CP Violation and EDMs in a Supersymmetry Breaking Scenario

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Outline

Introduction

- For a supersymmetric extension of the standard model, additional CP violation comes from phases in the soft terms M_a, $A_{ij}^{u,d,e}$, μ and $B\mu$.

- Current bounds on electric dipole moments(EDM) of ^{205}Tl, n and ^{199}Hg

$$
\begin{aligned}
|d_{Tl}| &< 9 \times 10^{-25}\ e\,\mathrm{cm} \\
|d_n| &< 3 \times 10^{-26}\ e\,\mathrm{cm} \\
|d_{Hg}| &< 3 \times 10^{-29}\ e\,\mathrm{cm}
\end{aligned}
$$

  Note: the Hg bound is recently updated [W. C. Griffith et al, arXiv:0901.2328]

- The EDM constraints on the CP violation in new physics is stringent. To suppress the EDMs [Abel and Lebedev, hep-ph/0103320]:
  - small phases $\lesssim 10^{-3} - 10^{-2}$
  - decoupling $m_{\tilde{f}} \gtrsim 10$ TeV
  - EDM cancellation

- In the talk, we are interested in a type of SUSY breaking scenarios with the following feature:
  - sfermion masses $m_{\tilde{f}} \sim m_{3/2}$
  - gaugino masses $M_a \ll m_{3/2}$ suppressed at least by a one-loop factor. This also implies the sfermion masses $m_{\tilde{f}} \gtrsim 10$ TeV.
  - $\mu, B\mu \sim m_{3/2}$

- This kind of spectrum seems not natural based on the original motivation for low-energy supersymmetry. However, it may well be an interesting possibility from the top-down perspective. [Acharya etal, arXiv:0801.0478]

- This "partial sequestering" for gaugino masses is not unusual in the string motivated models. [Conlon and Quevedo, hep-th/0605141]

- SUSY breaking is mediated through Planck suppressed operators in an effective theory motivated from string compactification.
- Naively if there are many SUSY breaking fields, CP-violating phases are naturally present in soft supersymmetry breaking terms.
- The sfermion masses $\gtrsim$ 10 TeV $\Longrightarrow$ EDM constraints on the SUSY CP-phases are weak. However, EDMs bounds may be saturated with large SUSY CP-phases. Thus it is interesting to examine the implication for EDMs in such a scenario.
- As we will see, it is very plausible that SUSY CP-phases are dominantly from Yukawa phases instead of from soft supersymmetry breaking.

- The effective 4D SUGRA theory from compactification

$$\begin{aligned} K &= \hat{K}(h_i) + \tilde{K}_{\alpha\beta}(h_i) C^{\alpha\dagger} C^{\beta} + (Z H_u H_d + h.c.) \\ W &= \hat{W}(h_i) + Y'_{\alpha\beta\gamma}(h_i) C^{\alpha} C^{\beta} C^{\gamma} \end{aligned}$$

  where C_α are the matter fields in the MSSM. h_i are the hidden sector fields including the geometric moduli fields z_i and other gauge singlets ϕ_i (e.g. meson field $\phi = Q\tilde{Q}$).

- It is important to stabilize internal dimensions and spontaneously break SUSY. An old idea is to consider non-pert. superpotential

$$W = W_0 + \sum_{n=1}^{N_W} W_n, \quad W_n = d_n e^{-b_n^i z_i}$$

  d_n in general can be polynomial functions of ϕ_i fields.

- Dynamical relaxation of the phases, i.e. the phases of W_n are the same at the minimum of the scalar potential.

