CP VIOLATION IN SUSY, STRINGS AND BRANES

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Abstract

A review is given of CP violation in a broad class of models based on supersymmetry, superstrings and brane models. Such models contain typically large CP violating phases which affect a variety of supersymmetric phenomenon at low energies and affect search for supersymmetry at colliders and in dark matter experiments. We focus here on few such phenomena, specifically the mixing of the CP even and the CP odd Higgs bosons which can be induced by loop corrections and on CP violation in the muon sector. Possible signals for the observation of CP violation are also discussed.

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In this talk we discuss the origin of CP phases in SUSY/string/brane models and the implications of these phases for the electric dipole moments of the quarks and the leptons and explore the constraints placed on them by the current experimental limits on the phases. We also investigate the low energy implications of phases for SUSY phenomena at colliders and elsewhere. We begin by reviewing the status of CP in the Standard Model. Here the electro-weak sector of the theory has one CP violating phase in the CKM matrix\cite{1}. An important constraint on the CKM matrix is that of unitarity and we display one relation that arises from this constraint\cite{1}

\[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \]  

(1)

The constraint of Eq.(1) can be represented by a unitarity triangle whose angles \( \alpha, \beta, \gamma \) are defined by

\[ \alpha = \arg(-V_{td}V_{tb}^*/V_{ud}V_{ub}^*), \quad \beta = \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*), \quad \gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*) \]

Currently there are essentially four direct pieces of evidence for CP violation seen in nature. Two of these arise in the neutral Kaon system in the form of \( \epsilon \) and \( \epsilon' / \epsilon \) which are experimentally measured to be

\[ \epsilon = (2.28 \pm 0.02) \times 10^{-3}, \quad \epsilon' / \epsilon = (1.72 \pm 0.18) \times 10^{-3} \]  

(2)

The third one arises in the neutral system in the \( B_0^d \rightarrow J/\Psi K_s \) decay which gives a direct measurement of \( \sin(2\beta) \)

\[ \sin(2\beta) = (0.75 \pm 0.10) \quad \text{BaBar} ; \quad 0.99 \pm 0.15 \quad \text{Belle} \]  

(3)

The fourth piece of evidence in favor of CP violation comes from the baryon asymmetry in the universe so that

\[ n_B/n_\gamma = (1.5 - 6.3) \times 10^{-10} \]  

(4)

The results of the first three given by Eqs.(2) and (3) are consistent with CP violation given by the Standard Model. Further, there is also an internal consistency among the results of the first three, i.e., the determination of \( \sin(2\beta) \) of Eq.(3) is compatible with the indirect constraints on unitarity triangle from \( \epsilon, |V_{ub}/V_{cb}|, \) and the mass difference of neutral B mesons \( \Delta M_{B_d} \) etc. However, it is well known that an explanation of the baryon asymmetry in the universe implies the need of a CP violation above and beyond that given by the Standard Model\cite{1}. Further, if future more precise determinations of the angles \( \alpha, \beta, \gamma \) indicate some breakdown of the unitarity triangle that would be one sign of new physics beyond the standard model. Another implication of CP violation is in generation of the electric dipole moments of elementary fermions. In the lepton sector the edms arise at the multiloop level and are too small to be observed\cite{4}. The results are exhibited in Table 1.

