PHASES AND CP VIOLATION IN SUSY

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Abstract

We discuss CP violation in supersymmetric theories and show that CP phenomena can act as a probe of their origins, i.e., compactification and spontaneous supersymmetry breaking. CP violation as a probe of the flavor structure of supersymmetric theories is also discussed. A brief overview is given of several low energy phenomena where CP phases can produce new effects. These include important CP effects in processes involving sparticles and CP mixing effects in the neutral Higgs boson system. We also discuss the possibility of violations of scaling in the electric dipole moments (EDMs) due to the presence of nonuniversalities and show that with inclusion of nonuniversalities the muon EDM could be up to 1-2 orders of magnitude larger than implied by scaling and within reach of the next generation of experiments. Thus the EDMs are an important probe of the flavor structure of supersymmetric theories.

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1 Introduction

In this talk we give a brief overview of recent developments on CP violation in supersymmetric theories. We begin with a discussion of the current experimental status of CP violation in the Standard Model[1]. The electro-weak sector of the Standard Model has one CP violating phase in the CKM matrix. An important constraint on the Cabbibo-Kobayashi-Maskawa (CKM) matrix is that of unitarity and one such constraint is $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$. This constraint can be represented by a unitarity triangle whose angles α, β, γ are defined by the relations $\alpha = arg(-V_{td}V_{tb}^*/V_{ud}V_{ub}^*)$, $\beta = arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$, and $\gamma = arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ Currently there are four pieces of experimental evidence for the existence of CP violation in nature. Two of these come from the kaon system in the form of ϵ and ϵ'/ϵ. A third piece of evidence appeared last year from a direct measurement of sin(2β) in B meson decays $B_d^0(\overline{B_d^0}) \to J/\Psi K_s$ which gave $\sin 2\beta = (0.75 \pm 0.10)$ (BaBar) and $\sin 2\beta = (0.99 \pm 0.15)$ (Belle). The fourth piece of evidence for CP violation is indirect as it comes from the existence of baryon asymmetry in the universe so that $n_B/n_\gamma = (1.5 - 6.3) \times 10^{-10}$. Now the first three pieces of evidence appear to be consistent with the CP violation given by the Standard Model while the fourth one points to a new source of CP violation above and beyond the one from the standard model. CP violation also leads to electric dipole moments of elementary particles. However, in the lepton sector of the standard model EDMs arise at the multi loop level[2] and are typically more than ten orders of magnitude smaller than the current experimental limits[3, 4] and thus for all practical purposes too small to be experimentally observed in the foreseeable future. This means that the observation of a lepton EDM would be a clear indication of new physics beyond the standard model. In addition to the CP violation arising from the CKM matrix in the electro-weak sector of the Standard Model, one also has an additional CP violation given by the strong interaction of the theory, in the form of a term $\theta_G \frac{\alpha_s}{8\pi} G\tilde{G}$ which can give a huge EDM to the neutron unless θ is fine tuned to be very small.

There is a large amount of literature now on how to suppress the strong CP violation effects. Some of the early ideas discussed in this connection consist of using axions, a massless up quark or a symmetry argument to suppress CP violating effects[5]. There is also considerable recent literature on this subject. which we discuss briefly. The analysis of Ref.[6] invokes the idea of a gluino-axino and uses a Peccei-Quinn mechanism for the gluino rather than the quarks. Thus it is proposed that the axion couple to the gluino rather than the quark and that supersymmetry breaking have the same origin as the axion. One finds then that the θ_{QCD} is canceled exactly by the minimization of the dynamical gluino phase and thus the calculation of the EDMs in MSSM becomes unambiguous. The analysis of Ref.[7] is based on Left-Right symmeteric models. In these models the strong CP parameter $\bar{\theta}$ is zero at the tree level, due to parity (P), but is induced due to P -violating effects below the unification scale. It is estimated that $\bar{\theta} \leq 10^{-16}$ for models with universal scalar masses. In more general SUSY breaking scenario, one finds $\bar{\theta} \sim (10^{-8} - 10^{-10})$ close to experimental observation. In the analysis of Ref.[8] a solution to the strong CP problem using supersymmetry[8] is proposed. Thus the work of Ref:[8] envisions a solution to the strong CP problem based on supersymmetric non-renormalization theorem. In this scenario CP is broken spontaneously and its breaking is communicated to the MSSM by radiative corrections. The strong CP phase is protected by a SUSY non-renormalization theorem and remains exactly zero while the loops can generate a large CKM phase from wave function renormalization. Finally in the analysis of Ref.[9] a solution based on gauging away the strong CP problem is proposed. Thus the work of Ref.[9] proposes a solution that involves the existence of an unbroken gauged $U(1)_X$ symmetry whose gauge boson gets a Stuckelberg mass term by combining with a pseudoscalar field $\eta(x)$ which has a axion like coupling to $G\tilde{G}$. Thus the θ parameter can be gauged away by a $U(1)_X$ transformation. This leads to mixed gauge anomalies which are canceled by the addition of an appropriate Wess-Zumino term.

