Probing new CP-odd thresholds with electric dipole moments

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Based on work with:
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[For a recent review, see hep-ph/0504231]
Naturalness and new CP-odd thresholds

Success of CKM CP-violation (with natural O(1) phase) in K and B-meson mixing, and e.g. constraints on soft-SUSY phases

**Assumption:** non-CKM CP-violation is "irrelevant"

\[ L = L_{SM}^{CKM} + \sum \frac{O_{n}^{CP}}{\Lambda^{n}} \]

**Q:**
- Can it resolve the problems which motivate new CP-odd sources? (e.g. baryogenesis)
- What is the threshold sensitivity?

- Sensitivity through EDMs of neutrons, and para- and dia-magnetic atoms and molecules (violate T,P)
Plan

• A review of (hadronic) EDM calculations

• EDMs vs supersymmetry
  — Review of the (current) SUSY CP problem
  — Constraints on new CP-odd thresholds

• EDMs vs baryogenesis

• Concluding remarks
### Experimental Status

<table>
<thead>
<tr>
<th>EDM Type</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron EDM</td>
<td>$</td>
<td>d_n</td>
</tr>
<tr>
<td>Thallium EDM (paramagnetic)</td>
<td>$</td>
<td>d_{Tl}</td>
</tr>
<tr>
<td>Mercury EDM (diamagnetic)</td>
<td>$</td>
<td>d_{Hg}</td>
</tr>
</tbody>
</table>

NB: *Small* SM background (via CKM phase)

\[ d_n \sim 10^{-32} - 10^{-34} \text{e cm} \quad \text{[Khriplovich & Zhitnitsky ‘86]} \]

Future experimental progress → see the rest of this meeting!

Anticipate $\mathcal{O}(10^{-2} - 10^{-3})$ gain in sensitivity for each channel

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Classification of CP-odd operators at 1GeV

Effective field theory is used to provide a model-independent parametrization of CP-violating operators at 1GeV

\[ \mathcal{L} = \sum_i \frac{c_i}{M^{d-4}} O^{(i)}_d \]

Dimension 4:

\[ \tilde{\theta} \alpha_s G\tilde{G} \]

\[ \tilde{\theta} = \theta_0 + \text{ArgDet}(M_q) \]

Dimension “6”:

\[ \sum_{q=u,d,s} d_q \bar{q} F \sigma \gamma_5 q + \sum_{q=u,d,s} \bar{d}_q \bar{q} G \sigma \gamma_5 q + d_e \bar{e} F \sigma \gamma_5 e + w g_s^3 G G \bar{G} \]

Dimension “8”:

\[ \sum_{q=u,d,s} C_{qq} \bar{q} q \bar{q} i \gamma_5 q + C_{qe} \bar{q} q e i \gamma_5 e + \cdots \]
Effective field theory is used to provide a model-independent parametrization of CP-violating operators at 1GeV

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Dimension 6:

\[
\sum_{q=u,d,s} d_q \bar{q} F \sigma_5 q + \sum_{q=u,d,s} \bar{d}_q \bar{q} G \sigma_5 q + d_e \bar{e} F \sigma_5 e + w q^3_s G G\tilde{G}
\]

Dimension 8:

\[
\sum_{q=u,d,s} C_{qq} \bar{q} q i \gamma_5 q + C_{qe} \bar{q} e i \gamma_5 e + \cdots
\]

\[ C_S \tilde{N} N \bar{e} i \gamma_5 e \]
Origin of the EDMs

Energy

TeV

QCD

nuclear

atomic

Fundamental CP phases

$d_e$

$C_{qe}, C_{qq}$

$\theta, d_q, \tilde{d}_q, w$

pion-nucleon coupling ($\tilde{g}_{\pi NN}$)

EDMs of paramagnetic atoms ($d_{Tl}$)

EDMs of diamagnetic atoms ($d_{Hg}$)

Neutron EDM ($d_n$)
Calculating the EDMs - TI

1. TI EDM (paramagnetic)

\[ d_{TI} \sim -10 \alpha^2 Z^3 d_e (1 \text{ GeV}) - e \sum_{q=d,s,b} C_{qe} (1 \text{ GeV}) \frac{2 \text{ GeV}^2}{m_q} \]

\[ 10 \alpha^2 Z^3 \approx 585 \]  