| \( e \) | \( \leq 10^{-38} \) | \( < 4.3 \times 10^{-27} \) |
| \( \mu \) | \( \leq 10^{-35} \) | \( < 1.1 \times 10^{-18} \) |
| \( \tau \) | \( \leq 10^{-34} \) | \( < 3.1 \times 10^{-16} \) |
The results of Table 1 show that typically the standard model prediction of the electron edm is more than ten orders of magnitude smaller than the current experimental limit\cite{3, 4} and the situation for other leptons is even worse. There is no conceivable way that in the foreseeable future experimental accuracy can be improved to the level needed to observe the leptonic edms. Thus an observation of a leptonic edm in the future would be a clear indication of new physics beyond the Standard Model. The situation in the quark sector of QCD is more complicated. Here QCD generates a new CP violation from the term $\theta G G^\dagger$ from topological effects. The effective $\bar{\theta} = \theta G + \text{arg}(\text{det}M_uM_d) + ..$ gives a neutron edm $d_n \simeq 1.2 \times 10^{-16} \bar{\theta}_{\text{ecm}}$ and the current limit $d_n < 6.5 \times 10^{-26} \text{ecm}$ implies $\bar{\theta} < 6 \times 10^{-10}$. As is well known the smallness of $\bar{\theta}$ poses a problem and how to suppress this contribution has been dealt with quite extensively in the literature. The basic idea on how to control it consist of using axions, using a massless up quark or by using a symmetry argument to suppress CP violating effects\cite{5}. Some of the recent variants of these ideas consist of using a gluino-axion model\cite{6}, Left-Right models\cite{7}, use of SUSY non-renormalization theorem\cite{8} and gauging away the strong CP problem\cite{9}.

1 The EDM problem of SUSY, String and Brane Models

For the rest of the paper we assume that the strong CP problem has been resolved. However, even with solution of the strong CP problem a broad class of models based on supersymmetry, strings and branes contain a large number of CP violating phases which arise from the soft SUSY breaking sector of the theory\cite{10}. These large phases are indeed helpful for baryogenesis, but are problematic otherwise in that an order of magnitude calculation points to violations of the edm constraints. There are several ways of overcoming these constraints. One class of models consists of just fine tuning the phases to be small\cite{11}. Another possibility is that the effect of large phases on the edm of the quarks and the leptons are suppressed by making masses in the range of several TeV which would suppress the EDMs\cite{12, 13}. This solution is contrary to the spirit of SUSY since large masses are contrary to the spirit of naturalness. A variation of this possibility is to make the phases in the first two generations small or vanishing while they are large in the third generation\cite{14}. While this would produce the desired suppression it also constitutes a fine tuning unless small phases are shown to arise in a natural fashion in some string or brane models. A yet another class of models are those where the dangerous phases, i.e. the phases that enter in the EDMs are small, but otherwise the phases are large\cite{15}. Finally there is the possibility of internal cancellations\cite{16, 17}: In this mechanism the phases are typically large but internal cancellations occur generating a drastic reduction of the edms. Since the smallness of the edms is by a cancellation, one expects that the edms should be observed by an improvement in experiment be a factor of $O(10)$. This possibility has been checked in SUGRA, in MSSM, and in string and brane models. We note in passing that some of the atomic edms are also very accurately known\cite{18}. However, there are significant uncertainties associated with nuclear and atomic physics effects.
in the theoretical computations of the atomic edms and thus imposition of such constraints has to be done with care.

2 CP violation as probe of flavor structure

CP violation can act as a probe of the flavor structure of susy theories. This can happen if the contribution of the SUSY CP violation to K and B physics is significant. In this context there are three main scenarios. The first of these is that one has negligible contribution from the SUSY phases to K and B physics and that all of the CP violation in the K and B physics has standard model origin, i.e., arises from $\delta_{CKM}$. In this case SUSY CP phases can still be large, but their contribution to the K and B system is constrained to be small. This could happen in a variety of ways such as from mass suppression or from the absence of new flavor structure in the soft SUSY breaking sector of the theory beyond what is present in the Yukawas. Whatever, the origin of this suppression in this case the K and B systems are not relevant probes of CP violation of SUSY, string and brane models. Further, one does not find any need for a new flavor structure beyond what is present in the Yukawas. The second possibility is that there are sizable contribution from SUSY phases: Here in addition to the large SUSY CP phases, a new flavor structure is needed\[19, 20\]. For example, one needs non-negligible flavor changing term in the off diagonal component in the LR mass matrix $(\delta_{ij})_{LR}(d) = (m^2_{LR}(d))_{ij}/\tilde{m}_q^2$ to get a significant contribution to $\epsilon'/\epsilon$. Finally, there is a third possibility and that is the extreme viewpoint that all of the CP phenomena in K and B system arises from SUSY phases\[21\]. Again in this case a new flavor structure is necessary in addition to large phases. However, there is no compelling reason for this extreme viewpoint. In any case if one of the two latter scenarios hold then CP violation in the K and B system will act as a probe of the flavor structure of the theory.