2 Large Phases in SUSY, String, and Brane Models

Assuming that the strong CP problem is solved we still have a SUSY CP problem. Thus in the minimal supergravity model[10, 11] one has two arbitrary phases which are theoretically unrestricted and can get large. Similarly in a broad class of string and brane models one finds that soft susy breaking generates CP violating phases of sizes which are typically $O(1)$. Thus one finds that even in the absence of the strong CP problem one has a SUSY CP problem in that in most models based on SUSY, string and branes the phases of the soft parameters are large and this is problematic for the satisfaction of the EDM constraints. Many avenues have been explored on how to overcome this problem. Some possible solutions to this problem that have been discussed are the following: (i) Arrange the satisfaction of the EDMs by fine tuning the phases to be small[12]. (ii) Assume the phases are large but suppress their effects on the EDMs of the quarks and the leptons by making masses of the sparticles heavy[13]. Effectively this requires that the sparticle masses lie in the range of several TeV. While this is a valid solution it appears contrary to the concept of naturalness[14]. (iii) Arrange so that the phases in the first two generations and the flavor blind phases vanish and the only phases present are in the third generation[15]. (iv)Internal cancellations[16, 17]: Here one looks for regions of the parameter space where, one has cancellations between the various contributions to the EDMs of the leptons and of the quarks. If this mechanism holds then one will expect to observe EDMs by a factor of 10 improvement in experiment. In addition to the above there are several variants of the above ideas available in the literature[18, 19]. The EDM of the mercury $^{199}H_g$ is known to a great degree of accuracy[20] and one may wish to impose this constraint on the SUSY phases. However, atomic EDMs have several uncertainties which are not fully understood. These include uncertainties associated with particle physics effects (such as the uncertainties associated with the strange quark content of the nucleons[21]), uncertainties associated with the nuclear physics models at low energy, and uncertainties associated with atomic physics effects. In addition to the above estimates made in computing the atomic EDMs have ignored the effects of the CP violating dimension six operator[22]. While the effect of the CP violating dimension six operator may be small in some regions of the parameter space there is no reason to believe it would be small in all allowed regions of the MSSM parameter space.

An interesting issue concerns the origin of CP violation. The two possibilities that present themselves are (1) compactification and (2) spontaneous symmetry breaking.