[Liu & Kelly ‘92]  

relativistic violation  
of Schiff thm  

arises from  
\[ \bar{e} i \gamma_5 e \bar{\Psi} N \]  

[Bouchiat ‘75;  
Khatsymovsky et al. ‘86]
2. neutron EDM

- Chiral Logarithm: [Crewther, Di Vecchia, Veneziano & Witten '79]

\[ d_n(\theta) = c_1 \ln \frac{\Lambda}{m_\pi} + c_2 \]

\[ |\theta| < 10^{-9} \]

[also Baluni '79]
Calculating the EDMs - n

2. neutron EDM

- QCD Sum Rules: [Pospelov & AR ‘99-’00]
  - Neutron current: \( j_n \sim d^T C \gamma_5 u d \)
  - Correlator: \( \int d^4x e^{ip\cdot x} \langle \bar{j}_n(x), j_n(0) \rangle_{\mathcal{Q}_{P,F}} = \Pi_0(p) + \Pi_1^{\mu\nu}(p)F_{\mu\nu} + \cdots \)
Calculating the EDMs - n

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\[
\Pi_1(p, \theta, d_q, \bar{d}_q) \cdot F \sim \frac{d_n \lambda^2 m_n}{(p^2 - m_n^2)^2} \{ F \sigma_5, \slashed{p} \} + \cdots
\]

\[ d_n \vec{E} \cdot \vec{S} \]
2. neutron EDM

- **QCD Sum Rules: Results**
  
  — Important condensates:

\[
\langle \bar{q}\sigma_{\mu\nu}q\rangle_F = \chi e_q F_{\mu\nu} \langle \bar{q}q\rangle \\
\langle \bar{q}G\sigma q\rangle = -m_0^2 \langle \bar{q}q\rangle
\]

\[
d_n = (0.4 \pm 0.2) \frac{\langle \bar{q}q\rangle}{(225 \text{ MeV})^3} \left[ 4d_d - d_u + \frac{1}{2} \chi m_0^2 (4e_d \tilde{d}_d - e_u \tilde{d}_u) + \cdots \right] + O(d_s, w, C_{qq}) \\
= 2.7e(\tilde{d}_d + 0.5\tilde{d}_u)
\]

Sensitive only to ratios of light quark masses

[Pospelov & AR ‘99,’00]

NB: PQ axion used to remove $\tilde{\theta}$

\[
\theta_{ind} = \frac{1}{2} m_0^2 \sum_{q=u,d,s} \frac{\tilde{d}_q}{m_q}
\]
Calculating the EDMs - Hg

3. Hg EDM (diamagnetic)

\[ d_{Hg} \sim 10^{-3} d_{nuc} \]

[Schiff '63]
3. Hg EDM (diamagnetic)

\[ d_{\text{Hg}} \sim 10^{-3} d_{\text{nuc}} \]

- Misalignment of nuclear charge and dipole moment distribution

\[ d_{\text{Hg}} \sim -3 \times 10^{-17} \text{fm}^3 + O(d_e, C_{qq}) \]

Schiff moment

\[ S \sim -0.06 g_{\pi NN} \tilde{g}_{\pi NN}^{(1)} e \text{fm}^3 + \cdots \]

[Schiff '63]

[Dzuba et al. '02]

[Flambaum et al. '86; Dmitriev & Senkov '03; de Jesus & Engel '05]
3. Hg EDM (diamagnetic)

- EDM (predominantly) due to CP-odd pion-nucleon coupling:

\[
\langle d_q \rangle = \frac{\tilde{d}_u - \tilde{d}_d}{2f_\pi} \left\langle N \right\rvert \sum_{q=u,d} \bar{q}g_s G_\sigma q \left\lvert N \right\rangle + \cdots
\]
3. Hg EDM (diamagnetic)

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\[ g_{\pi NN}(\bar{d}_q) = \frac{\bar{d}_u - \bar{d}_d}{2f_\pi} \left\langle N \left| \sum_{q=u,d} \bar{q}g_\sigma G\sigma q - m_0^2 \bar{q}q \right| N \right \rangle + \cdots \]
Calculating the EDMs - Hg