3 Origins of CP violation

We discuss now the possible origins of CP violation is SUSY, string and brane models. One possible origin is string compactification. One may call this hard CP violation since this type of CP violations can exist even without the breaking of supersymmetry. Now Yukawa couplings which are formed via string compactification will carry this type of CP violation and the CKM phase $\delta_{CKM}$ which arises from the Yukawas is therefore a probe of CP violation arising from string compactification. A second source of CP violation is spontaneous symmetry breaking which generates CP phases via the soft breaking parameters. Specifically soft SUSY CP phases have origin in spontaneous supersymmetry breaking as they arise from moduli fields achieving complex VEV’s. In SUGRA/heterotic string models the scale where VEV formation appears is the Planck/string scale. However, in gauge mediated breaking, or in M theory/brane models the scale where soft CP phases appear could be as low as 10 TeV region. Additionally, there is the possibility that new sources of CP violation can occur from spontaneous symmetry breaking at the electro-weak scale, e.g., in extensions of MSSM with
the addition of two Higgs singlets. While spontaneous CP violation does not occur in the Higgs sector of MSSM, or in NMSSM it can occur in extensions of MSSM with the addition of two Higgs singlets\[22\]. If SUSY contributions to K and B physics turn out to be small, then one has a rather clean bifurcation, i.e., the CP violations in K and B physics are probe of string compactification, and baryogenesis and other CP phenomena that may be seen in sparticle decays etc become a probe of spontaneous symmetry breaking.

We discuss now the question if there is any connection between the CKM phase and the SUSY phases. Specifically we want to know if the largeness of the CKM phase has any implication regarding the size of the SUSY phases. Now it turns out that CP phases arising from the soft parameters are essentially unrelated to $\delta_{\text{CKM}}$. The reason for this is easily understood since SUSY phases arise from spontaneous supersymmetry breaking while $\delta_{\text{CKM}}$ arises from Yukawa couplings which have their origin in the string compactification\[23\] and thus largely there is not a direct connection between the two types of phases. There is, however, one exception to this in that the trilinear soft term contains a dependence on Yukawas so that\[24\]

$$A_{\alpha\beta\gamma} = F^i \partial_i Y_{\alpha\beta\gamma} + ..$$

(5)

Here we find that large phases of the Yukawas could enter in the soft trilinear parameters. Unfortunately this relationship is not rigid since large phases can be manufactured for the soft parameters even when the CKM phase is vanishing, and conversely the SUSY phases can be zero even when the CKM phase is maximal. For example, in a class of models $A_0 = 0$ and thus the CP phase of the Yukawas has no influence on the soft parameters. However, in a broad class of SUSY/string/brane models large CP phases do occur independent of any connection with $\delta_{\text{CKM}}$. In mSUGRA\[25, 26\], $\theta_\mu$ and $\alpha_{A_0}$ can be large and similarly in nonminimal sugra models, in heterotic string and brane models the phases in general would be large.

