Resolution to the Supersymmetric CP Problem with Large Soft Phases via D-Branes

M. Brhlik,[1] L. Everett,[1] G. L. Kane,[1] and J. Lykken[2]
[1]*Randall Laboratory, Department of Physics, University of Michigan, Ann Arbor, Michigan 48109*
[2]*Theoretical Physics Department, Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
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We examine the soft supersymmetry breaking parameters that result from various ways of embedding the standard model (SM) on D-branes within the type I string picture, allowing the parameters to have large CP-violating phases. One embedding naturally provides the relations among soft parameters to satisfy the electron and neutron electric dipole moment constraints even with large phases, while with other embeddings large phases are not allowed. The results generally suggest how low energy data might teach us about Planck scale physics.

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The parameters of the Lagrangian of the minimal supersymmetric standard model (MSSM) include a number of CP-violating phases, which arise both in the soft breaking sector and in the phase of the supersymmetric mass parameter μ (for a careful count see [1]). The presence of these phases has typically been neglected in phenomenological analyses due to what traditionally has been called the supersymmetric CP problem: the electric dipole moments (EDM's) of the fermions receive one-loop contributions due to superpartner exchange which for large phases can exceed the experimental bounds. The current bounds for the electron [2] and neutron [3],

$$|d_e| < 4.3 \times 10^{-27}\ e\,\mathrm{cm}\ (95\%\ \mathrm{C.L.})\,, \tag{1}$$

$$|d_n| < 6.3 \times 10^{-26}\ e\,\mathrm{cm}\ (90\%\ \mathrm{C.L.})\,, \tag{2}$$

were thought to constrain the phases to be $\mathcal{O}(10^{-2})$ for sparticle masses at the TeV scale [4–6]. However, the results of a recent reinvestigation of this issue [7,8] have demonstrated that cancellations between different contributions to the electric dipole moments can allow for phenomenologically viable regions of parameter space with phases of $\mathcal{O}(1)$ and light sparticle masses. The phases, if non-negligible, not only have significant phenomenological implications for CP-violating observables (such as in the K and B systems), but also have important consequences for the extraction of the MSSM parameters from experimental measurements of CP-conserving quantities, since almost none of the Lagrangian parameters are directly measured [9].

The results of [7,8] indicate that the cancellations can occur only if the soft breaking parameters satisfy certain approximate relations which are testable in future experiments; such relations may provide clues to the mechanism of supersymmetry breaking and the form of the underlying theory. The purpose of this paper is to determine if classes of four-dimensional superstring models allow for (or predict) viable large phase solutions. We find that large phases consistent with the EDM constraints naturally arise in some models, while in others the constraints cannot be satisfied.

CP is a discrete gauge symmetry in string theory, and thus can only be broken spontaneously [10]. If this breaking occurs via the dynamics of compactification and/or supersymmetry breaking, then the four-dimensional effective field theory will exhibit explicit CP-violating phases. The origin of the nonperturbative dynamics of supersymmetry breaking in superstring theory is unknown, but progress can be made by utilizing a phenomenological approach first advocated by Ref. [11]. They assume that supersymmetry breaking effects are communicated dominantly by the dilaton S and moduli T_i, which have F-component vacuum expectation values (VEV's) parametrized as follows [11,12]:

$$\begin{aligned} F^S &= \sqrt{3}\,(S + S^*) m_{3/2} \sin\theta\, e^{i\alpha_S}\,, \\ F^i &= \sqrt{3}\,(T_i + T_i^*) m_{3/2} \cos\theta\, \Theta_i e^{i\alpha_i}, \end{aligned} \tag{3}$$

in which $m_{3/2}$ is the gravitino mass and θ, Θ_i are Goldstino angles (with $\sum_i \Theta_i^2 = 1$), which measure the relative contributions of S and T_i to the supersymmetry breaking. The F-component VEV's are assumed to have arbitrary phases α_S, α_i, which provide sources for the CP-violating phases in the soft terms.

Within particular classes of four-dimensional string models the (tree-level) couplings of the dilaton, moduli, and MSSM matter fields are calculable, leading to specific patterns of the soft breaking parameters. We have analyzed [13] the soft terms arising in three classes of superstring models: (i) orbifold compactifications of perturbative heterotic string theory, (ii) Hořava-Witten type M theory compactifications, and (iii) type I string models (the type IIB orientifolds). Our results indicate that the patterns of CP-violating phases consistent with the EDM constraints strongly depend on the type of string model under consideration.

