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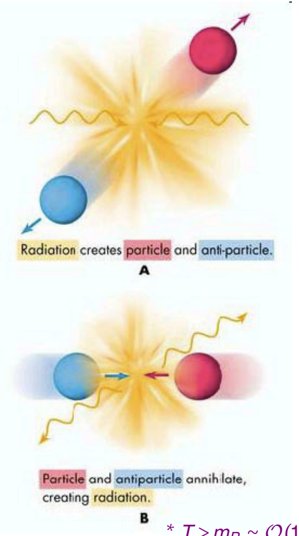
Theory IV: Electric Dipole Moments

Hadron Physics Summer School 2012

August 29, 2012 | Andreas Wirzba

Motivation: Matter Excess in the Early Universe*



matter : antimatter

as

1 000 000 001 : 1 000 000 000

Problem

Standard Model falls short by

several orders of magnitude!

$\longrightarrow$ What is missing?

* $T \geq m_B \simeq \mathcal{O}(1\,\mathrm{GeV})$: $(n_B - n_{\bar{B}})/(n_B + n_{\bar{B}}) \approx 10^{-9}$ [A.D. Dolgov (1997)]

Motivation: Matter Excess in the Present Universe

Matter-Antimatter Asymmetry

- Sakharov Conditions:

  JETP Lett. 5 (1967) 24

  1. baryon number B violation
  2. C- and CP(T)-symmetry violation
  3. no thermal equilibrium

- observed asymmetry * $(n_B - n_{\bar{B}})/n_\gamma = 6 \cdot 10^{-10}$
  vs. Standard Cosmological Model: $(n_B - n_{\bar{B}})/n_\gamma = 10^{-18}$
- Investigation of $\not{C}\not{P}$ induced by SM extensions required
- Complementary approaches:

  high energy ↔ high precision

* WMAP + COBE (2003): $n_B/n_\gamma = \left(6.1^{+0.3}_{-0.2}\right) \times 10^{-10}$, $n_\gamma \approx 411\,\mathrm{cm}^{-3}$ @ $T_{\mathrm{CMB}} \approx 2.736\,\mathrm{K}$

Outline:

1. Motivation: Matter–Antimatter Asymmetry
2. The Permanent EDM and its Features
3. CP-Violating Sources beyond the Standard Model
4. CP-Violating Sources at the Hadronic Level
5. Electric Dipole Moments of Neutron and Proton
6. Nuclear Electric Dipole Moments: the EDM of the Deuteron
7. Outlook

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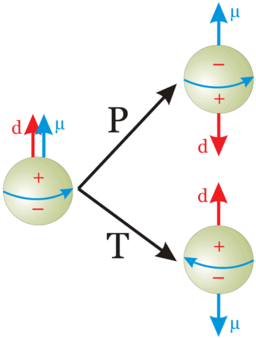
Come to the dark side of the force!

The Electric Dipole Moment (EDM)



EDM: $\vec{d} = \sum_i \vec{r}_i \, e_i \xrightarrow[\text{particles}]{\text{subatomic}} d \cdot \vec{\sigma}$

(polar) (axial)

$$H = -\mu \vec{\sigma} \cdot \vec{B} - d \vec{\sigma} \cdot \vec{E}$$

T: $H = -\mu \vec{\sigma} \cdot \vec{B} + d \vec{\sigma} \cdot \vec{E}$

P: $H = -\mu \vec{\sigma} \cdot \vec{B} + d \vec{\sigma} \cdot \vec{E}$

a non-vanishing permanent EDM of a stable subatomic particle is P- and T-violating

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

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

* calculation with input from Hg atom measurement: Griffith et al. (2009)

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

Khriplovich & Lamoreaux (1997)

- CP & P conserving magnetic moment ~ nuclear magneton μ_N

$$\mu_N = \frac{e}{2m_\mathrm{p}} \sim 10^{-14}\,\mathrm{e\cdot cm}$$

- EDM demands for parity P violation *:

$$\hookrightarrow \text{ pay the price } \sim 10^{-7}.$$

- EDM demands for CP violation :

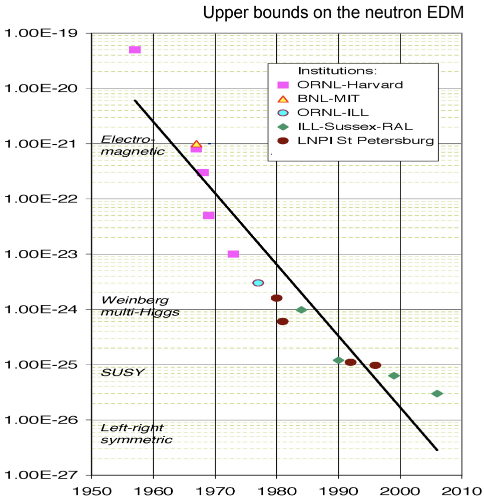
  Scale for $\not{CP}$ from K-decays† is $\sim 10^{-3}$ $\rightsquigarrow$ Pay this price.