4 CP phases and SUSY Phenomenon

If the CP phases are indeed large they will affect many susy phenomena at low energy. First CP phases affect sparticle masses, decay branching ratios and cross sections\[27\]. Specifically, the FCNC process $b \rightarrow s + \gamma$, the trileptonic signal\[28\] and collider phenomenology is affected. CP effects show up in K and B physics and quantities such as $\epsilon'/\epsilon$ are affected\[29\]. Quite interestingly the supersymmetric contribution to $g_{\mu} - 2$ is strongly affected\[29\]. The CP phases enter in the analysis of Higgs physics leading to mixing of CP even and CP odd neutral sectors\[30, 31, 32, 33\]. These mixings will have many interesting features including new signals at colliders\[34, 35, 36\]. Similar phenomena will occur for soft gaugino masses in experiments at colliders\[37\] and in phenomenology of sleptons\[38\]. Other phenomena which are sensitive to CP violation are the analyses of neutralino relic density\[39\], proton decay\[40\] and baryogenesis\[11\]. Additionally, there are a variety of other phenomena not yet investigated where the CP phases are likely to enter strongly. One now must ask how experiment will determine the phases. In general this is a more complicated question than
what one might imagine. The reason is that while for mSUGRA case one has two phases which one can choose to be the phase of $\mu$ and the phase of $A_0$, for the more general soft SUSY breaking scenarios there are in general a large number of independent phases which enter in various combinations in susy phenomena. In Table 2 we exhibit some examples of the processes and list the combination of the phases that enter in that process. One finds that in general a susy process will contain several combination of susy phases and thus one will need measurement of several process to pin down the phases. Some examples of the combinations of phases that enter in SUSY phenomena are given in Table 2.

### Table 2: Examples of CP phases in SUSY phenomena

<table>
<thead>
<tr>
<th>SUSY Quantity</th>
<th>Combinations of CP violating phases</th>
</tr>
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<tbody>
<tr>
<td>$m_{\tilde{t}<em>R}$ ($m</em>{\tilde{t}_L}$)</td>
<td>$\xi_2 + \theta_\mu (\xi_2 + \theta_\mu, \xi_1 + \theta_\mu)$</td>
</tr>
<tr>
<td>$b \rightarrow s + \gamma$</td>
<td>$\alpha_{A_t} + \theta_\mu, \xi_2 + \theta_\mu, \xi_3 + \theta_\mu, \xi_1 + \theta_\mu$</td>
</tr>
<tr>
<td>$W \rightarrow q\bar{q}_1 + \chi_1 \ldots$</td>
<td>$\xi_2 + \theta_\mu, \alpha_{A_{\tilde{q}}<em>1} + \theta</em>\mu, \alpha_{A_{\tilde{q}}<em>2} + \theta</em>\mu, \xi_1 + \theta_\mu,$</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow q\bar{q}_1 + \chi_1 \ldots$</td>
<td>$\xi_2 + \theta_\mu, \alpha_{A_R} + \theta_\mu, \xi_2 + \theta_\mu, \xi_1 + \theta_\mu,$</td>
</tr>
<tr>
<td>$g_\mu - 2$</td>
<td>$\xi_2 + \theta_\mu, \xi_1 + \theta_\mu, \alpha_{A_R} + \theta_\mu$</td>
</tr>
<tr>
<td>$m_{H_1}$ (small tan $\beta$)</td>
<td>$\alpha_{A_t} + \theta_\mu$</td>
</tr>
<tr>
<td>$m_{H_1}$ (large tan $\beta$)</td>
<td>$\alpha_{A_t} + \theta_\mu, \alpha_{A_R} + \theta_\mu, \xi_2 + \theta_\mu, \xi_1 + \theta_\mu$</td>
</tr>
<tr>
<td>$Z^+ \rightarrow Z + H_i$</td>
<td>$\alpha_{A_t} + \theta_\mu, \alpha_{A_R} + \theta_\mu, \xi_2 + \theta_\mu, \xi_1 + \theta_\mu$</td>
</tr>
<tr>
<td>$d_e$ ($d_\mu$)</td>
<td>$\xi_2 + \theta_\mu, \xi_1 + \theta_\mu, \alpha_{A_e} + \theta_\mu (\alpha_{A_e} + \theta_\mu)$</td>
</tr>
<tr>
<td>$d_n$</td>
<td>$\xi_3 + \theta_\mu, \xi_2 + \theta_\mu, \xi_1 + \theta_\mu, \alpha_{A_{n_1}} + \theta_\mu, \alpha_{A_{n_2}} + \theta_\mu$</td>
</tr>
</tbody>
</table>

Table Caption: $\theta_\mu$ is the phase of the Higgs mixing parameter $\mu$, $\xi_i$ is the phase of gaugino mass $\tilde{m}_i$ (i=1,2,3) and $\alpha_{A_q}$ is the phase of trilinear coupling $A_q$.