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\[
\tilde{g}_{\pi NN}(\tilde{d}_q) = \frac{\tilde{d}_u - \tilde{d}_d}{2f_\pi} \left\langle N \left| \sum_{q=u,d} \bar{q}_s G q - m_0^2 \bar{q}q \right| N \right\rangle + \cdots
\]

Using QCD sum-rules: [Pospelov ‘01]

\[
\tilde{g}_{\pi NN}(\tilde{d}_q) = (1 - 6) \frac{|\langle \bar{q}q \rangle|}{(225\text{MeV})^3} (\tilde{d}_u - \tilde{d}_d) + O(\tilde{d}_u + \tilde{d}_d, \tilde{d}_s, w)
\]

or using LET: [Falk et al ’99, Hisano & Shimizu ‘04]

NB: large errors due to cancelations

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# Resulting Bounds on fermion EDMs & CEDMs

<table>
<thead>
<tr>
<th>EDM Type</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tl EDM (20%)</td>
<td>[</td>
</tr>
<tr>
<td>Neutron EDM (50%)</td>
<td>[</td>
</tr>
<tr>
<td>Hg EDM (+200%)</td>
<td>[ e</td>
</tr>
</tbody>
</table>

**Sensitivity:** \[ d_f \sim e \frac{m_f}{M_{CP}^2} \] \[ \Rightarrow M_{CP} \geq \mathcal{O}(10 - 50) \text{TeV} \]
Constraints on TeV-Scale models

- **E.G. MSSM:** In general, the MSSM contains many new parameters, including multiple new CP-violating phases, e.g.

\[
\Delta \mathcal{L} \sim -\mu \tilde{H}_1 \tilde{H}_2 + B\mu \ H_1 H_2 + h.c.
- \frac{1}{2} \left( M_3 \tilde{\lambda}_3 \tilde{\lambda}_3 + M_2 \tilde{\lambda}_2 \tilde{\lambda}_2 + M_1 \tilde{\lambda}_1 \tilde{\lambda}_1 \right) + h.c.
- A_{ij}^d \ H_1 \tilde{q}_{Li} \tilde{q}_{Rj} + h.c + \cdots
\]

With a universality assumption, 2 new physical CP-odd phases \( \{\theta_\mu, \theta_A\} \)

- **EG: 1-loop EDM contribution:**

\[
\frac{d_d}{m_d} \sim \frac{1}{16\pi^2 M_4} \frac{\mu m_{\tilde{g}}}{M_3} \sin \theta_\mu
\]

\( M \sim \) sfermion mass
SUSY CP Problem

\[ M_{soft} = 500 \text{ GeV} \]

Generic Implications \[ \Rightarrow \] Soft CP-odd phases \[ O(10^{-2} - 10^{-3}) \]

[Olive, Pospelov, A.R., Santoso ‘05]
[Also: Barger et al. ‘01, Abel et al. ‘01, Pilaftsis ‘02]
SUSY CP Constraints

Decoupling 1st/2nd generation

EW baryogenesis

MSSM parameter space

split SUSY

large tan$\beta$

2 HDM

phases $< O(10^{-3} - 1)$

References:

- [Chang, Keung & Pilaftsis ‘98]
- [Weinberg ‘89; Dai et al. 90]
- [Chang, Keung & Pilaftsis ‘98]
- [Weinberg ‘89; Dai et al. 90]
- [Barr, Zee ‘92]

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If soft terms conserve CP & flavour to avoid fine-tuning, what is the sensitivity to irrelevant operators (new thresholds)?

**Dim 5:**

\[
\mathcal{W} = \mathcal{W}_{MSSM} + \frac{y_h}{\Lambda} (H_u H_d)^2 + \frac{Y^{qe}}{\Lambda} QULE + \frac{Y^{qq}}{\Lambda} QUQD + \text{seesaw} + \text{baryon}
\]

- Contributions to e.g. EDMs will scale as “dim=5”
  \[
d_f \sim \frac{v_{EW}}{m_{soft}\Lambda}
\]
- Sensitivity depends on flavor structure of \(Y^{ff}\)
  — we will assume \(Y^{ff'} \neq Y_f Y_{f'} \sim 1\)
SUSY threshold sensitivity

Dimension-3,6 operators generated at the soft threshold

\[ \Delta m_e \sim m_e \Rightarrow \Lambda > 10^6 \text{GeV} \]
SUSY threshold sensitivity