- In summary:

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

* $G_F \cdot m_\pi^2 \sim 10^{-7}$ with $G_F \approx 1.166 \cdot 10^{-5}\,\mathrm{GeV}^{-2}$, † $|\eta_{+-}| \equiv \frac{|A(K_L^0 \to \pi^+\pi^-)|}{|A(K_S^0 \to \pi^+\pi^-)|} = (2.232 \pm 0.011) \cdot 10^{-3}$

Upper bounds on d_n in the course of time



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

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(Permanent) EDMs of (stable) non-selfconjugate* particles with spin

EDM operator $\vec{d} = \int d^3x \, \vec{x} \rho(\vec{x})$ in stationary state $|j\rangle$ of definite parity

$\langle j|\vec{d}|j\rangle = d\langle j|\vec{J}|j\rangle$: time reversal: $\vec{d} \to \vec{d}, \quad \vec{J} \to -\vec{J},$

space reflection: $\vec{d} \to -\vec{d}, \quad \vec{J} \to \vec{J}$

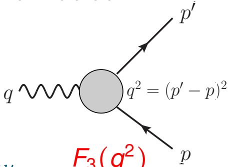
If $d \neq 0$ and state $|j\rangle$ has no degeneracy (besides rotations), *then* $\not{P}$&$\not{T}$.

- $|j\rangle$ can be 'elementary' particle (quark, charged lepton, $W^\pm$ boson, Dirac neutrino, ...) or a 'composite' neutron, proton, nuclei, atom, molecule
- Do not confuse with huge EDM of H_2O or NH_3 molecules — no $\not{P}$&$\not{T}$: Ground state of these molecules at non-zero temperatures is mixture of 2 opposite parity states: above theorem does not apply
- If the interactions are described by a *local, Lorentz-invariant, hermitian* Lagrangian, then CPT invariance holds: then $\not{T} \iff \not{CP}$
- Thus, under very mild assumptions: EDM $d \neq 0 \Rightarrow \not{P}$ and $\not{CP}$

* *self-conjugate particle* ≡ particle equal to its antiparticle: all its "charges" are zero

Permanent EDMs and Form Factors

- Consider here $s = \frac{1}{2}$ fermions: f= quark, lepton or 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 $d_f := F_{3,f}(0)/(2m_f)$

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

- Likewise $\not{C}\not{P}$ chromo (color quark) EDM in quark-gluon vertex

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

or weak dipole moment (WDM) in ffZ-boson 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

$$\mathcal{L}_{\rm EDM} = -\mathrm{i}\frac{d_f}{2}\,\bar{f}\sigma^{\mu\nu}\gamma_5 f\,F_{\mu\nu} = -\mathrm{i}\frac{d_f}{2}\,\bar{f}_L\,\sigma^{\mu\nu} f_R\,F_{\mu\nu} + \mathrm{i}\frac{d_f}{2}\,\bar{f}_R\,\sigma^{\mu\nu} f_L\,F_{\mu\nu}$$

- has mass dimension 5 (*i.e.* $\mathrm{dim}(d_f) = \mathrm{e}\times\mathrm{length} = \mathrm{e}\times\mathrm{mass}^{-1}$)
  $\Rightarrow$ non-renormalizable *effective* interaction
- In renormalizable theories, $\mathcal{L}_{\rm EDM}$ must be induced by quantum corrections, *i.e.* at 1-loop order or higher
- If EDM or chromo EDM or WDM non-zero, then $\not{CP}$ in *flavor-diagonal* amplitudes
  - Note: $\not{CP}$ in SM model via CKM matrix is flavor changing. Thus extra $\not{P} \simeq 10^{-7}$ factor multiplying naive estimate $d \simeq 10^{-24}\,\mathrm{e\,cm}$.
- $\mathcal{L}_{\rm EDM}$ flips fermion chirality $\frac{1}{2}(\mathbb{1}-\gamma_5)f = f_L \leftrightarrow f_R = \frac{1}{2}(\mathbb{1}+\gamma_5)f$
  $\Rightarrow$ fermion mass m_F term (e.g. via Higgs) must be involved:
  $$d_F \propto m_f^n\,, \quad n = 1, 2, 3$$
  i.e. mass scaling depends on model of $\not{CP}$

CP violation in the Standard Model (SM)

3 generations of 'up/down' quarks (& 'el./neutrino' leptons)

with interactions with gluons, the photon, $W^\pm$, Z, and Higgs boson

Empirical facts:

- $0 < m_u < m_d < m_s < m_c < m_b < m_t$ and $m_e < m_\mu < m_\tau$
- quarks & leptons in mass basis $\neq$ quarks & leptons in weak-interaction basis
- $\mathcal{L}_{SM} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm gauge-fermion} + \mathcal{L}_{gauge-Higgs} + \mathcal{L}_{Higgs-fermion}$ CP invariant,
  - except θ term of QCD (see below)
  - and charged-weak-current interaction $\mathcal{L}_{cc} \subset \mathcal{L}_{gauge-fermion}$

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

  - V: CKM (Cabibbo-Kobayashi-Maskawa matrix), U: lepton-mixing (Maki-Nakagawa-Sakata m.)