### 5 Effects of CP violation in the Higgs sector

One of the interesting phenomenon of soft SUSY CP violating phases in that they induce a CP violation in the Higgs sector at the one loop level\cite{30, 32, 33}. To account for the induced CP violation in the Higgs sector one can parametrize the Higgs fields so that

$$
(H_1) = \begin{pmatrix} H_1^0 \\ H_1^\dagger \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} v_1 + \phi_1 + i\psi_1 \\ H_1^\dagger \end{pmatrix}
$$

$$
(H_2) = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} = \frac{e^{i\theta_H \mu}}{\sqrt{2}} \begin{pmatrix} H_2^+ \\ v_2 + \phi_2 + i\psi_2 \end{pmatrix}
$$

(6)

In the basis $\{\phi_1, \phi_2, \psi_{1D}, \psi_{2D}\}$ defined by

$$
\psi_{1D} = \sin \beta \psi_1 + \cos \beta \psi_2
$$

$$
\psi_{2D} = -\cos \beta \psi_1 + \sin \beta \psi_2
$$

(7)

$\psi_{2D}$ decouples and the remaining $3 \times 3$ matrix is
\[ M_{Higgs}^2 = \begin{pmatrix}
M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 + \Delta_{11} & -(M_Z^2 + M_A^2) s_\beta c_\beta + \Delta_{12} & \Delta_{13} \\
-(M_Z^2 + M_A^2) s_\beta c_\beta + \Delta_{12} & M_Z^2 s_\beta^2 + M_A^2 c_\beta^2 + \Delta_{22} & \Delta_{23} \\
\Delta_{13} & \Delta_{23} & (M_A^2 + \Delta_{33})
\end{pmatrix} \]  

The analysis for the cases of \( t - \bar{t} [30, 32, 33] \) and \( W, H^+, \tilde{W} [32] \) exchanges is straightforward and can be carried out analytically since diagonalization of only \( 2 \times 2 \) matrices are involved. The analysis of \( Z, A, H^0, \chi^0 \) exchange is more involved and requires a calculus of eigenvalues [42, 31, 33]. We review here briefly this technique. The loop corrections to the Higgs \((mass)^2\) matrix are in general given by

\[ \Delta M_{ab}^2 = \frac{1}{32\pi^2} \sum_i \left( \frac{\partial \lambda_i^2}{\partial \Phi_a} \frac{\partial \lambda_i^2}{\partial \Phi_b} \log \frac{\lambda_i^2}{Q^2} + \lambda_i^2 \frac{\partial^2 \lambda_i^2}{\partial \Phi_a \partial \Phi_b} \log \frac{\lambda_i^2}{eQ^2} \right)_0 \]  

The computation of the derivatives for the neutralino mass matrix requires special attention. One can now establish that

\[ F(\lambda) = \text{Det}(M^\dagger M - \lambda I) = \lambda^n + \epsilon^{(n-1)} \lambda^{n-1} + \epsilon^{(n-2)} \lambda^{n-2} + .. + \epsilon^{(1)} \lambda + \epsilon^{(0)} = 0 \]  

The co-efficients are explicit functions of the background fields \( \Phi_\alpha = \{ \phi_1, \phi_2, \psi_1, \psi_2 \} \). while the eigen values are implicit functions of the background fields through the satisfaction of the eigen value equation. One can now establish that

\[ \frac{\partial \lambda_i}{\partial \Phi_\alpha} = - \left( \frac{D_\alpha F}{D_\lambda F} \right)_{\lambda = \lambda_i} \]  

