Probing new CP-odd thresholds with EDMs

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Based on work with:
M. Pospelov,
S. Huber & Y. Santoso

[For a review, see hep-ph/0504231]
Precision Tests as Probes for New Physics

Precision searches for new physics (at energy scale $\Lambda$):

\[ \frac{\Delta E}{E} \sim \left( \frac{m}{\Lambda} \right)^n \]

Especially powerful for tests of "symmetries" of the SM:
- e.g. Baryon no., Lepton no., Flavour, T (or CP), etc.

**e.g.: lepton number violation and neutrino mass**

The Standard Model (above the EW scale) allows a single dimension five operator:

\[ L = L_{SM} + \frac{Y}{\Lambda} \bar{L}_L^c \tilde{H} \tilde{H}^T L_L + [\text{dim} \geq 6] \]

\[ M_\nu = \frac{\nu^2}{\Lambda} \]

Data $\Rightarrow \Lambda \approx 10^{11} - 10^{15}$ GeV
Probing the Higgs Sector
Higgs and CP-violation

In a complementary way, we can also use precision probes of the couplings.

In particular, we can efficiently probe the CP structure of the (chirality changing) vertex.
Higgs and CP-violation

With a convenient choice of basis we can associate all SM CP-violation with Yukawa couplings

\[
\sin(\delta_{KM}) \propto \text{Det}[Y_u Y_u^\dagger, Y_d Y_d^\dagger]
\]

[Jarlskog ‘85]

• Experimentally \( \delta_{KM} \sim O(1) \), and consistently explains CP-violation in K and B meson mixing and decays

\[
\bar{\theta}_{QCD} \sim \text{Arg} \text{Det}[Y_u Y_d]
\]

• Experimentally, \( \theta < 10^{-9} \) ! (strong CP problem)

Do we anticipate other CP-odd sources?
CP-violation and EDMs

- Baryogenesis requires extra CP-violation
- Most “UV completions” of the SM (e.g. MSSM) provide additional sources of CP-violation

Within the SM, CP-violation is hidden behind the flavour structure $J_{CP} \sim 10^{-5} \sin(\delta_{KM})$

⇒ Look for CP-violation in flavour diagonal channels, with small SM bkgd

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

Currently, all experimental data ⇒ EDMs vanish to very high precision thus leading to very strong constraints on new physics.
Outline of the Talk

• Current status of the EDM bounds

• 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
• Measure Larmor precession frequency in (anti-)aligned E and B fields

\[ \hbar \omega_L^1 = 2\mu \cdot B + 2d \cdot E \]

\[ \hbar \omega_L^2 = 2\mu \cdot B - 2d \cdot E \]

\[ d = \frac{\hbar}{4E} (\omega_L^1 - \omega_L^2), \quad \sigma_d \sim \frac{\hbar S}{ET \sqrt{N}} \]
Experimental Bounds on the neutron EDM

Log($d_n$) vs [e cm]

-20
-22
-24
-26
-28
-30
-32


Oak Ridge, ILL & PSI
ILL/RAL/Sussex
SM
### Experimental Status

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron EDM</td>
<td>[Baker et al. ‘06]</td>
</tr>
<tr>
<td>Thallium EDM (paramagnetic)</td>
<td>[Regan et al. ‘02]</td>
</tr>
<tr>
<td>Mercury EDM (diamagnetic)</td>
<td>[Romalis et al. ‘00]</td>
</tr>
</tbody>
</table>

There are \(~10\) new experiments (either operating or in development) (optimistically) \(\mathcal{O}(10^{-2} - 10^{-3})\) gain in sensitivity for each channel.
Experimental Status

Small SM background (via CKM phase)

EG: for the neutron EDM

\[ d_n \sim 10^{-32} - 10^{-34} \text{ e cm} \]

[Khriplovich & Zhitnitsky ‘86]
Classification of CP-odd operators at 1GeV

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

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

**Dimension 4:**  \[ \bar{\theta}\alpha_s G\tilde{G} \]

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

**Dimension “6”:**  
\[ \sum_{q=u,d,s} d_q \bar{q}F \sigma_5 q + \sum_{q=u,d,s} \tilde{d}_q \bar{q}G \sigma_5 q + d_e \bar{e}F \sigma_5 e + w g_s^3 G G \tilde{G} \]

