Electric dipole moments: a theory overview

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A permanent Electric Dipole Moment (EDM)

- signal of $T$ and $P$ violation ($CP$)
- insensitive to $CP$ violation in the SM
- BSM $CP$ violation needed for baryogenesis

neutron

- large window & strong motivations for new physics!

current bound
\[ |d_n| < 3.0 \cdot 10^{-13} \text{ e fm} \]
J. M. Pendlebury et al., ‘15

SM
\[ d_n \sim 10^{-19} \text{ e fm} \]
M. Pospelov and A. Ritz, ‘05
what do we learn from EDM measurements?
multiscale problem, involving atomic, nuclear & hadronic physics
The reach of EDM experiments

Non standard top couplings: top weak-EDM

- electron EDM much more constraining than LHC

\[ \Lambda > 7 \text{ TeV} \]
Non standard top couplings: top chromo-EDM

- runs onto gluon-CEDM and light-quark CEDM $\Longrightarrow$ nEDM
- nucleon ME have $\sim 100\%$ uncertainties
  bounds weaker by factor of 10, commensurable with LHC
Effective Field Theories

- model independent link to collider phenomenology
- minimal set of low-energy operators
- connection with flavor/low energy probes
- from quarks to hadrons non-perturbative matching (LQCD)
- EDMs of nucleons & light nuclei
EFT for T violations

- one dim-4 operator: QCD $\bar{\theta}$ term

$$\mathcal{L}_{T4} = m\bar{\theta}q_i\gamma_5q$$

in principle $\bar{\theta} = O(1)$

... strong CP problem

- 9 (+ 10 w. strangeness) dim-6 hadronic operators:

  - gluon CEDM $C_{\tilde{G}}$
  - quark (C)EDM $c_{g,\gamma}^{(u,d,s)}$
  - LL RR 4-quark $\Xi_{ud,us,ds}^{(1,8)}$
  - LR LR 4-quark $\Sigma_{ud,us}^{(1,8)}, \Sigma_{us,S}^{(1,8)}$

- electron, muon EDMs
  + 3 (+1) scalar and tensor semileptonic operators

$$\mathcal{L}_{qe} = C_{Le\tilde{d}Q} \bar{\tilde{e}}_L e_R \tilde{d}_R d_L + C_{LeQu}^{(1)} \bar{\tilde{e}}_L e_R \bar{u}_L u_R + C_{LeQu}^{(3)} \bar{e}_L \sigma^\mu\nu e_R \bar{u}_L \sigma_\mu\nu u_R$$
• new physics models induce one, a subset or all these operators

- qEDM $c_{\gamma}^{(u,d)}$
- qCEDM $c_{g}^{(u,d)}$
- gCEDM $C_{\tilde{G}}$
- LR LR $\Sigma^{ud}$
- LL RR $\Xi^{ud}$
- (semi-) leptonic

- split SUSY
- MSSM
- 2 Higgs Doublet Model
- Leptoquarks
- LR symmetric models

From quarks to nucleons: quark bilinears.

- single nucleon charges well determined by LQCD
- and so are qEDM contribs. to $d_n$
- and $C_{LedQ}, C_{LeQu}^{(1,3)}$ to molecules, paramagnetic/diamagnetic atoms

I. Khriplovich and S. Lamoreaux, ‘97; K. Yanase et al, ‘18

little theory uncertainty on (semi-) leptonic operators
From quarks to nucleons. Hadronic operators.

\[ \mathcal{L}_T = -2\bar{N} \left( \bar{d}_0 + \bar{d}_1 \tau_3 \right) S^\mu \nu NF_{\mu \nu} - \frac{\bar{g}_0}{F_\pi} \bar{N} \pi \cdot \tau N - \frac{\bar{g}_1}{F_\pi} \tau_3 \bar{N} N \]

- operators in \( \mathcal{L}_T \) & scaling of couplings dictated by chiral symmetry
- \( \bar{d}_0, \bar{d}_1 \) neutron & proton EDM,
  one-body contribs. to \( A \geq 2 \) nuclei
- \( \bar{g}_0, \bar{g}_1 \) pion loop to nucleon & proton EDMs
  leading \( \mathcal{T} \) OPE potential

relative size of the coupling
depends on chiral/isospin properties of \( \mathcal{T} \) source
From quarks to nucleons. Hadronic operators.