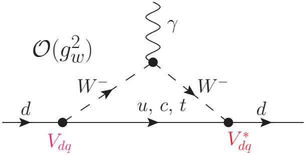
3 angles + 1 ~~CP~~ phase δ_{KM} — 3 angles +1(3) ~~CP~~ phase(s) for Dirac (Majorana) ν_i's

EDMs in the SM

- $\not{CP}$ effects $\propto \prod_{i>j}\left(\frac{m_{u_i}^2 - m_{u_j}^2}{M_{EW}^2}\right)\prod_{k>l}\left(\frac{m_{d_k}^2 - m_{d_l}^2}{M_{EW}^2}\right)\cdot J_{\rm KM} \simeq 10^{-15} J_{\rm KM}$

  with $J_{\rm KM} = \mathrm{Im}(V_{ud}^* V_{ub} V_{cb}^* V_{cd}) = -\mathrm{Im}(V_{cb}^* V_{cd} V_{td}^* V_{tb}) \simeq 3\cdot 10^{-5}$

  and, especially, flavor-changing (!)
- EDM flavor-neutral $\Rightarrow$ predictions of KM mechanism tiny ($\propto G_F^2$)
- 1-loop



  CP phase δ_{KM} cancels
  $\hookrightarrow$ prefactor real $\Rightarrow d_{\rm q}^{\rm 1\,loop} = 0$
- 2-loop: $d_{\rm q}^{\rm 2\,loop} = d_{\rm cq}^{\rm 2\,loop} = 0$ Shabalin (1978)
- 3-loop: $\mathcal{O}(g_W^4 g_s^2)$, δ_{KM} induces $d_{\rm q}$ only at ≥ 3 loops: $d_{\rm n}^{\rm KM} \simeq 10^{-34} \ldots 10^{-31}\,{\rm e\,cm}$

  Shabalin (1978); Khriplovich & Zhitnitsky (1982); Czarnecki & Krause (1997)

Effective Lagrangian on the quark/gluon level

Construction of an effective (low-energy) Lagrangian that incorporates the relevant $\not{C}\not{P}$ (light) quark, gluon & electromagnetic interactions

- SM (light quarks w. Higgs integrated out) with at most marginal(dim=4) terms:

$$
\begin{aligned}
\mathcal{L}_{SM} &= \mathcal{L}_{EW} + \mathcal{L}_{QCD} \qquad \equiv \mathcal{L}_{SM}^{\mathrm{CP}} + \mathcal{L}_{cc} \\
&= \mathcal{L}_{EW} + \sum_{f=u,d,s} \bar{q}_f^c \left(\mathrm{i}\gamma^\mu D_\mu^{cc'} - \delta^{cc'} m_f \right) q_f^{c'} - \tfrac{1}{4} G_{\mu\nu}^a G^{a\,\mu\nu}
\end{aligned}
$$

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&= \mathcal{L}_{EW} + \sum_{f=u,d,s} \bar{q}^c_f \left(\mathrm{i}\gamma^\mu D^{cc'}_\mu - \delta^{cc'} m_f\right) q^{c'}_f - \frac{1}{4} G^a_{\mu\nu} G^{a\,\mu\nu} + \frac{\theta\, g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\,\mu\nu}
\end{aligned}$$

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- Add $\not{CP}$ non-relevant (dim=5 and higher) effective terms to $\mathcal{L}_{SM}$:

$$\mathcal{L}_{SM} \quad \to \quad \mathcal{L}_{SM} + \mathcal{L}^{\not{CP}}_{\mathrm{dim}=5} + \mathcal{L}^{\not{CP}}_{\mathrm{dim}=6} + \cdots \equiv \mathcal{L}^{\mathrm{CP}}_{SM} + \mathcal{L}_{cc} + \mathcal{L}_{\not{CP}} \quad \text{with}$$