**Dimension “8”:**  
\[ \sum_{q=u,d,s} C_{qq} \bar{q}q \bar{q}i \gamma_5 q + C_{qe} \bar{q}q \bar{e}i \gamma_5 e + \cdots \]
Classification of CP-odd operators at 1GeV

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Dimension “8”: \[ \sum_{q=u,d,s} C_{qq\bar{q}} q \bar{q} i \gamma_5 q + C_{qe\bar{q}} q \bar{q} \bar{e} i \gamma_5 e + \cdots \]

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

Fundamental CP phases

- EDMs of paramagnetic atoms ($d_{Tl}$)
- EDMs of diamagnetic atoms ($d_{Hg}$)

Energy

TeV

QCD

nuclear

atomic

Neutron EDM ($d_n$)

$C_{S,P,T}$

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

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

$C_{qe, C_{qq}}$

$d_e$
Origin of the EDMs

- EDMs of paramagnetic molecules (YbF, PbO, HfF\(^+\))
- Atoms in traps (Rb, Cs)
- EDMs of diamagnetic atoms (Hg, Xe, Ra, Rn)
- Neutron EDM (\(d_n\))
- EDMs of nuclei and ions (deuteron, etc)
- Nuclei and ions
- Atoms in traps
- Fundamental CP phases
- Energy
  - TeV
  - QCD
  - Nuclear
  - Atomic

6/28/2007
Next-generation Experiments

Fundamental CP phases

$C_{qe}, C_{qq}$

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

$C_{S,P,T}$

$\bar{g}_{\pi NN}$

EDMs of paramagnetic molecules (YbF, PbO, HfF$^+$)
Atoms in traps (Rb, Cs)

EDMs of diamagnetic atoms (Hg, Xe, Ra, Rn)

Neutron EDM ($d_n$)

Deuteron EDM @ BNL!
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]

arises from \( \bar{e}i\gamma_5 e\bar{N}N \)

relativistic violation of Schiff thm

[Salpeter '58; Sandars '65]

[Bouchiat '75; Khatsymovsky et al. '86]
Future - e.g. paramagnetic molecules

e.g. YbF, PbO

[Hinds; DeMille]

\( \alpha^2 Z^3 E_{\text{eff}}(\vec{E}) \)

\( d_e \)

\[ \hbar \Delta \omega_L = E_{\text{eff}} d_e + O(C_S) \]

[Kozlov et al.]

\( O(10^5 E_{\text{ext}}) \)
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]
2. neutron EDM

- QCD Sum Rules: [Pospelov & AR ‘99-’00, Chan & Henley ‘99]
  - Neutron current: $j_n \sim d^T C\gamma_5 ud$
  - Correlator: $\int d^4xe^{ip\cdot x}\langle j_n(x), j_n(0)\rangle_{CP,F} = \Pi_0(p) + \Pi_1^{\mu\nu}(p)F_{\mu\nu} + \cdots$
Calculating the EDMs - n

2. neutron EDM

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

\[
\Pi_1(p, \theta, d_q, \bar{d}_q) \cdot F \sim \frac{d_n \lambda^2 m_n}{(p^2 - m_n^2)^2} \{ F \sigma_{\gamma_5, \mu} \} + \cdots
\]

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

- QCD Sum Rules: Results
  — Important condensates:

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

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

\[ 2.7e(\tilde{d}_d + 0.5\tilde{d}_u) \]

Sensitive only to ratios of light quark masses

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

\[ \theta_{\text{ind}} = \frac{1}{2} m_0^2 \sum_{q=u,d,s} \frac{\tilde{d}_q}{m_q} \]

Future developments: $d_n(\vartheta)$ in LQCD

[Berruto et al; Shintani et al.]
3. Hg EDM (diamagnetic)

\[ d_{Hg} \sim 10Z^2 \left( \frac{R_N}{R_A} \right)^2 d_{nuc} \sim 10^{-3} d_{nuc} \]

[Schiff '63]
Calculating the EDMs - Hg

3. Hg EDM (diamagnetic)

\[ d_{Hg} \sim 10Z^2(R_N/R_A)^2d_{nuc} \sim 10^{-3}d_{nuc} \]

- Misalignment of nuclear charge and dipole moment distribution

- Schiff moment

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

\[ \tilde{g}^{(1)}_{\pi NN}(\tilde{d}_q) \]

