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Theory of hadronic electric-dipole moments

Ferrara International School Niccolò Cabeo 2013

Physics Beyond the Standard Model: *the Precision Frontier*

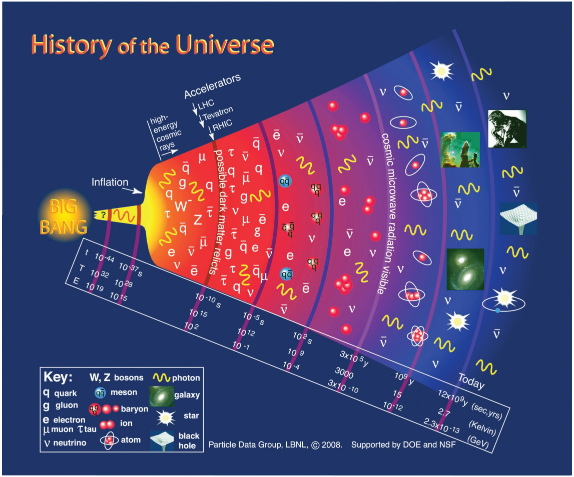
May 24, 2013 | Andreas Wirzba

Outline:

1. Motivation: Matter–Antimatter Asymmetry in the Universe
2. The Permanent EDM and its Features
3. CP-Violating Sources *in* the Standard Model
4. CP-Violating Sources *Beyond* the Standard Model
5. Electric Dipole Moments of the Nucleon
6. Electric Dipole Moments of the Deuteron (and Helium-3)
7. Conclusions and Outlook

Motivation: Matter Excess in the Universe

Big Bang Nucleosynthesis (BBN) & Cosmic Microwave Background (CMB)



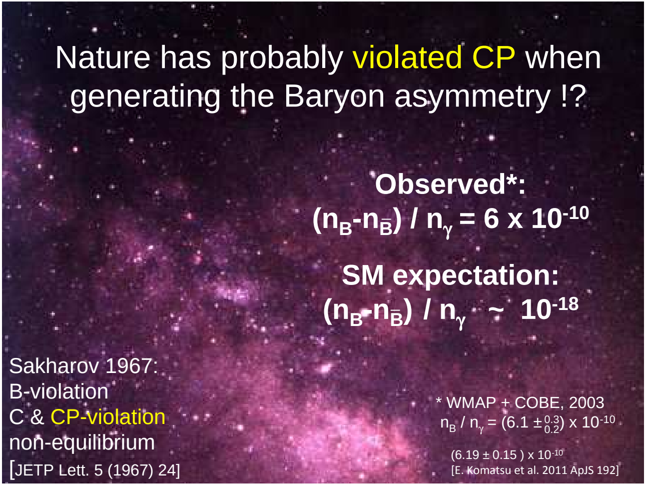
1. End of inflation:
   $n_B = n_{\bar{B}}$
2. BBN: $(10 \ldots 0.1)$ MeV
3. $t_{CMB} \sim 3 \times 10^5$ y:

   SM(s) *prediction:*
   $(n_B - n_{\bar{B}})/n_\gamma|_{CMB} \sim 10^{-18}$

   WMAP+COBE (2003) *observation*:
   $n_B/n_\gamma|_{CMB} = (6.1 \pm 0.3) 10^{-10}$

What is missing?

Motivation: Baryon Asymmetry in the Universe



(adapted from Klaus Kirch (PSI), Fermilab, Feb. 13, 2013)

Dynamical generation of net baryon number

requires the concurrence of three conditions:

Sakharov Conditions

JETP Lett. 5 (1967) 24

1. baryon number B violation .... to depart from initial $B = 0$
2. C and CP violation .... to distinguish B and $\bar{B}$ production
3. no thermal equilibrium .... to escape $\langle B \rangle$=0 if CPT holds

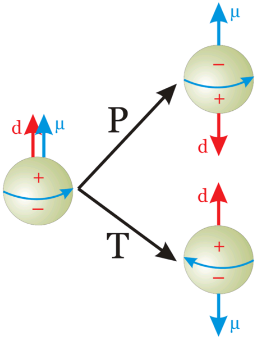
- Investigation of $\cancel{CP}$: possible window to physics beyond SM
- Complementary approaches:

  high energy collider physics (new particles, EWSB, . . .)

