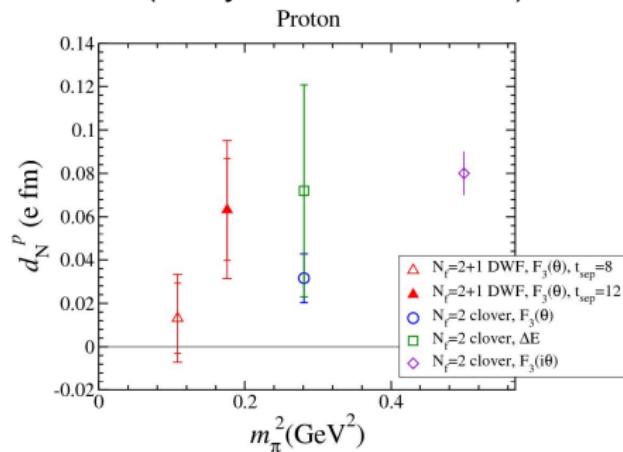
We'll always have ... the lattice

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

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



- ▽ $N_f=2+1$ DWF, $F_3(\theta)$, $t_{\text{sep}}=8$
- ▼ $N_f=2+1$ DWF, $F_3(\theta)$, $t_{\text{sep}}=12$
- $N_f=2$ DWF, $F_3(\theta)$
- $N_f=2$ clover, $\Delta E(\theta)$
- $N_f=2$ clover, $F_3(\theta)$
- ◊ $N_f=2$ clover, $F_3(i\theta)$



- △ $N_f=2+1$ DWF, $F_3(\theta)$, $t_{\text{sep}}=8$
- ▲ $N_f=2+1$ DWF, $F_3(\theta)$, $t_{\text{sep}}=12$
- $N_f=2$ clover, $F_3(\theta)$
- $N_f=2$ clover, ΔE
- ◊ $N_f=2$ clover, $F_3(i\theta)$

$$\theta = 1$$

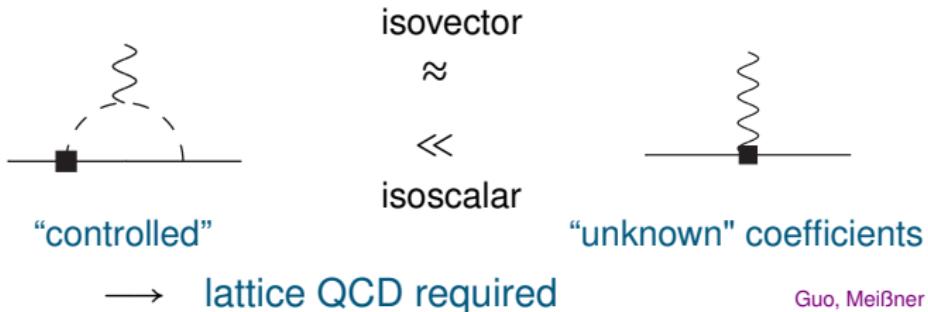
(adapted from Eigo Shintani (Mainz & RBRC), MITP Workshop, Mainz, Oct. 10, 2013)

Don't mention the ... light nuclei

θ -Term Induced Nucleon EDM:

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

single nucleon EDM:



two nucleon EDM:

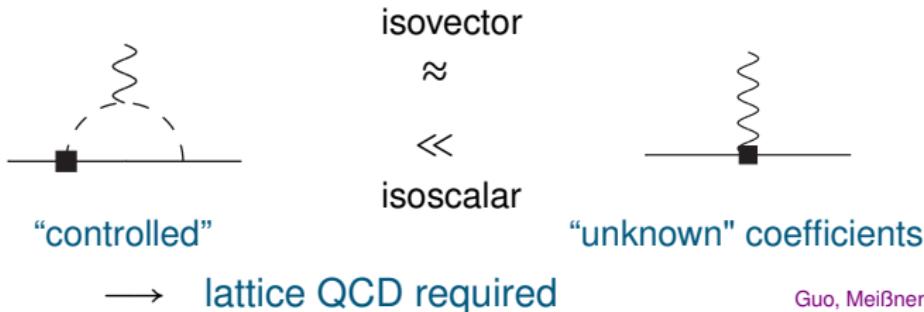
Sushkov, Flambaum, Khraplovich (1984)