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From quarks to nucleons. Hadronic operators

\[ \bar{\theta} \times \epsilon_\chi \]

\[ \Lambda_\chi^2 \bar{c}^{(u,d)}_g \times \epsilon_\chi \]

\[ \Lambda_\chi^2 \bar{c}_\gamma^{(u,d)} \times \epsilon_\chi \]

\[ \Lambda_\chi^2 \Xi^{(1,8)}_{u,d} \times \epsilon_\chi \]

\[ \Lambda_\chi^2 \bar{C}_\tilde{G} \times \epsilon_\chi \]

\[ \Lambda_\chi^2 \Sigma^{(1,8)}_{u,d} \times \epsilon_\chi \]

\[ \bar{g}_0 / F_\pi \]

\[ \bar{g}_1 / F_\pi \]

\[ \bar{d}_0 F_\pi \]

\[ \bar{d}_1 F_\pi \]

\[ \Lambda_\chi \sim 1 \text{ GeV} \]

\[ \epsilon_\chi \sim \frac{m_\pi}{\Lambda_\chi} \sim 0.15 \]

WARNING

naive dim. analysis!

- chiral breaking operators generate large \( \bar{g}_0 \)
- chiral & isospin breaking large \( \bar{g}_1 \)
- enhanced nuclear EDMs
- can we be more precise?
Pion-nucleon couplings. $\tilde{\theta}$ term.

- $\chi$-symmetry relates $\pi$-N couplings to spectral properties
- LQCD calculations of $m_n - m_p$ determines $\bar{g}_0$

$$ \frac{\bar{g}_0}{F_\pi}(\bar{\theta}) = \left(\frac{m_n - m_p}{F_\pi}\right)|_{\text{str}} \frac{1 - \varepsilon^2}{2\varepsilon} \bar{\theta} = (15.5 \pm 2.0 \pm 1.6) \cdot 10^{-3} \bar{\theta} $$

LQCD $\chi$PT

- precise prediction of chiral log in $d_n(\bar{\theta})$
Pion-nucleon couplings. qCEDM

• \( \pi \)-N couplings poorly determined

\[
\begin{align*}
\frac{\bar{g}_0}{F_\pi} &= (5 \pm 10) (m_u \tilde{c}_g^{(u)} + m_d \tilde{c}_g^{(d)}) \text{ fm}^{-1} \\
\frac{\bar{g}_1}{F_\pi} &= (20^{+40}_{-10}) (m_u \tilde{c}_g^{(u)} - m_d \tilde{c}_g^{(d)}) \text{ fm}^{-1}.
\end{align*}
\]

QCD sum rules, M. Pospelov and A. Ritz, ‘05

PRELIMINARY thanks to D. Brantley, CalLat coll.
Pion-nucleon couplings. qCEDM

can use similar relations to spectrum

\[ \bar{g}_0 = (m_u \tilde{c}^{(u)}_g + m_d \tilde{c}^{(d)}_g) \left( \frac{d}{d\tilde{c}_3} - r \frac{d}{d\tilde{m}_\epsilon} \right) (m_n - m_p) \]

\[ \bar{g}_1 = (m_u \tilde{c}^{(u)}_g - m_d \tilde{c}^{(d)}_g) \left( \frac{d}{d\tilde{c}_0} + r \frac{d}{d\tilde{m}} \right) (m_n + m_p) \]

\[ \tilde{c}_{0,3}: \text{iso-scalar (-vector) chromo-magnetic operators} \]

results coming soon!
Nucleon EDM

- LQCD effort to determine nucleon EDM from $\bar{\theta}$, $\tilde{c}_g^{(u,d)}$, $C\tilde{G}$
  - BLN-RIKEN, LANL, Michigan State, Cyprus, Bonn-Julich,…
- chiral symmetry predicts $m_\pi$ dependence
  & $q^2$ dependence of the EDFF $F_3$

see Sergey Syritsyn’s talk
From nucleons to nuclei. Light nuclei

- in storage ring experiments, constituent EDMs are not screened
- correction to the wavefunction dominate for $\chi$-breaking operators unless forbidden by isospin selection rules
- one- and two-body contribs. comparable for $\chi$-inv operators
- nuclear theory is well under control

From nucleons to nuclei. Light nuclei

<table>
<thead>
<tr>
<th>Potential (references)</th>
<th>$d_n$</th>
<th>$d_p$</th>
<th>$\tilde{g}<em>0/F</em>\pi$</th>
<th>$\tilde{g}<em>1/F</em>\pi$</th>
<th>$\tilde{C}<em>1 F</em>\pi^3$</th>
<th>$\tilde{C}<em>2 F</em>\pi^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perturbative pion (141, 129)</td>
<td>1</td>
<td>1</td>
<td>—</td>
<td>-0.23</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Av18 (125, 130, 131, 86, 132)</td>
<td>0.91</td>
<td>0.91</td>
<td>—</td>
<td>-0.19</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>N$^2$ LO (131, 86)</td>
<td>0.94</td>
<td>0.94</td>
<td>—</td>
<td>-0.18</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

from EM and U. van Kolck, ‘15

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C. P. Liu and R. Timmermans, ‘05; J. de Vries et al, ‘11;
N. Yamanaka and E. Hiyama, ‘15
From nucleons to nuclei. Diamagnetic atoms