$$\begin{aligned}\mathcal{L}_{\not{CP}} &= \mathcal{L}^{\not{CP}}_{\mathrm{dim}=4} + \mathcal{L}^{\not{CP}}_{\mathrm{dim}=5} + \mathcal{L}^{\not{CP}}_{\mathrm{dim}=6} + \cdots \\ &= \frac{\theta g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\,\mu\nu} - \mathrm{i} \sum_{f=u,d,s} \frac{d_q}{2} \bar{q}_f \sigma^{\mu\nu} \gamma_5 q_f F_{\mu\nu} - \mathrm{i} \sum_{f=u,d,s} \frac{d_{cq}}{2} \bar{q}_f \sigma^{\mu\nu} \gamma_5 T^a q_f G^a_{\mu\nu} \\ &\quad + \frac{w_{3G}}{3} f^{abc} G^a_{\mu\nu} \tilde{G}^{b\,\nu\rho} G^{c\,\mu}_{\rho} + \sum_{f,g=u,d,s} C_{fg} \left(\bar{q}_f q_f \right) \left(\bar{q}_g \mathrm{i}\gamma_5 q_g \right)\end{aligned}$$

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$$= \mathcal{L}_{EW} + \sum_{f=u,d,s} \bar{q}^{c}_{f} \left(\mathrm{i}\gamma^{\mu} D^{cc'}_{\mu} - \delta^{cc'} m_f \right) q^{c'}_{f} - \tfrac{1}{4} G^{a}_{\mu\nu} G^{a\,\mu\nu} + \frac{\theta\, g_s^2}{32\pi^2} G^{a}_{\mu\nu} \tilde{G}^{a\,\mu\nu}$$

- Add $\not{CP}$ non-relevant (dim=5 and higher) effective terms to $\mathcal{L}_{SM}$:

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$$\mathcal{L}_{\not{CP}} = \mathcal{L}^{\not{CP}}_{\mathrm{dim}=4} + \mathcal{L}^{\not{CP}}_{\mathrm{dim}=5} + \mathcal{L}^{\not{CP}}_{\mathrm{dim}=6} + \cdots$$

$$= \frac{\theta g_s^2}{32\pi^2} G^{a}_{\mu\nu} \tilde{G}^{a\,\mu\nu} - \mathrm{i} \sum_{f=u,d,s} \frac{d_q}{2} \bar{q}_f \sigma^{\mu\nu} \gamma_5 q_f F_{\mu\nu} - \mathrm{i} \sum_{f=u,d,s} \frac{d_{cq}}{2} \bar{q}_f \sigma^{\mu\nu} \gamma_5 T^a q_f G^{a}_{\mu\nu}$$

$$+ \frac{w_{3G}}{3} f^{abc} G^{a}_{\mu\nu} \tilde{G}^{b\,\nu\rho} G^{c\,\mu}_{\rho} + \sum_{f,g=u,d,s} C_{fg} \left(\bar{q}_f q_f \right) \left(\bar{q}_g \mathrm{i}\gamma_5 q_g \right)$$

- Note: because of d_q and $d_{cq} \propto m_f \longrightarrow \mathcal{L}^{\not{CP}}_{\mathrm{dim}=5}$ effectively dim=6 !

Strong CP violation: dimension 4

- QCD has non-trivial vacua with topological quantum number $|n\rangle$:
- Cluster decomposition theorem $\longrightarrow$ QCD vacuum characterized by the parameter θ value: $|\theta\rangle = \sum_{n=-\infty}^{\infty} e^{-\mathrm{i}n\theta}|n\rangle$ with $\Delta n = \frac{g_s^2}{32\pi^2}\int d^4x_E\, \tilde{G}^a_{\mu\nu} G^{a\,\mu\nu} \in \mathbb{Z}$
- $\hookrightarrow \not{P}$ & $\not{T}$ (=$\not{CP}$) term in QCD Lagrangian
  (remember $\epsilon^{\mu\nu\alpha\beta} \neq 0$ only if $\mu\nu\rho\sigma$ = 0123 modulo permutations)

$$\mathcal{L}_{QCD} = \mathcal{L}_{QCD}^{\mathrm{CP}} + \theta \frac{g_s^2}{32\pi^2} \tilde{G}^a_{\mu\nu} G^{a,\mu\nu} = \mathcal{L}_{QCD}^{\mathrm{CP}} + \theta \frac{g_s^2}{32\pi^2} \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\alpha\beta}$$

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- Under $U_A(1)$ rotation of the quark fields $q_f \to {\rm e}^{{\rm i}\alpha\gamma_5/2} q_f \approx (1 + {\rm i}\frac{1}{2}\alpha\gamma_5) q_f$:

$$\mathcal{L}_{QCD} \to \mathcal{L}_{QCD}^{\rm CP} - \alpha \textstyle\sum_f m_f \bar{q} i\gamma_5 q + (\theta - N_f\alpha) \frac{g_s^2}{32\pi^2} \tilde{G}^a_{\mu\nu} G^{a,\mu\nu}$$

$$\hookrightarrow \mathcal{L}_{SM}^{\rm str\,\not{CP}} = \mathcal{L}_{SM}^{\rm CP} - \bar{\theta} m^* \textstyle\sum_f \bar{q}_f i\gamma_5 q_f \quad \text{with } \bar{\theta} = \theta + \arg\det\mathcal{M} \text{ and } m^* = \frac{m_u m_d}{m_u + m_d}$$