where \( D_\lambda \) differentiates the \( \lambda \) dependence in \( F \), \( D_\lambda F(\lambda) = dF/d\lambda \) and \( D_\alpha \) differentiates only the co-efficients, i.e., \( D_\alpha F = \epsilon^{(n-1)} \lambda^{(n-1)} + \epsilon^{(n-2)} \lambda^{(n-2)} + .. + \epsilon^{(1)} \lambda + \epsilon^{(0)} \), and \( [D_\alpha, D_\lambda] = 0 \). These equations provide us with a technique for analyzing cases where the analytic solutions to the eigen values are not available. It is well known that the \( t - \bar{t} \) exchange generates a large CP even-CP odd higgs mixing [30, 32]. However, significant contributions can arise from the \( W - W - H^+ \) exchanges especially for large \( \tan \beta [32] \). Specifically, for \( \tan \beta \geq 30 \) the chargino contributions can dominate the stop contribution. Significant contributions also arise from the \( Z, A, H^0, \chi^0 \) exchanges [33]. The contributions from this sector are comparable to the contributions from the stop and chargino sectors for values of \( \tan \beta \geq 5 \). If large CP phases exist, then collider experiments will provide signals such as three peaks in \( Z^* \to Z + H_i \) and modified rates of \( h \to b\bar{b} \). Further, signals may emerge from decays of the neutral and charged Higgs bosons of the type \( H^0 \to \chi^0_i \chi^\mp_j \) and \( H^\pm \to \chi^0_i \chi^\mp_j [13] \). An interesting observation in made in the analysis of Ref. [44] in that if a mixing effect is observed experimentally then among the three possibilities, i.e., the fine tuning, the heavy sparticle spectrum, and the cancellation mechanism, it is only the cancellation mechanism that can survive under the naturalness constraint [44, 45].
6 CP violation in the muon system

The supersymmetric correction to the muon anomalous magnetic moment $a_{\mu}^{SUSY} = (g_{\mu} - 2)/2$ [4] is a sensitive function of the phases and shows a rapid variation with the $\mu$ phase and the SU(2) phase $\xi_2$ [29]. As a consequence of the phases the chargino contribution need not be much larger than the neutralino contribution to $a_{\mu}^{SUSY}$ as is usually the case [47]. If an $a_{\mu}^{SUSY} \geq 10^{-10}$ emerges at BNL then this limit will significantly constrain CP phases [47, 48]. Further, it is possible to generate models with low sparticle spectra satisfying BNL and EDM constraints [47]. There is a recent proposal to probe $d_\mu$ with a sensitivity of $d_\mu \sim O(10^{-24})ecm$ [49]. In most theoretical models the charge lepton edms scale, i.e.,

$$\frac{d_\mu}{d_e} \approx \frac{m_\mu}{m_e}$$  \hspace{1cm} (12)

$d_e < 4.3 \times 10^{-27}ecm$ implies $d_\mu < 10^{-25}ecm$ below the sensitivity of the proposed BNL experiment. Large muon edms can be gotten only by the breakdown of scaling, e.g., in the two higgs doublet model [50], in Left-Right models [51], and in models with non-universalities in the slepton sector [52, 53] where $\alpha_{A_\mu} \neq \alpha_{A_e}$, $|A_\mu| \neq |A_e|$.

7 Conclusions

The discussion given here shows that CP violation is an important probe of susy/string/brane models. It is most likely that there are more than one origin of CP violation. One of these is string compactification, and another, spontaneous symmetry breaking. Thus CP violation is a probe of string compactification as well as of symmetry breaking. Further, CP violation could also be a probe of the flavor structure of supersymmetric models if the SUSY contributions to K and B physics are significant. One also finds that the edms if observed could provide a further probe of the flavor structure of supersymmetric theories. In this context the proposed BNL experiment to measure the muon edm at the sensitivity of $10^{-24}ecm$ is important as a probe of the flavor structure of susy/string/brane models. Further, collider experiments have the potential to tell a lot about CP violation specifically regarding the existence of CP beyond the K and B systems. This will occur via analyses of sparticle masses and decays, production cross sections, and via possible observation of CP even-CP odd mixing in the neutral Higgs system.

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