θ -Term Induced Nucleon EDM:

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

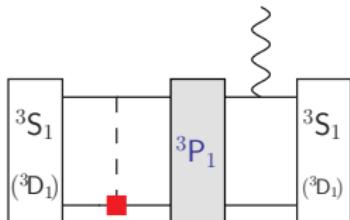
single nucleon EDM:



two nucleon EDM:



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}, I) \rightarrow "LO"

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

Ref.	potential	no 3P_1 -int	with 3P_1 -int	total
JBC (2013)*	AV_{18}	-1.93×10^{-2}	$+0.48 \times 10^{-2}$	-1.45×10^{-2}
JBC (2013)	CD Bonn	-1.95×10^{-2}	$+0.51 \times 10^{-2}$	-1.45×10^{-2}
JBC (2013)*	ChPT (N^2LO) [†]	-1.94×10^{-2}	$+0.65 \times 10^{-2}$	-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}	$+0.40 \times 10^{-2}$	-1.43×10^{-2}

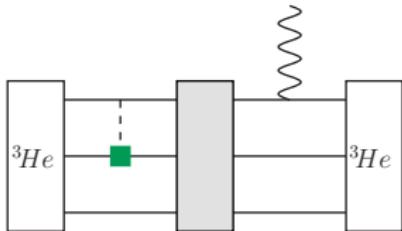
*: in preparation

[†]: cutoffs at 600 MeV (LS) and 700 MeV (SFR)

BSM \cancel{CP} sources:

LO $g_1^\theta \pi NN$ -vertex also exists in qCEDM and 4qLR cases

^3He EDM: quantitative results for g_0 exchange



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

θ -term, qCEDM \rightarrow LO

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

units: $g_0(g_A m_N/F_\pi)\text{efm}$

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 ($N^2\text{LO}$) ^t	-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}

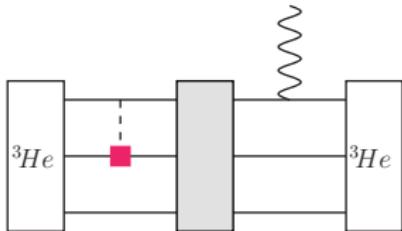
*: in preparation

^t: 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



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

θ -term \rightarrow NLO

qCEDM, 4qLR \rightarrow LO !

Ref.	potential	units: $g_1(g_A m_N/F_\pi)\text{efm}$		
		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)*	$\text{ChPT}(N^2\text{LO})^\dagger$	-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

† : cutoffs at 600 MeV (LS) and 700 MeV (SFR)

Results for 3H also available (not shown)

In the pipeline: $\cancel{\text{CP}}$ 3π -vertex contribution (4qLR: LO)

Quantitative EDM results in the θ -term scenario

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

$$\begin{aligned} -d_1^{\text{loop}} &\equiv \frac{1}{2}(d_n - d_p)^{\text{loop}} \\ &= (2.1 \pm 0.9) \cdot 10^{-16} \bar{\theta} \text{ e cm} \quad (\text{Bsaisou et al. (2013)}) \end{aligned}$$

$$\begin{aligned} d_n &= +(2.9 \pm 0.9) \cdot 10^{-16} \bar{\theta} \text{ e cm} \quad (\text{Guo \& Mei\ss{}ner (2012)}) \\ d_p &= -(1.1 \pm 1.1) \cdot 10^{-16} \bar{\theta} \text{ e cm} \quad (\text{Guo \& Mei\ss{}ner (2012)}) \end{aligned}$$

Deuteron:

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

Helium-3:

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

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

Testing Strategies in the θ EDM scenario

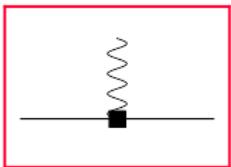
Remember:

$$\begin{aligned} d_D &= d_n + d_p - (0.54 \pm 0.39) \cdot 10^{-16} \bar{\theta} \text{ ecm} && (\text{Bsaisou et al. (2013)}) \\ d_{^3\text{He}} &= \tilde{d}_n + (1.06 \pm 0.67) \cdot 10^{-16} \bar{\theta} \text{ ecm} && (\text{JBC (2013)}) \end{aligned}$$