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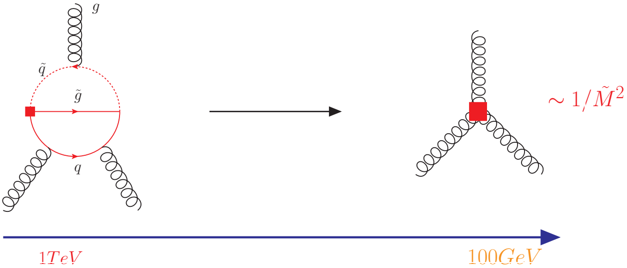
$$\hookrightarrow \mathcal{L}^{\rm str\,\not{CP}}_{SM} = \mathcal{L}^{\rm CP}_{SM} - \bar{\theta} m^* \sum_f \bar{q}_f i\gamma_5 q_f \quad \text{with } \bar{\theta} = \theta + \arg \det \mathcal{M} \text{ and } m^* = \frac{m_u m_d}{m_u + m_d}$$

- Estimate of natural θEDM size (note $\bar{\theta} \to 0$ if one $m_f \to 0$):

$$d_{\rm N}^{\theta} \sim \bar{\theta} \cdot \frac{e}{2m_N} \cdot \frac{m_q}{m_N} \sim \bar{\theta} \cdot 10^{-14}\,\mathrm{e\cdot cm} \cdot 10^{-2} \sim \bar{\theta} \cdot 10^{-16}\mathrm{e\cdot cm}$$

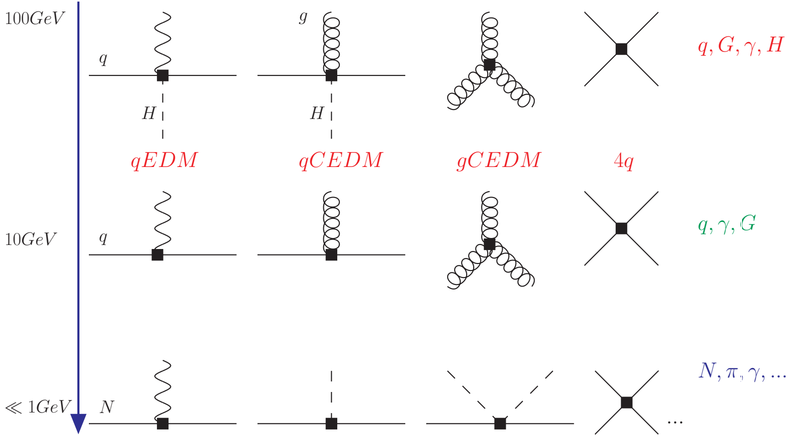
CP-violating sources beyond SM: dimension 6

- *CP*-violation from extensions of the standard model
  ⇒ SUSY, multi-Higgs, Left-Right Symmetric Models, ...
- Treatment of SM as an effective field theory:
  - All higher d.o.f. than those of a given scale are integrated out:
  - ↪Theory contains only relevant d.o.f. and non-relevant contact terms governed by symmetry: Lorentz + SM gauge symmetries
  - All information about the physics beyond this scale are collected in the values of the low-energy constants (LECS)



CP-violating sources beyond SM: dim. 6

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



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

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↪ Symmetries, esp. Chiral Symmetry and Goldstone Theorem
Low-Energy Effective Field Theory with External Sources

Effective CP-violating sources on the hadronic level:

Non perturbative techniques required: e.g. 2-flavor-ChPT

J. DeVries et.al. (2010, 2011)

J. Bsaisou, C. Hanhart, U.-G. Meißner, A.W. (2012, in preparation)

- Symmetries of QCD preserved by the effective field theory
- Association of terms by chiral transformation properties
  (each source transforms *differently* under chiral symmetry)

$\not{P}$ & $\not{T}$ hadronic operator	θ	qEDM 1	qEDM τ_3	qCEDM 1	qCEDM τ_3	gCEDM 4q
$N^\dagger \vec{\tau}\cdot\vec{\pi} N$	√	–	–	√	–	(√)
$N^\dagger \pi_3 N$	–	–	–	–	√	(√)
$N^\dagger S^\mu v^\nu N F_{\mu\nu}$	√	√	–	√	√	√
$N^\dagger S^\mu v^\nu \tau_3 N F_{\mu\nu}$	√	–	√	√	√	√

(√): Suppressed by Goldstone theorem

All sources contribute to nucleon EDMs

Measurement of nuclear EDMs required for disentanglement!