First, we note that the general results of [8] (to which we refer the reader for details) demonstrate that sufficient cancellations among the various contributions

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to the EDM's are difficult to achieve unless there are large relative phases in the gaugino mass parameters. This feature is due to the approximate $U(1)_R$ symmetry of the Lagrangian of the MSSM [14], which allows one of the phases of the gaugino masses to be set to zero at the electroweak scale without loss of generality [8,14]. The phases of the gaugino mass parameters do not run at one-loop order; therefore, if the phases of the gaugino masses are universal at the string scale, they will be approximately zero at the electroweak scale [after the $U(1)_R$ rotation]. Cancellations among the chargino and neutralino contributions to the electron EDM are then necessarily due to the interplay between the phases of A_e and μ (φ_{A_e} and φ_μ); in this case [8] the pure gaugino part of the neutralino diagram adds destructively with the contribution from the gaugino-higgsino mixing, which in turn has to cancel against the chargino diagram. As a result, the cancellation mechanism is generally insufficient, and hence the phases must naturally be $\lesssim 10^{-2}$ (the traditional bound) [5].

This feature is predicted [15] in perturbative heterotic models at tree level, due to the universal coupling of the dilaton to all gauge groups in the gauge kinetic function $f_a = k_a S$ (in which k_a is the Kač-Moody level of the gauge group). Nonuniversal gaugino masses do occur at the loop level due to moduli-dependent threshold corrections. Hence, nontrivial CP effects require both moduli dominance and large threshold effects in order to overcome the tendency of the dilaton F term to enforce universal gaugino masses [13,16]. Similar statements apply to the soft breaking parameters derived in the M theory scenarios [19], which predict universal gaugino masses. Therefore, only a very small fraction of the $\varphi_\mu - \varphi_{A_e}$ parameter space leads to models allowed by the electron EDM [13].

However, nonuniversal gaugino masses are possible at tree level in type I string models. We focus on examples within the four-dimensional type IIB orientifold models [12,20–22], in which consistency conditions require the addition of open string (type I) sectors and Dirichlet-branes, upon which the open strings must end. We note that orientifolds are illustrative of a much larger class of models in the type I picture, with more general configurations of nonperturbative objects (e.g., D-brane bound states) in more general singular backgrounds (e.g., conifolds [23]).

While the number and type of D-branes required in a given model depends on the details of the orientifold group, we consider the general situation with one set of nine-branes and three sets of five-branes (5_i). Each set of coincident D-branes gives rise to a (generically non-Abelian) gauge group. Chiral matter fields also arise from the open string sectors, and can be classified into two categories. The first category consists of open strings which start and end on D-branes of the same sector; the corresponding matter fields are typically either fundamental or antisymmetric tensor representations under the gauge group of that set of branes. The second category consists of open strings which start and end on different sets of branes; in this case, the states are bifundamental representations under the gauge groups from the two D-brane sectors.

Model-building techniques within this framework are at an early stage and there is as yet no "standard" model; furthermore this framework does not provide any generic solution to the related problems of the runaway dilaton, supersymmetry breaking, or the cosmological constant. On the other hand, recent investigations [12] have uncovered the generic structure of the tree-level couplings of this class of models.

Of particular importance for the purposes of this study is that the dilaton no longer plays a universal role as it did in the perturbative heterotic case, as seen from the (tree-level) gauge kinetic functions determined in [12] using T duality and the form of the type I low energy effective action: $f_9 = S$, $f_{5_i} = T_i$. This result illustrates a distinctive feature of this class of models: in a sense there is a different "dilaton" for each type of brane. This fact has important implications both for gauge coupling unification [12] and the patterns of gaugino masses, which strongly depend on the details of the SM embedding into the five-brane and nine-brane sectors. For example, if the SM gauge group is associated with a single D-brane sector, the gaugino masses are universal, just as in the perturbative heterotic models (at tree level) [13], as can be seen from the similarity between the tree-level expressions for f in each case.

However, perhaps the SM gauge group is not associated with a single set of branes, but rather is embedded within multiple D-brane sectors. We consider for definiteness the case in which SU(3) and SU(2) originate from the 5_1 and 5_2 sectors. In this case, the quark doublet states necessarily arise from open strings connecting the two D-brane sectors; as these states have a nontrivial hypercharge assignment, their presence restricts $U(1)_Y$ to originate from the 5_1 and/or 5_2 sectors as well. We consider here two models of the soft terms corresponding to the two simplest possibilities for the hypercharge embedding, which are to have $U(1)_Y$ in either the 5_1 or 5_2 sector. The remaining MSSM states may either be states which (like the quark doublets) are trapped on the intersection of these two sets of branes, or states associated with the single 5_i sector which contains $U(1)_Y$. In any event the natural starting point for constructing models with these features are orientifolds which realize identical grand unified theory (GUT) gauge groups and massless matter on two sets of intersecting 5-branes. The existence of such symmetrical arrangements is often guaranteed by T duality. For example, Shiu and Tye [22] have exhibited an explicit model which realizes the Pati-Salam gauge fields of $SU(4) \times SU(2)_L \times SU(2)_R$ and identical chiral matter content on two sets of 5-branes.

