Theory Outlook
EDM Searches at Storage Rings

ECT*, Trento, October 5, 2012 | Andreas Wirzba
Outline:

1. Observations and the physics case
2. Theory input
3. What to measure?
4. Reliable quantitative statements
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Come to the dark side of the force!
Naive estimate of the EDM scale of the nucleon
Khriplovich & Lamoreaux (1997); Kolya Nikolaev’s talk

- CP & P conserving magnetic moment $\sim$ nuclear magneton $\mu_N$
  \[ \mu_N = \frac{e}{2m_p} \sim 10^{-14} \text{ e} \cdot \text{cm} \]

- EDM $\neq 0$ requires parity P violation $^*$:
  $\Rightarrow$ pay the price $\sim 10^{-7}$.

- EDM $\neq 0$ requires CP violation $^\dagger$: the price is $\sim 10^{-3}$.

In summary:

\[ d_N \sim 10^{-7} \times 10^{-3} \times \mu_N \sim 10^{-24} \text{ e} \cdot \text{cm} \]

In SM (with $\bar{\theta} \equiv 0$): extra P violation to undo flavor change:

\[ d_N^{\text{SM}} \sim 10^{-7} \times 10^{-24} \text{ e} \cdot \text{cm} \sim 10^{-31} \text{ e} \cdot \text{cm} \]

More sophisticated calculations: Ramsey-Musolf’s & Uraltsev’s talks

$^*$ $G_F \cdot m^2_\pi \sim 10^{-7}$ with $G_F \approx 1.166 \cdot 10^{-5} \text{ GeV}^{-2}$,
$^\dagger |\eta_{+-}| \equiv \frac{|A(K^0_L \rightarrow \pi^+ \pi^-)|}{|A(K^0_S \rightarrow \pi^+ \pi^-)|} = (2.232 \pm 0.011) \cdot 10^{-3}$
The physics case
The $N$-EDM range for testing or excluding theories beyond $\text{SM}_{\bar{\theta}=0}$:

\[
\therefore \quad 10^{-24} \text{e} \cdot \text{cm} < d_N < 10^{-31} \text{e} \cdot \text{cm}
\]

Using current bound $d_n < 2.9 \cdot 10^{-26} \text{e} \cdot \text{cm}$ & $d_p < 7.9 \cdot 10^{-25} \text{e} \cdot \text{cm}$


\[\rightarrow \text{the actual test range is rather}\]

\[\therefore \quad 10^{-26} \text{e} \cdot \text{cm} < d_N < 10^{-31} \text{e} \cdot \text{cm}\]

Quoting Michael Ramsey-Musolf:

- ‘$n$-EDM has killed more theories than any other single experiment’
- EDMs provide a powerful probe on EW baryogenesis
- *Next generation of EDM searches* ($\sim 10^{-28} \text{e} \cdot \text{cm}$) *may conclusively test* MSSM EW baryogenesis.

Bill Marciano: $H \rightarrow \gamma\gamma$ beyond SM expectations ($1.5 - 2\sigma$) testable in 2-loop Higgs contributions to fermion EDMs rather than in diboson decays at LHC
Input from many corners of theoretical physics:

(similarly to EDM measurements which use expertise/experts from many areas of experimental research, accelerator physics, non-linear dynamics)

- High energy (beyond-SM) physics, LHC results (Bill Marciano)
- EW Baryogenesis (Michael Ramsey-Musolf)
- Lattice QCD (Gerrit Schierholz and Taku Izubuchi)
- Chiral perturbation theory for nEDM (and pEDM) and relation (chiral & volume extensions) to Lattice QCD (Ulf Meißner)
- Low-energy effective field theory for deuteron, $^3$He (and $^3$H) EDMs (Bira van Kolck, Jan Bsaisou, Jordy de Vries)
What to measure (\textit{?})
in the case of quark- and/or gluon-type EDMs?

1. A positive measurement of the permanent EDM of any non-self-conjugating particle with spin (elementary or composed) is sufficient to establish the principle.

2. To disentangle the mechanism, more measurements are needed: $d_n$, $d_p$, $d_D$, ... for quark- and gluon-type EDMs.

3. The most distinctive mechanism is the dimension-four QCD $\theta$-term. Measurements of the proton and neutron (and the deuteron) EDM might be sufficient to extract and test the $\bar{\theta} \leq 10^{-10}$ angle.
Reliable quantitative statements

Note: EDMs measurements are low-energy measurements

Thus, the pertinent theoretical treatment must be of low-energy and non-perturbative nature! We have two candidates:

1. lattice QCD
2. and low-energy effective field theories (extensions of chiral perturbation theory)
   - In the long run lattice QCD will have the highest potential to predict proton and neutron EDMs:
   - at least for the QCD $\theta$-term induced EDMs.
   - But applicability is an open question for
     - dimension-six operators beyond the SM (e.g. qEDM, qCEDM, gCEDM or four-quark EDMs)
     - and even more so for light nuclei (e.g. d, $^3$He, t, or $^7$Li)
The role of EFT
EDM-Translator from “quarkish” to “hadronic” language?

[Image of C-3PO and R2-D2 from Star Wars]
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Symmetries, esp. Chiral Symmetry and Goldstone Theorem
Low-Energy Effective Field Theory with External Sources
Outlook:

- EDMs are **ideal probes** for the $CP$ physics beyond the SM.
- 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.
- $\theta$EDM: $d_{3\text{He}} - 2d_p - d_n \iff \bar{\theta} \iff \text{p-,n-EDM}$. 

\[ d_{3\text{He}} - 2d_p - d_n \]
Outlook: May the force be with us!

- EDMs are ideal probes for the $\mathcal{CP}$ physics beyond the SM
- EDMs of light nuclei provide independent information to $p$ and $n$
- EDMs of light nuclei may be larger & simpler than nucleon EDMs
- $q$EDM 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 $q$CEDM
- $\theta$EDM: $d^{3}_{\text{He}} - 2d_{p} - d_{n} \leftrightarrow \bar{\theta} \leftrightarrow p-,n$-EDM

From the theory point: a measurement of $p$, $n$, $d$, and $^{3}\text{He}$ EDM is necessary to disentangle the underlying physics