[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:

\[ \tilde{g}_{\pi NN}(\tilde{d}_q) = \frac{\tilde{d}_u - \tilde{d}_d}{2f_\pi} \left\langle N \right| \sum_{q=u,d} \bar{q}g_sG\sigma q \left| N \right\rangle + \cdots \]
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3. Hg EDM (diamagnetic)

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

Using QCD sum-rules: [Pospelov ‘01]

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

[or, using LETs: Falk et al ‘99; Hisano & Shimizu ‘04]

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

NB: large errors due to cancelations
Future - charged nuclei & octupoles

Deuteron EDM @ BNL [SREDM Collab.]

- Same (leading) dependence as Hg (but without Schiff suppression)

\[ d_D \sim (d_n + d_p) + d_{D_{\pi NN}} \]

\approx -2 \times 10^{-14} \bar{g}_{_{\pi NN}}^{(1)} e cm

[Lebedev, Olive, Pospelov, AR ‘04]

[Sensitivity: ]

\[ d_D \sim 10^{-29} \text{ cm} \iff d_{Hg} \sim 3 \times 10^{-17} \bar{g}_{_{\pi NN}}^{(1)} \sim 10^{-32} \text{ cm} \]

[Ra, Rn EDM [Holt et al, Chupp et al]]

- Nuclear octupole deformations enhance the Schiff moment, by O(100-1000) relative to Hg [Flambaum et al.]
Origin of the EDMs

Fundamental CP phases

- EDMs of paramagnetic atoms ($d_{Tl}$)
- EDMs of diamagnetic atoms ($d_{Hg}$)
- Neutron EDM ($d_n$)

Energy
- TeV
- QCD
- Nuclear
- Atomic
Origin of the EDMs

Energy

TeV

QCD

nuclear

atomic

Fundamental CP phases

EDM constraints
## Resulting Bounds on fermion EDMs & CEDMs

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Tl EDM (20%)</td>
<td>Neutron EDM (50%)</td>
</tr>
<tr>
<td>Hg EDM (+200%)</td>
<td></td>
</tr>
</tbody>
</table>

### Sensitivity:

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

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

\[
\Delta \mathcal{L} \sim -\mu \tilde{H}_1 \tilde{H}_2 + B\mu H_1 H_2 + h.c.
- \frac{1}{2} \left( M_3 \tilde{\lambda}_3 \tilde{\lambda}_3 + M_2 \tilde{\lambda}_2 \tilde{\lambda}_2 + M_1 \tilde{\lambda}_1 \tilde{\lambda}_1 \right) + h.c.
- A_{ij}^d H_1 \tilde{q}_Li \tilde{q}_Rj + h.c + \cdots
\]
• **E.G. MSSM:** In general, the MSSM contains many new parameters, including multiple new CP-violating phases, e.g.

\[ \Delta L \sim -\mu \tilde{H}_1 \tilde{H}_2 + B \mu H_1 H_2 + h.c. \]

\[-\frac{1}{2} \left( M_3 \tilde{\lambda}_3 \tilde{\lambda}_3 + M_2 \tilde{\lambda}_2 \tilde{\lambda}_2 + M_1 \tilde{\lambda}_1 \tilde{\lambda}_1 \right) + h.c. \]

\[-A_{d}^d H_1 \tilde{q}_L \tilde{q}_R + h.c. + \cdots \]

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

• **EG: 1-loop EDM contribution:**

\[ \frac{d_d}{m_d} \sim \frac{1}{16\pi^2} \frac{\mu m_{\tilde{g}}}{M^4} \sin \theta_\mu \]

M \sim sfermion mass

[Ellis, Ferrara & Nanopoulos ‘82]
SUSY CP Problem

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

Generic Implications \implies \text{Soft CP-odd phases } O(10^{-2} - 10^{-3})

[Olive, Pospelov, AR, 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 \(< O\left(10^{-3} - 1\right)\)

[Chang, Keung & Pilaftsis ‘98]

[Weinberg ‘89; Dai et al. 90]

[Barr ‘92; Lebedev & Pospelov ‘02]

[Barr, Zee ‘92]
If soft terms (approximately) conserve CP & flavour, what is the sensitivity to irrelevant operators (new thresholds)?