θ-term at the hadronic level:

θ-term related to charge symmetry breaking (CSB) mass term:

Crewther et al. (1979); Ottnad et al. (2010);
Mereghetti et al. (2011); de Vries et al. (2011)

$$\epsilon = (m_u - m_d)/(m_u + m_d), \quad m^* = \frac{m_u m_d}{m_u + m_d} = (m_u + m_d)(1 - \epsilon^2)/4$$

$$\boxed{\frac{m_u - m_d}{2} \bar{q}\tau_3 q} \quad \overset{s \to s + ip}{\longleftrightarrow} \quad \boxed{m^* \bar{\theta} \bar{q} i \gamma_5 q}$$

$$\downarrow \qquad\qquad\qquad\qquad \downarrow$$

$$\boxed{\frac{\delta M_{str}}{2} N^\dagger \left(\tau_3 - \frac{1}{2F_\pi^2} \vec{\tau} \cdot \vec{\pi} \pi_3\right) N} \quad \overset{m \to m + im^* \theta}{\longleftrightarrow} \quad \boxed{\frac{\delta M_{str}}{2} \frac{(1-\epsilon^2)\bar{\theta}}{2F_\pi^2 \epsilon} N^\dagger \vec{\tau} \cdot \vec{\pi} N}$$

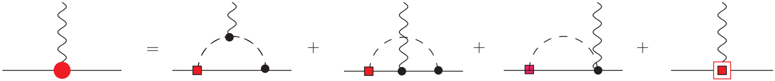
$$\delta M_{str} = (M_n - M_p)_{str}$$

Non-perturbative part of πNN-vertex fixed by CSB studies:
$\delta M_{str} = (2.0 \pm 0.3)$ MeV [Gasser, Leutwyler (1982)]

θ-term induced Nucleon EDM: complete 1-loop calculation

chiral $\mathcal{L}$: Crewther, di Vechia, Veneziano & Witten (1979/80)

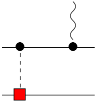
complete 1-loop: Ottnad, Kubis, Meißner & Guo (2010)



$$d_n = d_n^{\rm tree} + d_n^{\rm loop} = \left([2.9 \pm 1.1] + [(-3 \cdots -5) \pm 2]\right) \times 10^{-16} \bar{\theta}\, e\, \mathrm{cm}$$

$\Rightarrow$ $\bar{\theta} < 3 \times 10^{-10}$ (using $d_n < 3 \times 10^{-26}\, e\, \mathrm{cm}$)

- Counter term at LO: estimate is model dependent
  $\Rightarrow$ Lattice calculation required for reliable prediction
- EDM of p and n not related by isovector symmetry

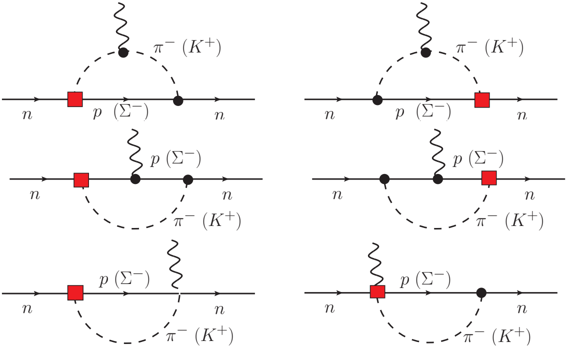


Nuclear EDMs might be larger and 'simpler'

Sushkov, Flambaum, Khriplovichv (1984)

Loop contributions to neutron EDM d_n

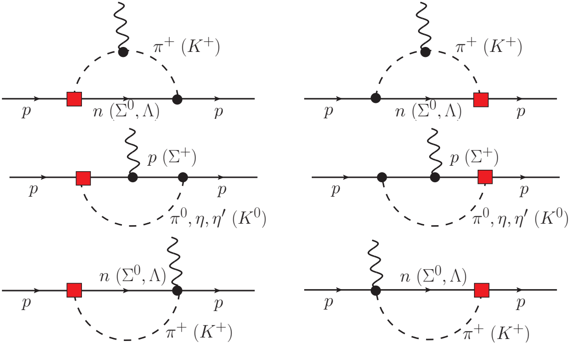
Ottnad, Kubis, Meißner & Guo, PLB **687** (2010) 42



- Note that the participating baryons and mesons in the loops are both charged and the baryons and mesons are the same in both loop topologies

Loop contributions to the proton EDM d_p

Ottnad, Kubis, Meißner & Guo, PLB **687** (2010) 42



- In contradistinction to d_n, the graphs relevant for d_p are *not symmetric* with respect to the photon coupling
- Note the additional neutral mesons in the second loop topology

Why $d_{\rm n} \neq -d_{\rm p}$?