  $\longleftrightarrow$

  high precision low-energy experiments (EDMs, flavor physics)

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)

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

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

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

Any non-vanishing EDM of some subatomic particle violates P & T

- Assuming CPT to hold, CP is violated as well
- Strongly suppressed in SM (CKM-matrix): $d_n \sim 10^{-31}\, e\,\mathrm{cm}$
- Current bounds: $d_n < 3 \cdot 10^{-26}\, e\,\mathrm{cm}$, $d_p < 8 \cdot 10^{-25}\, e\,\mathrm{cm}$

n: Baker et al. (2006), *p* prediction: Dimitriev and Sen'kov (2003)*

* input from Hg atom measurement of Griffith et al. (2009)

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

Khriplovich & Lamoreaux (1997)

- CP & P conserving magnetic moment ~ 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 $\sim 10^{-3}$

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

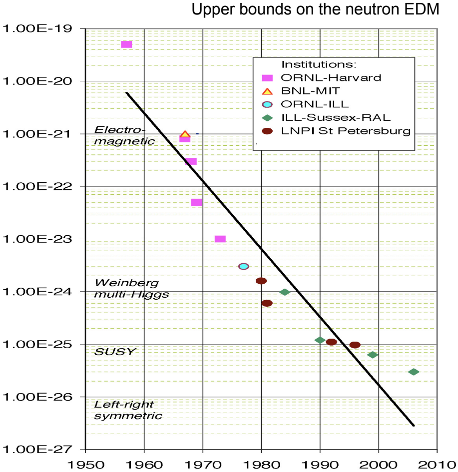
- In summary: $\boxed{d_N \sim 10^{-7} \times 10^{-3} \times \mu_N \sim 10^{-24}\, e\,\mathrm{cm}}$

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

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

- $d_N > 10^{-30}\, e\,\mathrm{cm} \to \cancel{CP}$ & physics beyond the $\mathrm{SM}_{\mathrm{KM}}$ *observed*

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 !

Theorem: Permanent EDMs of *non*-selfconjugate* particles *with* spin $j \neq 0$

Let $\langle j^{\mathrm{P}} | \vec{d} \, | j^{\mathrm{P}} \rangle = d \, \langle j^{\mathrm{P}} | \vec{J} \, | j^{\mathrm{P}} \rangle$ with $\vec{d} = \int \vec{r} \rho(\vec{r}) \mathrm{d}^3 r$ an EDM operator in a stationary state $|j^{\mathrm{P}}\rangle$ of definite parity P and spin $j \neq 0$, such that

$$\vec{d} \to \mp \vec{d} \quad \& \quad \vec{J} \to \pm \vec{J} \qquad \text{under} \quad \begin{cases} \text{space reflection,} \\ \text{time reversal.} \end{cases}$$

If $d \neq 0$ and state $|j^{\mathrm{P}}\rangle$ has no degeneracy (besides rotational), *then* $\cancel{P}$ & $\cancel{T}$.

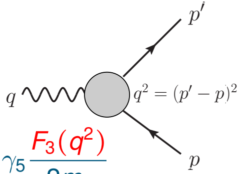
- State $|j^{\mathrm{P}}\rangle$ can be *'elementary'* particle (quark, charged lepton, $W^{\pm}$ boson, Dirac neutrino, ...) or a *'composite'* neutron, proton, nucleus, atom, molecule
- However, $d \neq 0$ *not* to be confused with huge EDMs of H_2O or NH_3 molecules: ground states of these molecules at non-zero temperatures or strong E-fields are mixtures of 2 opposite parity states: the theorem doesn't apply, neither $\cancel{T}$ nor $\cancel{P}$!

  Also not to be confused with *induced* EDM (polarization): *quadratic* (E^2) vs. linear (E) Stark effect $\leftrightarrow$ *induced* vs. permanent EDM
- If the interactions are described by a *local, Lorentz-invariant, hermitian* Lagrangian, then CPT invariance holds: thus $\cancel{T} \iff \cancel{CP}$

* *non*-selfconjugate particle is *not* its own antiparticle $\Rightarrow$ at least one "charge" *non*-zero

Permanent EDMs and Form Factors

Here $s = \frac{1}{2}$ fermions (f= quark, lepton, nucleon)



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

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

(Dirac $F_1(q^2)$, Pauli $F_2(q^2)$, electric dipole $F_3(q^2)$, and anapole $F_a(q^2)$ FFs)

- Quark, lepton or nucleon EDM $d_f := F_{3,f}(0)/(2m_f)$

$$\mathcal{H}_{\rm eff} = \mathrm{i}\frac{d_f}{2}\,\bar{f}\sigma^{\mu\nu}\gamma_5 f\, F_{\mu\nu} \longrightarrow -d_f\,\boldsymbol{\sigma}\cdot\mathbf{E} \longrightarrow \textit{linear}\ \text{Stark effect}$$

- Likewise chromo quark EDM with ~~CP~~ gluon-quark-quark vertex:

$$\mathrm{i}\frac{d_{cq}}{2}\,\bar{q}\sigma^{\mu\nu}\gamma_5 T^a G^a_{\mu\nu} q$$

or weak dipole moment (WDM) with Z-boson f-f vertex: $\mathrm{i}\frac{d_f^Z}{2}\,\bar{f}\sigma^{\mu\nu}\gamma_5 f\, Z_{\mu\nu}$.