<table>
<thead>
<tr>
<th>Nucl.</th>
<th>Best value</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a_0$</td>
<td>$a_1$</td>
</tr>
<tr>
<td>$^{199}$Hg</td>
<td>0.01 ± 0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>$^{129}$Xe</td>
<td>-0.008</td>
<td>-0.006</td>
</tr>
<tr>
<td>$^{225}$Ra</td>
<td>-1.5</td>
<td>6.0</td>
</tr>
</tbody>
</table>

from M. Ramsey-Musolf, J. Engel, U. van Kolck, ‘13

- constituent EDM are screened
- EDM depends on screening factor $A$ and the Schiff moment
  
  \[ S = -\frac{m_N g_A}{F_\pi} \left( a_0 \frac{\bar{g}_0}{F_\pi} + a_1 \frac{\bar{g}_1}{F_\pi} + a_2 \frac{\bar{g}_2}{F_\pi} \right) e \text{fm}^3 + (\alpha_n d_n + \alpha_p d_p) \text{fm}^2 \]

- $\pi$-N contrbs. affected by large theory uncertainties

- single nucleon contrib. better determined
  \[ \alpha_n = 1.9 \pm 0.1, \quad \alpha_p = 0.20 \pm 0.06 \]

V. F. Dmitriev and R. A. Senkov, ‘03
Disentangling $\mathcal{T}$ sources

<table>
<thead>
<tr>
<th>$(d_d - d_n - d_p)/d_n$</th>
<th>$v^2\tilde{c}_g^{(u)}$</th>
<th>$v^2\tilde{c}_g^{(d)}$</th>
<th>$v^2\Xi_{ud}$</th>
<th>$\bar{\theta}$</th>
<th>$v^2C_{\bar{G}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>${2, 50}$</td>
<td>${1, 22}$</td>
<td>${30, 300}$</td>
<td>${-1.4, -0.02}$</td>
<td>$\lesssim 1$</td>
</tr>
</tbody>
</table>

neutron, proton & deuteron EDM

$$d_d = d_n + d_p - 0.2 \frac{\bar{g}_1}{F_\pi}$$

• sensitive to $\bar{g}_1$, not sensitive to $\bar{g}_0$

$$\implies \text{isospin breaking operators } \tilde{c}_g^{(u)} - \tilde{c}_g^{(d)}, \Xi_{ud}$$

• qCEDM & LL RR: strong enhancement of $d_d$

• $\bar{\theta}$ term: ratio at most $\mathcal{O}(1)$

• gCEDM & LR LR: ratio $\lesssim 1$

• qEDM: $d_d = d_n + d_p$

need experiment & better LECs!
**Disentangling $\mathcal{T}$ sources**

- LQCD/experiment discrepancy in $\epsilon'/\epsilon$ could be explained with tiny right-handed currents

\[
\mathcal{L} = \frac{g}{\sqrt{2}} \left( \xi_{ud} \bar{u}_R \gamma^\mu d_R + \xi_{us} \bar{u}_R \gamma^\mu s_R \right) W_\mu + \text{h.c.}
\]

- in this scenario: $d_n$, $d_d$ and $d_{Ra}$ in the next generation of experiments
- and correlated!

falsify with better hadronic and nuclear input
Disentangling $T$ sources

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falsify with better hadronic and nuclear input
Conclusion

Exciting times for EDMs

- several experiments running or coming online
- increase sensitivity to CP violation by one-two orders of magnitude

To take full advantage of EDM experiments:

1. first principle calculations of $d_n, d_p$

   ongoing LQCD effort

2. robust estimates of $\pi$-N couplings $\bar{g}_0, \bar{g}_1$

   LQCD + $\chi$EFT

3. progress in many-body nuclear theory

   ...not there yet... stay tuned!
Introduction

- electron EDM
  (via ThO energy levels)

  \[ |d_e| \leq 8.7 \cdot 10^{-16} \text{ e fm} \]

  ACME collaboration, ‘14.

- neutron EDM

  \[ |d_n| \leq 3.0 \cdot 10^{-13} \text{ e fm} \]

  J. M. Pendlebury et al, ‘15

- Hg EDM

  \[ |d_{199\text{Hg}}| \leq 6.2 \cdot 10^{-17} \text{ e fm} \]

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