**Dim 5:**

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

- 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

<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>$\sim 10^7$</td>
<td>naturalness of $m_e$</td>
</tr>
<tr>
<td>Im($Y_{3311}^{*qq}$)</td>
<td>$\sim 10^{17}$</td>
<td>naturalness of $\bar{\theta}$, $d_n$</td>
</tr>
<tr>
<td>Im($Y_{ii11}^{qe}$)</td>
<td>$10^7 - 10^9$</td>
<td>Tl, Hg EDMs</td>
</tr>
<tr>
<td>$Y_{1112}^{q} = Y_{1121}^{q}$</td>
<td>$10^7 - 10^8$</td>
<td>$\mu \rightarrow e$ conversion</td>
</tr>
<tr>
<td>Im($Y_{1111}^{qq}$)</td>
<td>$10^7 - 10^8$</td>
<td>Hg EDM</td>
</tr>
<tr>
<td>Im($y_h$)</td>
<td>$10^3 - 10^8$</td>
<td>$d_e$ from Tl EDM</td>
</tr>
</tbody>
</table>

[Pospelov, AR, Santoso ‘05, ‘06]

**Models:** e.g. MSSM + extended Higgs sector

$\{N, H_u', H_d'\}$
(Electroweak) Baryogenesis

\[ \eta_b = (8.8 \pm 0.3) \times 10^{-11} \]  

[WMAP3 + BBN]

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

\[ \nu \neq 0 \]
\[ \nu = 0 \]

**BUT**  
- \( m_h \) too large for a strong 1st order PT  
  [Kajantie et al. ‘96]  
- insufficient CP-violation  
  [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  
  \[ d_e(\eta) \sim m_e m_\nu^2 G_F^2 \sim 10^{-43} \text{ e cm} \]  
  [Archambault, Czarnecki & Pospelov ‘04]
What is the minimal SM modification required for viable EWBG? (*)

\[ \delta L = \frac{1}{\Lambda^2} (H^\dagger H)^3 + \frac{Z_t}{\Lambda_{CP}^2} (H^\dagger H) t^c H Q_3 \]

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

\[ Z_f \rightarrow Z_q \delta_{ft} \]

\[ Z_f \rightarrow Z Y_f \]

\[ \Lambda = \Lambda_{CP} = M \]

[Huber, Pospelov, AR '06]

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.
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.
Next-generation Experiments

Energy

TeV

QCD

nuclear

atomic

Fundamental CP phases

$d_e$

$C_{qe}, C_{qq}$

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

$C_{S,P,T}$

$\bar{g}_{\pi NN}$

Neutron EDM ($d_n$)

EDMs of paramagnetic molecules (YbF, PbO, HfF$^+$)
Atoms in traps (Rb, Cs)

EDMs of nuclei and ions atoms (deuteron, etc)

EDMs of diamagnetic atoms (Hg, Xe, Ra, Rn)
Next-generation Experiments

Fundamental CP phases

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EDMs of nuclei and ions atoms (deuteron, etc)

EDMs of paramagnetic molecules (YbF, PbO, HfF$^+$)

Atoms in traps (Rb, Cs)

EDMs of diamagnetic atoms (Hg, Xe, Ra, Rn)

Neutron EDM ($d_n$)

Deuteron EDM @ BNL!
### Future experimental progress

#### Paramagnetic atoms & molecules

<table>
<thead>
<tr>
<th>Substance</th>
<th>( d_e \approx 10^{-30} \text{ e cm} )</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>PbO</td>
<td>[\text{DeMille et al. (Yale ‘06/07)}]</td>
<td></td>
</tr>
<tr>
<td>YbF</td>
<td>[\text{Hinds et al. (Imperial ‘06/07)}]</td>
<td></td>
</tr>
<tr>
<td>solid state (garnet)</td>
<td>( d_e \approx 10^{-31} \text{ e cm} )</td>
<td>[\text{LANSCE ‘06/07}]</td>
</tr>
</tbody>
</table>

#### Neutron

<table>
<thead>
<tr>
<th>Substance</th>
<th>( d_n \approx 1 \times 10^{-27} \text{ e cm} )</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCN bottle (Hg comag)</td>
<td>[\text{PSI ‘07/09}]</td>
<td></td>
</tr>
<tr>
<td>UCN in liquid He4 (He3 comag)</td>
<td>( d_n \approx 1 \times 10^{-28} \text{ e cm} )</td>
<td>[\text{LANSCE ‘07/10; Sussex et al. ‘07/10}]</td>
</tr>
</tbody>
</table>