Generic features of EDM, chromo EDM or WDM

$$\mathcal{L}_{\rm EDM} = -\mathrm{i}\frac{d_f}{2}\,\bar{f}\sigma_{\mu\nu}\gamma_5 f\,F^{\mu\nu} = -\mathrm{i}\frac{d_f}{2}\,\bar{f}_{\rm L}\,\sigma_{\mu\nu}f_{\rm R}\,F^{\mu\nu} + \mathrm{i}\frac{d_f}{2}\,\bar{f}_{\rm R}\,\sigma_{\mu\nu}f_{\rm L}\,F^{\mu\nu}$$

1. Sum of the mass dimension of these fields: $\frac{3}{2}+\frac{3}{2}+2=5$,
   $\hookrightarrow$ $\dim(d_f) = e\times$ length $= e\times$ mass^{-1} (such that $\int d^4x\,\mathcal{L} \sim \text{mass}^0$)
   $\hookrightarrow$ non-renormalizable *effective* interaction

2. For any non-zero EDM (or WDM), $\cancel{CP}$ is flavor *diagonal*!

   Note that $\cancel{CP}$ in SM model (via CKM matrix) is flavor *changing*.
   $\hookrightarrow$ extra $\sim 10^{-7}$ factor multiplies naive estimate $d_n \simeq 10^{-24}\,e\,$cm.

3. *Chirality* in $\mathcal{L}_{\rm EDM}$ flipped: $\frac{1}{2}(\mathbb{1}-\gamma_5)f = f_{\rm L} \leftrightarrow f_{\rm R} = \frac{1}{2}(\mathbb{1}+\gamma_5)f$

   $\Rightarrow$ fermion mass m_f insertion (e.g. via Higgs mechanism) needed:

   $$d_f \propto m_f^n\,,\qquad n = 1, 2, 3 \quad \text{(depending on the model of } \cancel{CP}\text{)}$$

   $\hookrightarrow$ $\cancel{CP}$ beyond SM: $\mathcal{L}^{\cancel{CP}}_{\rm BSM} = \cancel{\frac{1}{M_{\rm T\,viol}}\mathcal{L}_{\dim 5}} + \frac{1}{M^2_{\rm T\,viol}}\mathcal{L}_{\dim 6} + \ldots$

CP violation in the Standard Model

The conventional source: Kobayashi-Maskawa mechanism

Empirical facts: 3 generations of u/d quarks (& e/ν leptons)

- $0 < m_u < m_d < m_s < m_c < m_b < m_t$ and $m_e < m_\mu < m_\tau$
- quarks & leptons in mass basis $\neq$ quarks & leptons in weak-int. basis
- $\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{gauge-fermion}} + \mathcal{L}_{\text{gauge-Higgs}} + \mathcal{L}_{\text{Higgs-fermion}}$ is CP inv.,
  - with the exception of the θ term of QCD (see later)

    and the charged-weak-current interaction ($\subset \mathcal{L}_{\text{gauge-fermion}}$)

$$\mathcal{L}_{\text{c-w-c}} = -\frac{g_w}{\sqrt{2}} \sum_{ij=1}^{3} \bar{d}_{Li}\gamma^\mu V_{ij}\, u_{Lj}\, W_\mu^- - \frac{g_w}{\sqrt{2}} \sum_{ij=1}^{3} \bar{\ell}_{Li}\gamma^\mu U_{ij}\, \nu_{Lj}\, W_\mu^- + \text{h.c.}$$

  - V: 3×3 unitary quark-mixing matrix (Cabibbo-Kobayashi-Maskawa m.)

    3 angles + 1 $\cancel{CP}$ phase δ_{KM}

    U: 3×3 unitary lepton-mixing matrix (Maki-Nakagawa-Sakata matrix)

    3 angles +1(3) $\cancel{CP}$ phase(s) for Dirac (Majorana) ν_i's

$\not{C}\!\not{P}$ and EDMs and in the SM with $J_{\mathrm{KM}} = \mathrm{Im}(V_{tb}V_{td}^* V_{cd} V_{cb}^*) \simeq 3\cdot 10^{-5}$

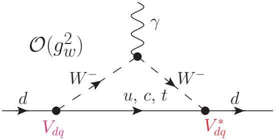
$$\propto \left(\frac{m_t^2-m_c^2}{M_{EW}^2}\right)\left(\frac{m_c^2-m_u^2}{M_{EW}^2}\right)\left(\frac{m_t^2-m_u^2}{M_{EW}^2}\right)\cdot\left(\frac{m_b^2-m_s^2}{M_{EW}^2}\right)\left(\frac{m_s^2-m_d^2}{M_{EW}^2}\right)\left(\frac{m_b^2-m_d^2}{M_{EW}^2}\right)\cdot J_{\mathrm{KM}} \simeq 10^{-15} J_{\mathrm{KM}},$$