- Soft terms from gravity mediation

$$M_a^{\text{tree}}(\mu) = \frac{g_a^2(\mu)}{8\pi}\left(\sum_I e^{\hat{K}/2}F^I\partial_I f_a^{vis}\right)$$
$$A_{\alpha\beta\gamma} = e^{\hat{K}/2}F^I\partial_I\left[\ln\left(e^{\hat{K}}Y'_{\alpha\beta\gamma}/\tilde{K}_\alpha\tilde{K}_\beta\tilde{K}_\gamma\right)\right]$$

- Phases in soft terms can be generated from: $F^I\partial_I\hat{K}$, $F^I\partial_I\tilde{K}_{\alpha\beta}$, $F^I\partial_I f_a$ and $F^I\partial_I \ln Y'$. Here the supergravity F-terms of chiral fields $F^I = \hat{K}^{I\bar{J}}F_{\bar{J}} \equiv \hat{K}^{I\bar{J}}(\partial_{\bar{J}}\overline{W} + (\partial_{\bar{J}}K)\overline{W})$ where I, J run over both z_i and ϕ.
- These quantities are real up to some rotatable phases if the following conditions are satisfied:
  - Kähler potential $\hat{K}$ and $\tilde{K}_i$ are real functions of $z_i + \bar{z}_i$ and $\bar{\phi}\phi$.
  - gauge kinetic functions $f_a = k_a^i z_i$ with real constant $\tilde{k}_a$.
  - Yukawa couplings $Y' = e^{\alpha_i z_i}Y'_0$ where α_i is real.
- These conditions can easily be satisfied in the effective theories from string/M-theory compactifications.

CP-violating phases

- Yukawa couplings typically contain phases which lead to CKM phases. If the trilinear matrices are not proportional to the Yukawa matrices, this leads to non-zero CP-violating phases. [Abel, Khalil and Lebedev, hep-ph/0012145 and hep-ph/0112260]
- The full trilinear coupling $\hat{A}_{ijk}$

$$\hat{A}_{ijk} = F_I \partial_I \left[\ln \left(e^{\hat{K}} Y'_{ijk} / \tilde{K}_i \tilde{K}_j \tilde{K}_k \right) \right] Y_{ijk}$$

- The Yukawa couplings are typically generated at the scale when moduli are stabilized (e.g., from the instanton effects), and therefore have nontrivial dependence on the moduli VEVs.
- The moduli dependence in the Yukawa couplings generically leads to non-universal A-terms. For simplicity, we take $A_{ijk} \sim \eta_{ijk} \times m_{3/2}$, where η_{ijk} is real and $\eta_{ijk} \sim \mathcal{O}(1)$.

Yukawa texture

- In string/M-theory compactification, chiral matter fields are typically localized in the extra internal dimensions. This motivate us to consider a hierarchical Yukawa texture

$$Y^u_{ij} \sim \epsilon^q_i \epsilon^u_j, \quad Y^d_{ij} \sim \epsilon^q_i \epsilon^d_j, \quad Y^e_{ij} \sim \epsilon^l_i \epsilon^e_j$$

  This is can either be obtained in some extra-dimensional setup [Arkani-Hamed and Schmaltz, hep-ph/9903417] or in Froggatt-Nielsen model.
- In the super-CKM bases where Yukawa matrices are diagonal

$$\hat{A}^{SCKM}_{ij} = (V_L)_{il} \hat{A}_{lk} (V_R)_{kj}$$

  Assuming the phases in the Yukawa matrices to be $\mathcal{O}(1)$, we expect

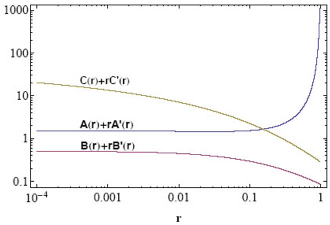
$$\begin{aligned} \mathrm{Im}(\hat{A}^{SCKM}_{11}) &\sim Y_{11}\ m_{3/2}, \quad \mathrm{Im}(\hat{A}^{SCKM}_{22}) \sim Y_{22}\ m_{3/2}, \\ \mathrm{Im}(\hat{A}^{SCKM}_{33}) &\sim \left(\frac{\epsilon_2}{\epsilon_3}\right)^2 Y_{33}\ m_{3/2} \end{aligned}$$

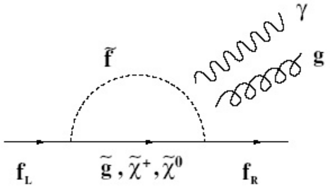
One-loop contribution to EDMs

- Chargino contribution to one-loop diagram is suppressed by small gaugino-higgsino mixing μ and loop function.
- The neutralino and gluino contribution to quark EDM(or CEDM) can be expanded in terms of small ratio $r \equiv M_a^2/m_{\tilde{q}}^2$. For example, for quark CEDM

$$d_q^C \sim \frac{g_s \alpha}{4\pi} \frac{m_q}{M_a^3} \mathrm{Im}(A_q) r^2 G(r)$$

  the function $G(r) = C(r) + rC'(r)$ for gluinos and $G(r) = B(r) + rB'(r)$ for neutralinos. The gluino diagram is the dominant contribution.
- The electron EDM dominantly comes from the neutralino diagram.