#### Diamagnetic atoms

<table>
<thead>
<tr>
<th>Substance</th>
<th>( d_{\text{Hg}} \approx 5 \times 10^{-29} \text{ e cm} )</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hg</td>
<td>[\text{Fortson, (Washington)}]</td>
<td></td>
</tr>
<tr>
<td>Liquid Xe</td>
<td>( d_{\text{Xe}} \approx 10^{-31} \text{ e cm} )</td>
<td>[\text{Romalis, (Princeton)}]</td>
</tr>
</tbody>
</table>

| Deuteron                         | \( d_D \approx 10^{-29} \text{ e cm} \)               | \[\text{SR EDM collab. (BNL)}\] |

+ many others ....
CP-violation and EDMs

- Baryogenesis requires extra CP-violation
- Most “UV completions” of the SM (e.g. MSSM) provide additional sources of CP-violation

**YES**

Within the SM, CP-violation is hidden behind the flavour structure

\[ J_{CP} \sim 10^{-5} \sin(\delta_{KM}) \]

*Are CP and flavour intrinsically linked?*

⇒ Look for CP-violation in flavour diagonal channels

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

Currently, all experimental data ⇒ EDMs vanish to very high precision thus leading to very strong constraints on new physics.
Computations

1. TI EDM (paramagnetic)  (atomic)

\[ d_{Ti} \sim -585d_e - 2e \sum_{q=d,s,b} C_{qe}/m_q \]

\[ \alpha^2 Z^3 \]

[Liu & Kelly '92; Khatsymovsky et al. '86]

2. neutron EDM  (chiralPT, NDA, QCD sum rules, …) \[ \Rightarrow |\theta| < 10^{-10} \]

\[ d_n \sim (0.4 \pm 0.2)[4d_d - d_u + 2.7e(\tilde{d}_d + 0.5\tilde{d}_u) + \cdots] + O(d_s, w, C_{qq}) \]

[Pospelov & AR '99,'00]

3. Hg EDM (diamagnetic)  (atomic+nuclear+QCD)

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

[\bar{g}_{\pi NN}(\tilde{d}_q) \sim (1 - 6)(\tilde{d}_u - \tilde{d}_d) + O(\tilde{d}_u + \tilde{d}_d, \tilde{d}_s, w)]

[Pospelov '01]

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Comments on the SR NEDM calculation

- Chiral properties
- Mixing with CP-conjugate currents
- Generic treatment of all CP-odd sources (…)

- Dependence on sea-quark EDMs
- Improvements in precision (?)

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

Lattice ?
Deuteron EDM

\[ d_D \sim (d_n + d_p) + d_D^{\pi NN} \]

\[ d_D^{\pi NN} \sim -2 \times 10^{-14} g_{\pi NN}^{(1)} e \text{cm} \]

[Khriplovich & Korkin ‘00]

• Same (leading) dependence as Hg (but without Schiff suppression)

\[ \theta_\mu = \frac{\pi}{10} \]

\[ d_D \sim 10^{-27} e \text{cm} \]
SUSY CP Problem

$M_{soft} = 500 \text{ GeV}$

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

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

MSSM parameter space: $\text{phases} < O(10^{-3} - 1)$

Decoupling 1st/2nd generation

Decoupling scalars (split SUSY, EW baryogenesis)

Decoupling fermions

2 HDM

large $\tan\beta$

[Chang, Keung & Pilaftsis ‘98]

[Weinberg ‘89; Dai et al. 90]

[Arkani-Hamed et al. ‘04]

[Barr, Zee ‘92]

[Barr ‘92; Lebedev & Pospelov ‘02]
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” (to leading order) at the weak scale

\[ L_{\text{new}}^{CP-odd} = \sum \frac{O_{n}^{CP-odd}}{\Lambda^n} \]

Questions:
- Can this scenario provide a viable baryogenesis mechanism?
- What is the threshold sensitivity?
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

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

\[ d_T(C_S), d_H(C_S), \mu \rightarrow e \Rightarrow \Lambda > 10^8 \text{GeV} \]