Jarlskog (1985)

$$\hookrightarrow \boxed{(n_B-n_{\bar B})/n_\gamma\big|^{\mathrm{SM}}_{T\sim 20\mathrm{MeV}} \sim 10^{-20} \text{ and } d_n^{\mathrm{SM}} \sim 10^{-20}\cdot 10^{-14}\, e\,\mathrm{cm} \sim 10^{-34}\, e\,\mathrm{cm}}$$

EDM flavor-neutral $\Rightarrow$ predictions of KM mechanism tiny ($\propto G_F^2$):

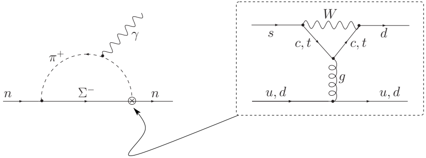
- 1-loop:



$\not{C}\!\not{P}$ phase δ_{KM} cancels
$\hookrightarrow$ prefactor real $\Rightarrow$ $d_q^{\text{1-loop}} = 0$

- 2-loop: $d_q^{\text{2-loop}} = d_{cq}^{\text{2-loop}} = 0$ (Shabalin (1978)).

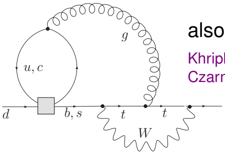
However, $d_{4\text{-}q}^{\text{2-loop}} \sim \mathcal{O}(g_W^4 g_s^2)$:



$d_n^{\mathrm{KM}} \simeq 10^{-32}\, e\,\mathrm{cm}$ because of long-range pion & 'strong penguin'

Gavela; Khriplovich & Zhitnitsky ('82)

- at $\geq$ 3-loops: $d_n^{\mathrm{KM}} \simeq 10^{-34} \ldots 10^{-31} e\,\mathrm{cm}$,

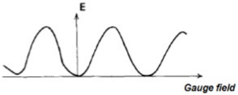


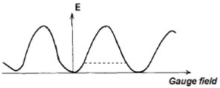
also $\mathcal{O}(g_W^4 g_s^2)$

Khriplovich (1986); Czarnecki & Krause ('97)

EDMs in the SM: unconventional θ-term mechanism

The topologically non-trivial vacuum structure of QCD





induces a direct $\cancel{P}\&\cancel{T} \rightsquigarrow \cancel{CP}$ interaction with a new parameter θ:

$$\mathcal{L}_{QCD} = \mathcal{L}^{\mathrm{CP}}_{\mathrm{QCD}} + \theta \frac{g_s^2}{64\pi^2}\epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

- Anomalous $\mathrm{U}_A(1)$ quark-rotations induce mixing with 'mass' term

$$\theta \frac{g_s^2}{64\pi^2}\epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma} \xrightarrow{\mathrm{U}_A(1)} -\bar\theta m_q^* \sum_f \bar q i\gamma_5 q_f \qquad (m_q^* = \frac{m_u m_d}{m_u+m_d} \text{ reduced mass})$$

  $\hookrightarrow$ *unknown* coupling constant is actually $\boxed{\bar\theta = \theta + \arg \mathrm{Det}\, \mathcal{M}_{\mathrm{quark}}}$

- Naive dim. analysis (NDA) estimate of $\bar\theta$-induced neutron EDM is

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

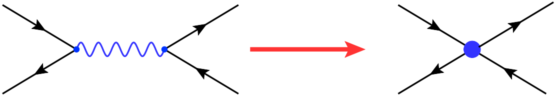
But $\boxed{|\bar\theta| < 10^{-10}}$ from upper bound $d_n^{\mathrm{emp}} < 2.9 \cdot 10^{-26}\, e\,\mathrm{cm}$ (Baker et al. (2006))

How to handle unknown physics beyond SM?

e.g. SUSY, multi-Higgs, Left-Right Symmetric Models, . . .

Roughly two methods

- Pick specific models (or rather classes of models)
  - extensive literature (now motivated by LHC constraints)
  - methods: (constituent) quark model estimates, Russian sum rules, lattice calculations, etc. (W. Marciano's talk)
- Application of Effective Field Theories (EFT), e.g.