Additional Higgsing and modding by discrete symmetries could then in principle produce the asymmetrical structures outlined above.

In the case with $U(1)_Y$ and SU(3) from the 5_1 sector, the gaugino masses and A terms take the form [12]

$$M_1 = \sqrt{3}\, m_{3/2} \cos\theta\, \Theta_1 e^{-i\alpha_1} = M_3 = -A_{t,e,u,d}\,, \quad M_2 = \sqrt{3}\, m_{3/2} \cos\theta\, \Theta_2 e^{-i\alpha_2}. \tag{4}$$

Note that the phases φ_1 and φ_3 of the mass parameters M_1 and M_3 are equal and distinct from that of the SU(2) gaugino mass parameter M_2. The soft mass squares are given by

$$m^2_{5_1 5_2} = m^2_{3/2}\left(1 - \frac{3}{2}\,(\sin^2\theta + \cos^2\theta\,\Theta_3^2)\right), \quad m^2_{5_1} = m^2_{3/2}(1 - 3\sin^2\theta)\,. \tag{5}$$

Similar expressions apply for the case in which $U(1)_Y$ and SU(2) are associated with the same five-brane sector, although in this case the relations among the phases are $\varphi_1 = \varphi_2 \neq \varphi_3$.

In our numerical analysis of these models, we impose the boundary conditions (4) and (5) at the GUT scale $M_G = 3 \times 10^{16}$ GeV (where we assume the couplings unify [24]), and evolve the parameters to the electroweak scale via the renormalization group (RG) equations. The sparticle masses and the CP-violating phases depend on the free parameters $m_{3/2}$, θ, $\Theta_i, i = 1,2,3$, which are related by $\Theta_1^2 + \Theta_2^2 + \Theta_3^2 = 1$, as well as the two phases α_1 and α_2 (physical results depend only on $\alpha_1 - \alpha_2$). To avoid negative scalar mass squares we restrict our consideration to values of θ which satisfy $\sin^2\theta < \frac{1}{3}$, and also assume that $\Theta_3 = 0$ (indicating that the modulus T_3 plays no role in supersymmetry breaking). B and μ are not determined by this embedding. However, we require that electroweak symmetry is broken radiatively as a result of RG evolution of the Higgs masses, so $B\mu$ and $|\mu|^2$ are expressed in terms of $\tan\beta$ and M_Z [25]. φ_μ remains an independent parameter, and thus the model depends on two phases at the GUT scale: $\alpha_1 - \alpha_2$ and φ_μ (though due to RG running the phases of the A terms at the electroweak scale will deviate from their string-scale values). We considered only small and moderate values of $\tan\beta$ since for models with large $\tan\beta$ two-loop contributions may become important [26].

We find, remarkably, that in order to satisfy the experimental constraints on the electron and neutron EDM's in this model, the large individual contributions from chargino, neutralino, and gluino loops do not have to be suppressed by small CP phases (or large sparticle masses). A cancellation between the chargino and neutralino loop contributions naturally causes the electron EDM to be acceptably small. As emphasized in [8], the contributions to chargino and neutralino diagrams from gaugino-higgsino mixing naturally have opposite signs and the additional φ_1 dependence of the neutralino exchange contribution can provide for a match in size between the chargino and neutralino contributions. In the neutron case, the contribution of the chargino loop is offset by the gluino loop contributions to the electric dipole operator O_1 and the chromoelectric dipole operator O_2. Since $\varphi_1 = \varphi_3$ in this scenario, the gluino contribution automatically has the correct sign to balance the chargino contribution in the same region of gaugino phases which ensures cancellation in the electron case. This simple and effective mechanism therefore provides extensive regions of parameter space where the electron and neutron EDM constraints are satisfied simultaneously while allowing for $\mathcal{O}(1)$ CP-violating phases.