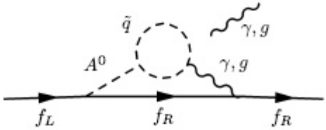


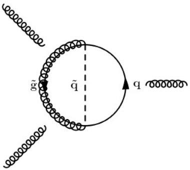


- Generally, Barr-Zee type diagrams involve chargino(or neutralino) in the loop are typically suppressed by the small gaugino-higgsino mixing.
- For Barr-Zee type diagrams with sfermions running in the loop, they are suppressed by the large A^0 mass.
- For neutron EDM, there is also a contribution from Weinberg operator.

$$d^G \approx -3\alpha_s \left(\frac{g_s}{4\pi}\right)^3 \frac{1}{m_{\tilde{g}}^3} \sum_{q=t,b} \mathrm{Im}(A_q^{\mathrm{SCKM}}) z_q H(z_1, z_2, z_q) \qquad (1)$$

where $z_i = m_{\tilde{q}_i}^2 / m_{\tilde{g}}^2$ for $i = 1, 2$, and $z_q = m_q^2 / m_{\tilde{g}}^2$ for $q = t, b$. If the CP-phases for the third generation is large, this contribution could be larger than the one-loop contribution.





EDM result

For the CP-phases in trilinears from Yukawas, the results are

- Neutron EDM (expt: $\lesssim 3 \times 10^{-26}$ e cm)

$$d_n^{NDA} \sim \left(\frac{m_{\tilde{g}}}{600\mathrm{GeV}}\right)\left(\frac{20\mathrm{TeV}}{m_{\tilde{q}}}\right)^3 3 \times 10^{-28} e\,\mathrm{cm}$$

- Mercury EDM (expt:$\lesssim 3 \times 10^{-29}$ e cm)

$$|d_{H_g}| \sim \left(\frac{m_{\tilde{g}}}{600\mathrm{GeV}}\right)\left(\frac{20\mathrm{TeV}}{m_{\tilde{q}}}\right)^3 \times 10^{-30}\mathrm{e\ \ cm}$$

- electron EDM (expt: $\lesssim 2 \times 10^{-27}$ e cm)

$$d_e \sim \left(\frac{m_{\tilde{B}}}{200\mathrm{GeV}}\right)\left(\frac{20\mathrm{TeV}}{m_{\tilde{e}}}\right)^3 \times 10^{-31}\mathrm{e\ \ cm}$$

Discussion

- Mercury EDM gives the strongest constraints on the squark masses if phases are order one in trilinears: $m_{\tilde{q}} \gtrsim 7$ Tev.
- Neutron EDM can be dominant by Weinberg operator if third generation phases are large. With stop or sbottom mass ~ 5 TeV and $\mathcal{O}(1)$ phases in A_{33}^{SCKM}, the neutron EDM bound can be saturated.
- $d_n \gtrsim 10^3 d_e$ – especially large compared to the typical supersymmetric models [Abel and Lebedev, JHEP 0601:133,2006]

Conclusion

- We have shown that the SUSY CP-phases in string theory motivated models are typically small, but trilinears can have gain $\mathcal{O}(1)$ CP-phases if they are not proportional to the Yukawas.
- The SUSY breaking scenario with partial sequestering gaugino masses leads to a different EDM pattern. If the SUSY CP-phases do come from Yukawa, the EDMs provide a way to probe the Yukawa texture.
- Though the upper bound obtained for EDMs is below the current experimental limits, the experimental bound for mercury EDM can be saturated – testable in the near future.