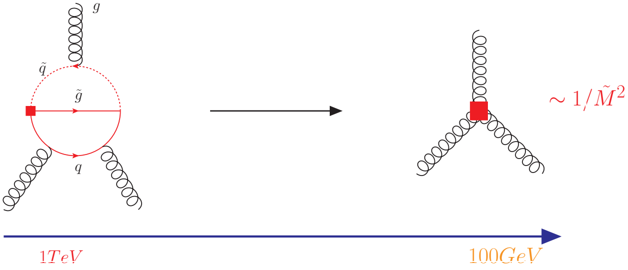


  - Write down *all* interactions among the relevant degrees of freedom (with masses $M <$ particular scale)
  - Interactions need to obey the relevant symmetries of the theory
  - Need a power-counting scheme to order the infinite # interactions

CP-violating sources beyond the SM (BSM)

Idea: BSM physics and also SM treated as effective field theories

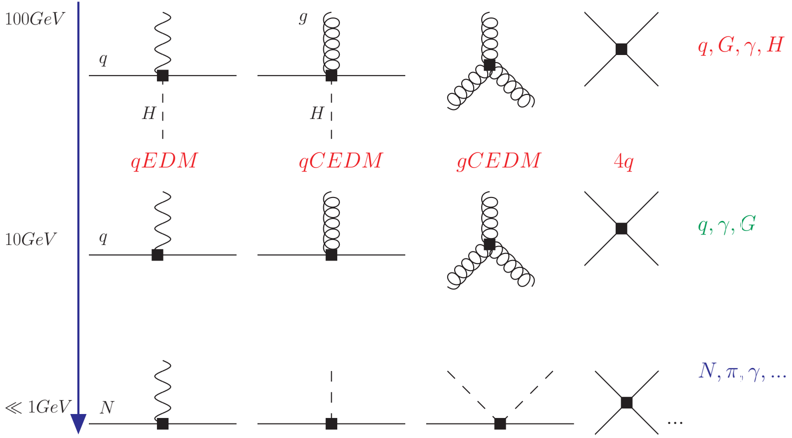
- All degrees of freedom beyond a specified scale are integrated out:
  $\hookrightarrow$remaining theory contains relevant degrees o.f. and non-relevant contact terms governed by symmetry: Lorentz + SM symmetries
- Relics of eliminated BSM physics ‘remembered’ by the values of the low-energy constants (LECS) of the CP-violating contact terms, e.g.



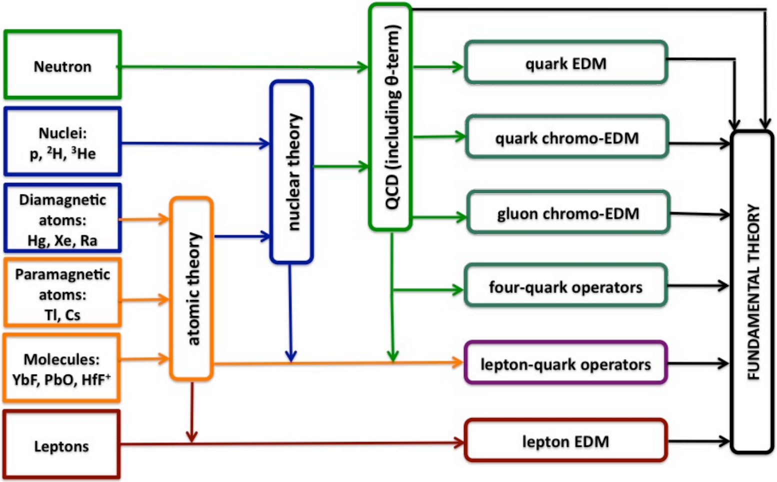
CP-violating sources beyond SM

Removal of the Higgs and transition to hadronic fields

Add to SM all possible T- and P-odd contact interactions



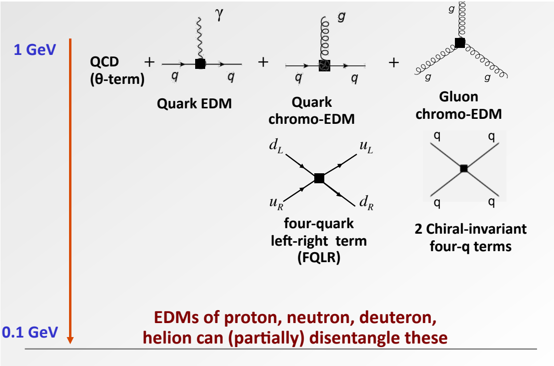
Finding the Sources of EDMs



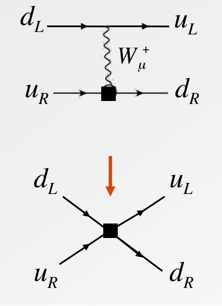
(adapted from Jordy de Vries, Jülich, March 14, 2013)

Relevant $\not{T}$ & $\not{P}$ quark sources up to dimension 6

W. Dekens & J. de Vries (2013)



FLQR term based on:



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

$$\text{Total \#} = 1(\bar\theta) + 2(\text{qEDM}) + 2(\text{qCEDM}) + 1(\text{gCEDM}) + 1(\text{FQLR}) + 2(\text{4q}) \;\; [+3(\text{semi-lept})]$$
$$= 1(\text{dim-four}) + 8[+3](\text{dim-six})$$

Caveat: implicit assumption that $m_s \gg m_u, m_d$

EDM-Translator from “quarkish” to “hadronic" language?