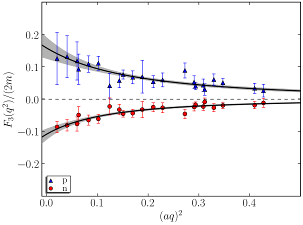
- $d_{\rm p}$ has additional (counter) terms due to
  - the contributions of additional neutral loop baryons
  - and contributions of additional neutral loop mesons
  - and the electric charge of the proton: additional LECs since $[Q, B_{\rm p}] \neq 0$ while $[Q, B_{\rm n}] = 0$.
- In the lattice calculation, additional noise because the charge form factor $F_1(q^2)$ and the electric dipole form factor $F_3(q^2)/2m_N$ mix in the electromagnetic current of the proton.

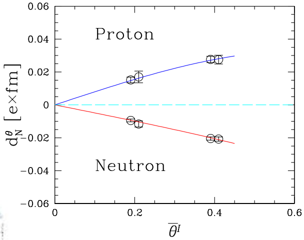
First lattice results for the nucleon EDM

R. Horsley et al., arXiv:0808.1428v2

- simulation details: $V = 16^3 \times 32$, $a \simeq 0.11\,\mathrm{fm}$, $m_\pi/m_\rho \simeq 0.8$ (!)
- proton and neutron dipole form factors:

(here $\bar\theta^I = 0.2$ with $\bar\theta = -\mathrm{i}\bar\theta^I$)





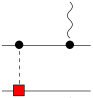
- extract:

$$d_{\rm n} = -0.049(5)\,\bar\theta\,\mathrm{e\,fm}\,, \quad d_{\rm p} = 0.080(10)\,\bar\theta\,\mathrm{e\,fm} \to |\bar\theta| < 6\cdot 10^{-12}$$

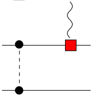
- Note: no isovector symmetry, $d_{\rm p} \neq -d_{\rm n}$!
- $d_{\rm p}$ noisy since $F_1(0)$ has to be subtracted from $\langle p', s'|J^\mu|p, s\rangle$

Nuclear EDM — Two-Nucleon Contribution

for gCEDM and 4q; changes for θ-term and qCEDM in [...];

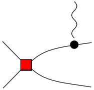


$$\frac{e\delta q}{f_\pi}\,\frac{1}{m_\pi^2}\,\frac{1}{E}\,\frac{m_\pi^2}{\Lambda f_\pi}\,[\times 1] \qquad \sim 1\ [1]$$

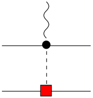


$$\frac{e\delta q}{\Lambda}\,\frac{1}{E}\,\frac{1}{f_\pi^2}\left[\times\frac{m_\pi^2}{\Lambda^2}\right] \qquad \sim 1\ \left[\ln\left(\frac{m_\pi^2}{\mu^2}\right)\frac{m_\pi^2}{\Lambda^2}+\mathrm{C}\right]$$

Sushkov, Flambaum, Khriplovich (1984)



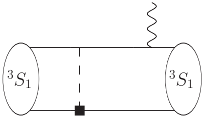
$$\frac{e\delta q}{\Lambda}\,\frac{1}{E}\,\frac{1}{f_\pi^2}\left[\times\frac{m_\pi^2}{\Lambda^2}\right] \qquad \sim 1\ \left[\frac{m_\pi^2}{\Lambda^2}\right]$$



$$\frac{e\delta q}{f_\pi M}\,\frac{1}{m_\pi^2}\,\frac{m_\pi^2}{\Lambda f_\pi}\,[\times 1] \qquad \sim \frac{E}{\Lambda}\ \left[\frac{E}{\Lambda}\right]$$

pion ranged operators enhanced for θ-term and qCEDM

Two-Nucleon Contribution to the Deuteron EDM at LO



$= ie(1 + \tau_3)$

$N^\dagger \vec{\pi} \cdot \vec{\tau} N$: $\quad {}^3S_1 \xrightarrow{\not{CP}} {}^1P_1 \xrightarrow{\gamma} {}^3\not{S}_1$

$N^\dagger \pi_3 N \quad$: $\quad {}^3S_1 \xrightarrow{\not{CP}} {}^3P_1 \xrightarrow{\gamma} {}^3S_1$

$\Rightarrow$ No θEDM contribution to ^2H at LO
θEDM contribution to ^3He at LO

in $G_\pi^{(1)} \times$ e fm

State	CDBonn [U] (3)	AV18 [U] (3)	Reid93 [U] (2)	ZRA [U] (1)
$^3S_1$	$-1.46 \cdot 10^{-2}$	$-1.41 \cdot 10^{-2}$		
$^3D_1$-adm.	$-0.48 \cdot 10^{-2}$	$-0.49 \cdot 10^{-2}$		
Total	$-1.94 \cdot 10^{-2}$	$-1.91 \cdot 10^{-2}$	$-1.92 \cdot 10^{-2}$	$-1.8 \cdot 10^{-2}$

(1): Khriplovich, Korkin (2000), J. de Vries et al. (2011)
(2): Afnan, Gibson (2010)
(3): Bsaisou, Hanhart, Meißner, Wirzba, . . . (2012, in prep.)