To demonstrate the coincidence of the regions allowed by the experimental constraints on the EDM's, we choose $m_{3/2} = 150$ GeV, $\theta = 0.2$, and $\tan\beta = 2$, which leads to a reasonably light superpartner spectrum. In Fig. 1, we plot the allowed regions for both electron and neutron EDM depending on the values of Θ_1 and $\Theta_2 = \sqrt{1 - \Theta_1^2}$ while Θ_3 is set to zero. Frame (a), where $\Theta_1 = 0.85$, shows a very precise overlap between the electron and neutron EDM allowed regions. In frame (b), the magnitudes of all three gaugino masses are equal but have

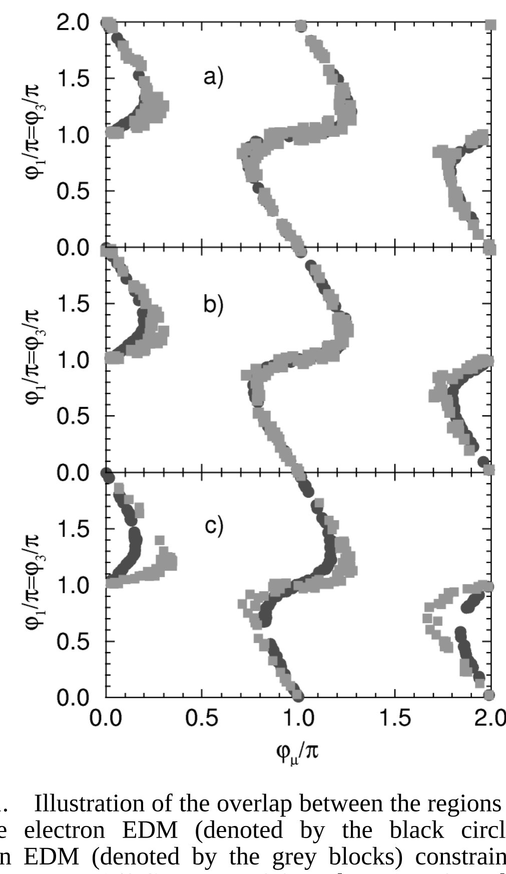

FIG. 1. Illustration of the overlap between the regions allowed by the electron EDM (denoted by the black circles) and neutron EDM (denoted by the grey blocks) constraints. We choose $m_{3/2} = 150\,\mathrm{GeV}$, $\theta = 0.2$, and $\tan\beta = 2$, and impose radiative electroweak symmetry breaking. Allowed points are shown for (a) $\Theta_1 = 0.85$, (b) $\Theta_1 = \sqrt{1/2}$, and (c) $\Theta_1 = 0.55$.

different phases due to the different origin of M_1 and M_3 compared to M_2. Finally, in frame (c) we set $\Theta_1 = 0.55$ so the magnitude of M_2 is significantly larger than that of $M_1 = M_3$; in this case the alignment between the EDM allowed regions is spoiled and only small CP-violating phases are allowed.

In general, the cancellation mechanism in this scenario provides a remarkably large range of allowed CP-violating soft phases and requires a specific correlation between φ_μ and $\varphi_1 = \varphi_3$ as shown in Fig. 1. It is also interesting to observe that the actual values of the electron and neutron EDM's for the allowed points in the phase parameter space are typically slightly below the experimental limit and should be within the reach of the next generation of EDM measuring experiments.

Equally remarkable, if we modify the way the SM is embedded in the D-brane sectors we are unable to satisfy the EDM constraints with phases larger than $\mathcal{O}(10^{-2})$. For example, the other possibility of arranging the SM gauge groups, such that $U(1)_Y$ is instead on the 5_2 brane with SU(2), does not allow for large phase solutions. The reasons for this behavior are similar to that of the Hořava-Witten scenario: we can use the $U(1)_R$ symmetry of the soft terms to put $\varphi_2 = \varphi_1 = 0$, which severely limits the possibility of cancellation between the chargino and neutralino contributions to the electron EDM. The effect of φ_{A_e} alone is not enough to offset the potentially large chargino contribution and thus only a very narrow range of values of $\alpha_1 - \alpha_2$ and φ_μ close to 0, $\pi, \ldots$ passes the electron EDM constraint.

There are a number of interesting implications of these results: They show explicitly how relations among soft parameters such as Eqs. (4) and (5) can naturally give small EDM's even with large phases. They illustrate how we are able to learn about (even nonperturbative) Planck scale physics using low energy data. If the soft phases are measured in (say) collider superpartner data, or at B factories, and found to be large, we have seen that they may provide guidance as to how the SM is to be embedded on branes. They illustrate very simply that large soft phases are at least consistent with, and perhaps motivated by, some string models. In particular, the requirement of nonuniversal phases of the gaugino mass parameters can naturally be realized in type I models in which the SM gauge group is split among different brane sectors. They suggest that d_n and d_e are not much smaller than the current limits.

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