EDM-Translator from “quarkish” to “hadronic" language?

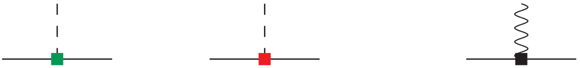
$\hookrightarrow$

Symmetries, esp. Chiral Symmetry and Goldstone Theorem
Low-Energy Effective Field Theory with External Sources
i.e. Chiral Pertubation Theory (suitably extended)

Hierachy among the sources at the hadronic EFT level

Each source transforms differently under chiral and isospin symmetry

$$\begin{array}{ccccccc} & & \cancel{CP},\ \mathrm{I} & & \cancel{CP},\ \cancel{\mathrm{I}} & & \cancel{CP},\ \mathrm{I} + \cancel{\mathrm{I}} & \\ \mathcal{L}^{\cancel{CP}}_{\text{EFT}} & = & g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N & + & g_1 N^\dagger \pi_3 N & + & N^\dagger(b_0 + b_1\tau_3) S^\mu v^\nu F_{\mu\nu} N & + \cdots \\ & & \Downarrow & & \Downarrow & & \Downarrow & \end{array}$$



...

dominant for $\bar{\theta}$ term	suppressed for $\bar{\theta}$ term	suppressed by $m_q^* \sim m_\pi^2$

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

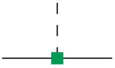
  $\hookrightarrow$ $\bar{\theta}$ source breaks chiral symmetry ($\propto m^*$) but conserves the isospin one
- $\boxed{g_0^\theta \gg g_1^\theta}$: NDA estimate: $g_1^\theta / g_0^\theta \sim \mathcal{O}(m_\pi^2/m_n^2)$ de Vries et al. (2011)

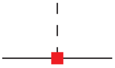
  resonance saturation: $g_1^\theta / g_0^\theta \sim \mathcal{O}(m_\pi/m_n)$! Bsaisou et al. (2013)

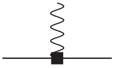
Hierachy among the sources at the hadronic EFT level

Each source transforms differently under chiral and isospin symmetry

$$
\begin{array}{ccccccc}
 & & \color{green}{\cancel{CP},\ \mathrm{I}} & & \color{red}{\cancel{CP},\ \cancel{\mathrm{I}}} & & \cancel{CP},\ \mathrm{I} + \cancel{\mathrm{I}} \\[1em]
\mathcal{L}^{\cancel{CP}}_{\mathrm{EFT}} & = & \color{green}{g_0} N^\dagger \vec{\pi}\cdot\vec{\tau} N & + & \color{red}{g_1} N^\dagger \pi_3 N & + & N^\dagger (b_0 + b_1\tau_3) S^\mu v^\nu F_{\mu\nu} N \quad + \cdots \\
 & & \Downarrow & & \Downarrow & & \Downarrow
\end{array}
$$







...

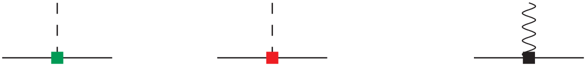
dominant for chromo qEDM source	dominant for chromo qEDM source	$m_q \sim m_\pi^2$ suppressed for chromo qEDM source

- chromo quark EDM: chiral & isospin symmetries are broken
  because of quark masses $\rightsquigarrow$ Goldstone theorem respected
- 4quark Left-Right EDM: explicit breaking of chiral & isospin symmetries
  because of underlying W boson exchange $\rightsquigarrow$ Goldstone theorem does not apply

Hierachy among the sources at the hadronic EFT level

Each source transforms differently under chiral and isospin symmetry

$$
\begin{array}{ccccccc}
 & & \cancel{CP},\ \mathrm{I} & & \cancel{CP},\ \cancel{\mathrm{I}} & & \cancel{CP},\ \mathrm{I}+\cancel{\mathrm{I}} \\
\mathcal{L}_{\mathrm{EFT}}^{\cancel{CP}} & = & g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N & + & g_1 N^\dagger \pi_3 N & + & N^\dagger(b_0+b_1\tau_3)S^\mu v^\nu F_{\mu\nu} N \quad +\cdots \\
 & & \Downarrow & & \Downarrow & & \Downarrow
\end{array}
$$



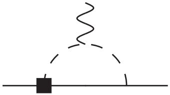
...

suppressed for quark EDM source | suppressed for quark EDM source | dominating for quark EDM source

- quark EDM: $N\pi$ (and NN) interactions are suppressed by $\alpha_{\mathrm{em}}/(4\pi)$
- gluon color EDM (and chiral-4quark EDM): relative $\mathcal{O}(m_\pi^2)$ suppression of $N\pi$ interactions because of Goldstone theorem

θ-Term Induced Nucleon EDM

single nucleon EDM:



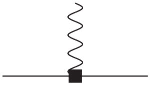
"controlled"

isovector

$\approx$

$\ll$

isoscalar



two unknown coefficients

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

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

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

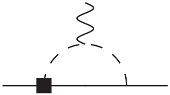
$$g_0^{\theta} = \frac{(m_n - m_p)^{\text{strong}}(1-\epsilon^2)}{4F_\pi\epsilon}\,\bar\theta \approx (-0.018 \pm 0.007)\bar\theta \qquad \left(\text{where } \epsilon \equiv \frac{m_u - m_d}{m_u + m_d}\right)$$

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

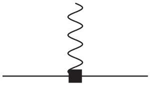
Ottnad et al. (2010); Bsaisou et al. (2013)

θ-Term Induced Nucleon EDM

single nucleon EDM:



isovector $\approx$ $\ll$ isoscalar



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

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

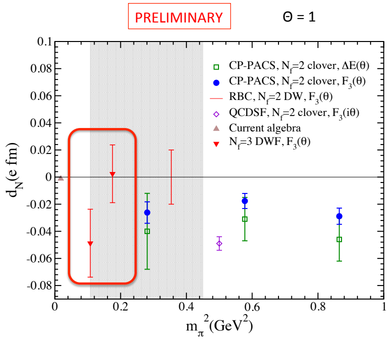
We'll always have ... the lattice

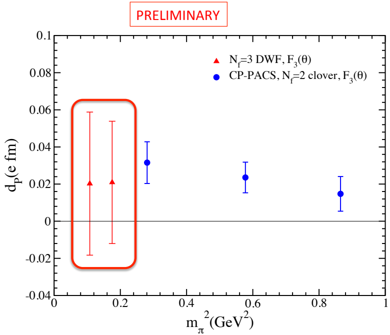
We'll always have ... the lattice

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

Results from *full* QCD calculations for the

neutron EDM and proton EDM





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

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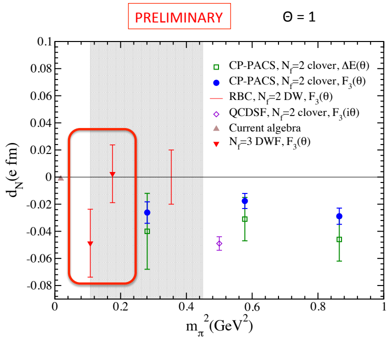

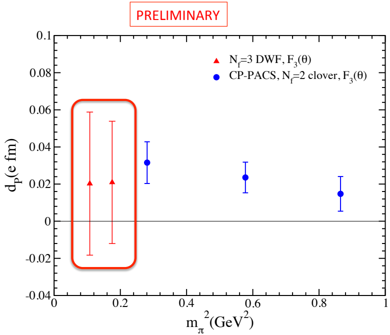

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Don't mention the ... light nuclei

θ-Term Induced Nucleon EDM:

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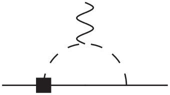
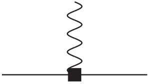
single nucleon EDM:



isovector $\approx$

$\ll$ isoscalar



"controlled"

unknown coefficient

$\longrightarrow$ lattice QCD required

Guo, Meißner (2012)

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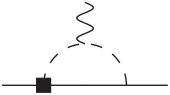

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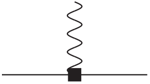


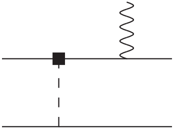
unknown coefficient

$\longrightarrow$ lattice QCD required

Guo, Meißner (2012)

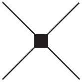
two nucleon EDM:

Sushkov, Flambaum, Khriplovich (1984)



controlled

$\gg$



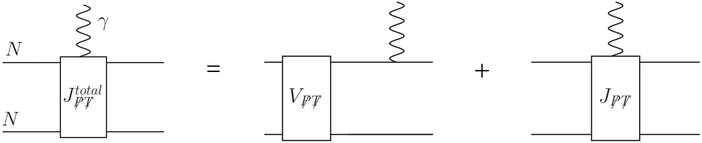
unknown coefficient

EDM of the Deuteron:

Deuteron 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)

Deuteron EDM from the $\bar{\theta}$-term

Bsaisou et al. (2013)

total deuteron EDM d_D:

$$d_D = d_n + d_p + d_D(2N)$$

- single-nucleon contribution: EFT has no predictive power
  $\longrightarrow$ experiment or lattice QCD needed

- two-nucleon contribution $d_D(2N)$: EFT has predictive power

$$d_D(2N) = \underbrace{-(0.59 \pm 0.39) \cdot 10^{-16}\, \bar{\theta}\, e\,\mathrm{cm}}_{\text{LO}} + \underbrace{(0.05 \pm 0.02) \cdot 10^{-16}\, \bar{\theta}\, e\,\mathrm{cm}}_{\text{N}^2\text{LO}}$$