Dimension-3,6 operators generated at the soft threshold

\[ \Delta m_e \sim m_e \Rightarrow \Lambda > 10^6 \text{GeV} \]

\[ d_{T_l}(C_S), d_{H_g}(C_S), \mu \rightarrow e \Rightarrow \Lambda > 10^8 \text{GeV} \]
SUSY threshold sensitivity

<table>
<thead>
<tr>
<th>operator</th>
<th>sensitivity to $\Lambda$ (GeV)</th>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_{3311}^{qe}$</td>
<td>$\approx 10^7$</td>
<td>naturalness of $m_e$</td>
</tr>
<tr>
<td>$\text{Im}(Y_{3311}^{qq})$</td>
<td>$\approx 10^{17}$</td>
<td>naturalness of $\tilde{\theta}$, $d_n$</td>
</tr>
<tr>
<td>$\text{Im}(Y_{ii11}^{qe})$</td>
<td>$10^7 - 10^9$</td>
<td>Tl, Hg EDMs</td>
</tr>
<tr>
<td>$Y_{1112}^{qe}$, $Y_{1121}^{qe}$</td>
<td>$10^7 - 10^8$</td>
<td>$\mu \to e$ conversion</td>
</tr>
<tr>
<td>$\text{Im}(Y_{qq}^{qq})$</td>
<td>$10^7 - 10^8$</td>
<td>Hg EDM</td>
</tr>
<tr>
<td>$\text{Im}(y_{hh})$</td>
<td>$10^3 - 10^8$</td>
<td>$d_e$ from Tl EDM</td>
</tr>
</tbody>
</table>

[Pospelov, AR, Santoso ‘05]

Models: e.g. MSSM + extended Higgs sector

\[ \{N, H'_u, H'_d\} \]
Minimal EW Baryogenesis

\[ \eta_b = 8.9 \times 10^{-11} \]

The SM satisfies, in principle, all 3 Sakharov criteria for baryogenesis

**BUT**
- \( m_h \) too large for a strong 1st order PT \[\text{[Kajantie et al. '96]}\]
- insufficient CP-violation \[\text{[Gavela et al. '94]}\]

**Alternatives:**

- EWBG still possible in the MSSM —needs one light stop, a large M1-phase, and a rather tuned spectrum

- Leptogenesis —decoupled from EW scale, difficult to test
  \[
d_e(\eta) \sim m_em_\nu^2G_F^2 \sim 10^{-43} \text{ e cm}
  \]
  \[\text{[Archambault, Czarnecki & Pospelov '04]}\]
Minimal EW Baryogenesis

⇒ What is the minimal SM modification required for viable EWBG ? (*)

\[ \delta L = \frac{1}{\Lambda^2} (H^\dagger H)^3 + \frac{Z_t}{\Lambda_{CP}^2} (H^\dagger H)t^c HQ_3 \]

require \( \Lambda \sim \Lambda_{CP} \sim 400 - 800 \text{ GeV} \)

⇒ makes predictions for the top-Higgs coupling, cf. LHC

Questions:

Tuning of other operators at such low thresholds ?

Do EDM bounds really allow such a scenario ?

* NB: Can also flip sign of quartic Higgs coupling
Barr-Zee diagrams

CP-odd top-Higgs coupling

Assuming MFV structure
Constraints

Next-generation EDM sensitivity:

\[ \Lambda_{CP} \sim 3 \text{ TeV} \]
Concluding Remarks

- Precision tests can play a crucial role in probing fundamental symmetries at scales well beyond the reach of colliders.

- EDMs currently provide stringent constraints on CP-phases in the soft-breaking sector of the MSSM.
Concluding Remarks

• Precision tests can play a crucial role in probing fundamental symmetries at scales well beyond the reach of colliders.

• EDMs currently provide stringent constraints on CP-phases in the soft-breaking sector of the MSSM.

• If the soft sector is real, EDMs and other precision flavor physics provide impressive sensitivity to new SUSY thresholds.

  next generation tests will push the scale close to that of RH neutrinos, etc.

• Current EDM bounds still allow for electroweak baryogenesis in a minimal dim=6 extension of the SM.

  next-generation expts will provide a conclusive test.
Appendices