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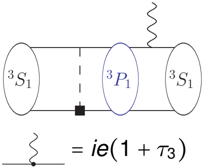

$N^\dagger \vec{\pi}\cdot\vec{\tau} N$: $\;{}^3S_1 \xrightarrow{\not{CP}} {}^1P_1 \xrightarrow{\gamma} {}^3\not{S}_1$

$N^\dagger \pi_3 N \;\;:\;\; {}^3S_1 \xrightarrow{\not{CP}} {}^3P_1 \xrightarrow{\gamma} {}^3S_1$

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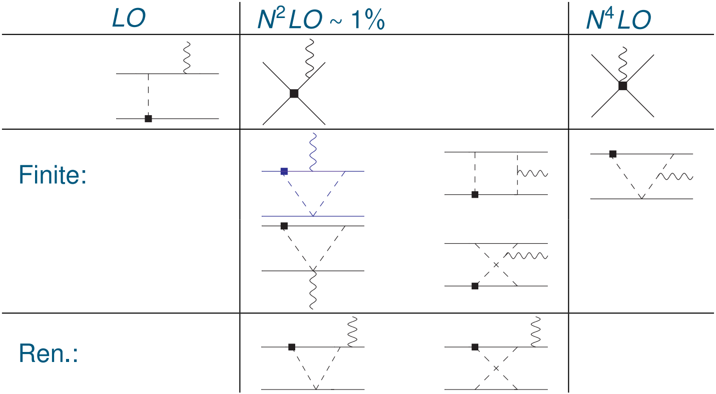
Total	$-1.94\cdot10^{-2}$	$-1.91\cdot10^{-2}$	$-1.92\cdot10^{-2}$	$-1.8\cdot10^{-2}$
$^3P_1$-int.	$0.43\cdot10^{-2}$		$0.39\cdot10^{-2}$	
Total	$-1.51\cdot10^{-2}$		$-1.52\cdot10^{-2}$	

(1): Khriplovich, Korkin (2000), J. de Vries et al. (2011)
(2): Afnan, Gibson (2010)
(3): Bsaisou, Hanhart, Meißner, Wirzba, . . . (2012, in prep.)

Two-Nucleon Contribution to the Deuteron EDM at NLO


$= N^\dagger \pi_3 N$ (qCEDM)

Bsaisou, Hanhart, Meißner, Wirzba . . . (2012, in prep.)



- All other topologies yield no EDM contribution, blue: also θEDM contr.
- Consistent power counting scheme

Outlook:

source	θ	qEDM		qCEDM		gCEDM
		1	τ_3	1	τ_3	4q
p	√	√	√	√	√	√
n	√	√	√	√	√	√
^2H					√	√
^3He	√			√	√	√

- EDMs are ideal probes for CP violation in the hadronic sector
- EDMs of light nuclei provide independent information to p and n
- EDMs of light nuclei may be larger & simpler than nucleon EDMs
- qEDM dominates if nuclear EDM is sum of nucleon EDMs
- Nuclear calculation possible up to accuracy of a few %
- Deuteron is a filter for the isospin-dependent qCEDM
- θEDM: $d_{^3\mathrm{He}} - 2d_\mathrm{p} - d_\mathrm{n} \quad \Leftrightarrow \quad \bar{\theta} \quad \Leftrightarrow$ p-,n-EDM

Outlook: *May the force be with us!*

source	θ	*qEDM*		*qCEDM*		*gCEDM*
		1	τ_3	1	τ_3	4q
p	√	√	√	√	√	√
n	√	√	√	√	√	√
^2H					√	√
^3He	√			√	√	√

- EDMs are ideal probes for CP violation in the hadronic sector
- EDMs of light nuclei provide independent information to p and n
- EDMs of light nuclei may be larger & simpler than nucleon EDMs
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- θEDM: $d_{^3\mathrm{He}} - 2d_\mathrm{p} - d_\mathrm{n} \quad \Leftrightarrow \quad \bar\theta \quad \Leftrightarrow$ p-,n-EDM

A measurement of *p*, *n*, *d*, and ^{3}He EDM is necessary to learn about the underlying physics