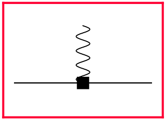
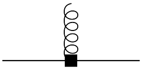
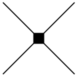
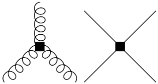
- helium-3: first results promising: $|d_{^3He}| > |d_n|$

de Vries et al. (2011); Song et al. (2012); Bsaisou et al. (in prep.)

testing procedures:

- strategy 1: measure d_n (or d_p) + Lattice-QCD $\rightsquigarrow\ \bar{\theta} \xrightarrow{\text{test}} d_D$
- strategy 2: measure d_n, d_p, d_D $\xrightarrow{d_D(2N)} \bar{\theta} \xrightarrow{\text{test}} d_{^3He}$

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

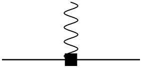
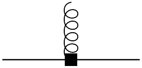
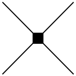
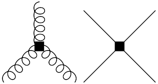
qEDM	*qCEDM*	*4qLR*	*gCEDM + 4qEDM*
$d_D \approx d_p + d_n$	$d_D > d_p + d_n$	$d_D > d_p + d_n$	$d_D \sim d_p + d_n$
$d_{^3He} \approx d_n$	$d_{^3He} > d_n$	$d_{^3He} > d_n$	$d_{^3He} \sim d_n$

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

2*N* contribution suppressed by photon loop!

here: only absolute values considered

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

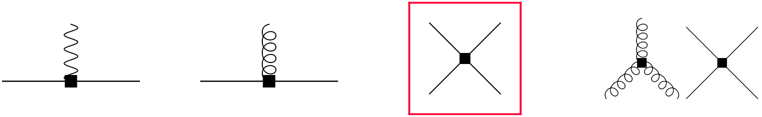
			
qEDM	*qCEDM*	*4qLR*	*gCEDM* + *4qEDM*
$d_D \approx d_p + d_n$ $d_{^3He} \approx d_n$	$d_D > d_p + d_n$ $d_{^3He} > d_n$	$d_D > d_p + d_n$ $d_{^3He} > d_n$	$d_D \sim d_p + d_n$ $d_{^3He} \sim d_n$

$\longrightarrow \quad g_0, g_1$

$2N$ contribution enhanced!

here: only absolute values considered

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



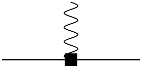
$qEDM$	$qCEDM$	$4qLR$	$gCEDM + 4qEDM$
$d_D \approx d_p + d_n$	$d_D > d_p + d_n$	$d_D > d_p + d_n$	$d_D \sim d_p + d_n$
$d_{^3He} \approx d_n$	$d_{^3He} > d_n$	$d_{^3He} > d_n$	$d_{^3He} \sim d_n$

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

$2N$ contribution enhanced!

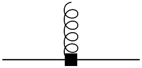
here: only absolute values considered

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



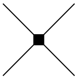
$qEDM$

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



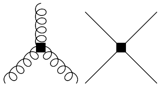
$qCEDM$

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



$4qLR$

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



$gCEDM + 4qEDM$

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

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

$2N$ contribution difficult to asses!

here: only absolute values considered

Summary and Outlook

- θEDM: relevant low-energy couplings quantifiable
  - strategy 1: measure d_n (or d_p) + Lattice-QCD $\leadsto \bar{\theta} \xrightarrow{\text{test}} d_D / d_{^3He}$
  - strategy 2: measure d_n, d_p & $d_D \xrightarrow{d_D(2N)} \bar{\theta} \xrightarrow{\text{test}} d_{^3He}$
- qEDM, qCEDM, 4QLR:
  - NDA required to asses sizes of low-energy couplings
  - disentanglement possible by measurements of d_n, d_p, d_D and $d_{^3He}$
- gCEDM, 4quark chiral singlet:
  controlled calculation/disentanglement difficult (lattice ?)
- Lattice might directly determine $\cancel{CP}$ $N\pi$ coupling constants g_0 and g_1, even for dimension-6 sources, which then can be used in d_D and $d_{^3He}$ EFT calculations
- next step: full calculation of $d_{^3He}$

Conclusions

- (Hadronic) EDMs play a key role in probing new sources of $\cancel{CP}$
- May be relevant for the baryon asymmetry of the universe (BAU)
  However, no theorem which directly links BAU with the EDMs.
  Moreover, no *smoking guns* exist so far
- EDMs of light nuclei provide independent information to nucleon EDMs and may be even larger & simpler
- Deuteron and helium-3 nuclei serve as isospin filters for EDMs

At least the EDMs of p, n, d, and ^{3}He EDMs have to be measured to disentangle the underlying physics

Many thanks to my colleagues

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

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

and: Werner Bernreuther, Bira van Kolck, Kolya Nikolaev

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