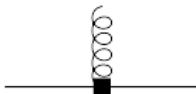
Testing strategies:

- plan A: measure d_n , d_p , and $d_D \xrightarrow{d_D(2N)} \bar{\theta} \xrightarrow{\text{test}} d_{^3\text{He}}$
- plan A': measure d_n , (d_p) , and $d_{^3\text{He}} \xrightarrow{d_{^3\text{He}}(2N)} \bar{\theta} \xrightarrow{\text{test}} d_D$
- plan B: measure d_n (or d_p) + Lattice QCD $\leadsto \bar{\theta} \xrightarrow{\text{test}} d_D$
- plan B': measure d_n (or d_p) + Lattice QCD $\leadsto \bar{\theta} \xrightarrow{\text{test}} d_p$ (or d_n)

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



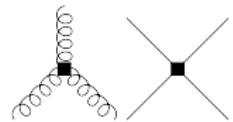
$qEDM$



$qCEDM$



$4qLR$



$gCEDM + 4qEDM$

$$d_D \approx d_p + d_n$$

$$d_{^3He} \approx d_n$$

$$d_D > d_p + d_n$$

$$d_{^3He} > d_n$$

$$d_D > d_p + d_n$$

$$d_{^3He} > d_n$$

$$d_D \sim d_p + d_n$$

$$d_{^3He} \sim d_n$$

→ $g_0, g_1 \propto \alpha/(4\pi)$

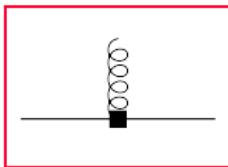
2N contribution suppressed by photon loop!

here: only absolute values considered

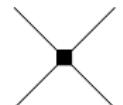
If $\bar{\theta}$ -term tests fail: use effective BSM dim. 6 sources de Vries et al. (2011)



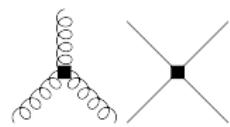
$qEDM$



$qCEDM$



$4qLR$



$gCEDM + 4qEDM$

$$d_D \approx d_p + d_n$$

$$d_{^3He} \approx d_n$$

$$d_D > d_p + d_n$$

$$d_{^3He} > d_n$$

$$d_D > d_p + d_n$$

$$d_{^3He} > d_n$$

$$d_D \sim d_p + d_n$$

$$d_{^3He} \sim d_n$$

→ g_0, g_1

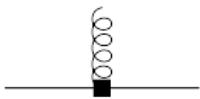
$2N$ contribution enhanced!

here: only absolute values considered

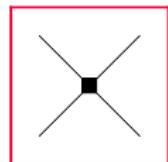
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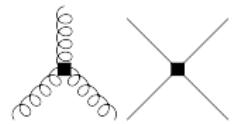
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$$d_{^3He} \sim d_n$$

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

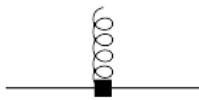
$2N$ contribution enhanced!

here: only absolute values considered

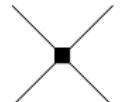
If $\bar{\theta}$ -term tests fail: use effective BSM dim. 6 sources de Vries et al. (2011)



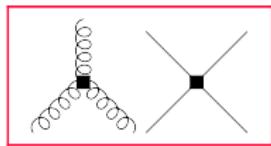
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$$d_D \sim d_p + d_n$$

$$d_{^3He} \sim d_n$$

→ g_1 , g_0 , $4N$ – coupling

$2N$ contribution difficult to asses!

here: only absolute values considered

Conclusions

- (Hadronic) EDMs play a key role in probing new sources of CP
- Measurements of hadronic EDMs are low-energy measurements
 - Predictions have to be given in the *empirical language of hadrons*
 - 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 ${}^3\text{He}$
have to be measured
to disentangle the underlying physics
by applying methods of EFT and lattice QCD

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and: Werner Bernreuther, Bira van Kolck, Kolya Nikolaev

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