Thus in the first case while the string or M theory in its uncompactified form is CP symmetric CP violation can appear after compactification. In such a circumstance the Yukawa couplings are the ones likely to get complex phases[23] which are eventually translated in terms of CP violation in the CKM matrix. Thus one can view the CP violation in the CKM matrix as directly originating from the string compactification. Regarding the second possibility CP violation can arise when the spontaneous breaking of supersymmetry occurs. In supergravity and string models[10, 11, 24] this breaking arises also at the string/Planck scale. Here one is led a priori to the presence of many more phases. (In gauge mediated breaking, or in M theory/brane models the scale where soft CP phases appear could be in the 10 TeV region.) There is yet another possibility for the origin of CP violation in the context of spontaneous breaking, and this is via spontaneous symmetry breaking in the electro-weak sector. Now while the spontaneous CP violation does not occur in the Higgs sector of MSSM it can occur in extensions of MSSM. Thus, for example, a recent analysis with an extensions of MSSM with the addition of two Higgs singlets exhibits such a spontaneous breaking[25]. There are now the following possibilities: (a) The SUSY contributions to K and B physics turn out to be small: In this case one has a rather clean demarcation, that is 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 supersymmetry breaking. (b) The second possibility is that the SUSY contributions to the K and B systems are significant. In this case one has a more involved picture in that both δ_{CKM} and the SUSY phases contribute here and thus one would need to disentangle the SUSY CP effects from the effects of δ_{CKM} to get any meaningful constraints on either δ_{CKM} or on the SUSY phases. On a more theoretical level one might ask if in MSSM there exists a connection at some level between the CP violation in the CKM matrix and the CP violation that arises in the soft parameters. A priori there does not appear to be a connection as the origins of these types of CP violations are very different, since one arises from string compactification and the other from spontaneous supersymmetry breaking. This is mostly true except that the soft trilinear couplings $A_{\alpha\beta\gamma}$ have a dependence on the Yukawa couplings $Y_{\alpha\beta\gamma}$ via the a term of the form $A_{\alpha\beta\gamma} \sim F^i\partial_i Y_{\alpha\beta\gamma}$ where i refer to the moduli fields. Thus in this case the CP violating phases in the Yukawa couplings will filter into the trilinear couplings $A_{\alpha\beta\gamma}$. However, the exact nature of compactification in string theory that takes us from 10 space time dimensions to 4 dimensions in string theory is not known. Similarly, the spontaneous breaking of supersymmetry in string theory is not fully understood. Thus in view of the above one cannot put strict theoretical restrictions on the size of CP violation either on δ_{CKM} that arises via string compactification or on the soft SUSY parameters that arise from spontaneous supersymmetry breaking.

3 CP phases and low energy phenomena

In the absence of any reliable string models that might in a natural fashion determine the CP phases to either vanish or be small, one has to assume that these phases will in general be sizable and that the resolution of the EDM problem comes about by one of the methods discussed in the previous section. In this circumstance when the phases are sizable a whole arrary of low energy phenomena will be affected. The list of such phenomena is indeed large and encompasses essentially all of current low energy phenomenology. We list below a few of these. They include sparticle masses and decay branching ratios and cross-sections[26, 27, 28, 29], Higgs boson decays, neutralino relic density and detection rates in dark matter detectors[30], g-2[31], CP even -CP odd mixing in neutral Higgs system[32, 33, 34, 35], FCNC $b \to s + \gamma$[36], trileptonic signal[37], ϵ'/ϵ[38], CP effects on e^+e^- and $\mu^+\mu^-$ collider phenomenology[39, 40, 41, 42], CP effects on $b\bar{b}$ system[43], baryogenesis[44], proton decay[45] and $B^0_{s,d} \to \mu^+\mu^-$[46]. Of the above we will discuss the CP effects in the neutral Higgs in some detail in Sec.4 and the effects of SUSY CP phases on $g_\mu - 2$ and on the muon EDM in Sec.5. Here we discuss briefly some general aspects of the phases. One question one might ask is how one may determine the phases. This is a more difficult task that might appear at the surface. The reason for this is that supersymmetric phenomena in general depend typically on a combination of phases and thus deciphering the phases would require a simultaneous determination of many observables. To see the complexity of this problem we exhibit the phase dependence of a few experimentally observable quantities. To streamline the discussion we begin by defining the soft parameters that enter the low energy theory that will be the focus of our discussion. The low energy theory in general consists of the following soft parameters[11]: sfermion masses $m_{\tilde{f}_L}, m_{\tilde{f}_R}$, the U(1), SU(2), and SU(3) gaugino masses $m_i = |m_i|e^{i\xi_i}$ (i=1,2,3), the trilinear soft parameters $A_f = |A_f|e^{i\alpha_{A_f}}$, and the Higgs mixing paramrter $\mu = |\mu|e^{i\theta_\mu}$. Let us now consider the chargino and neutralino masses. The chargino masses depend on the single combination $\xi_2+\theta_\mu$ while the neutralino masses depend on the phases ξ_1, ξ_2, μ. The FCFC decay $b \to s+\gamma$ depends on four combinations $\xi_1+\theta_\mu$,$\xi_2+\theta_\mu$,$\xi_3+\theta_\mu$ and $\alpha_{A_t} + \theta_\mu$. Similary, at least four combinations of phases appear in the decay of charginos $\tilde{W} \to q_1\bar{q}_2 + \chi_1$ which may be taken to be $\xi_1 + \theta_\mu$,$\xi_2 + \theta_\mu$, $\alpha_{q_1} + \theta_\mu$, and $\alpha_{q_2} + \theta_\mu$. Clearly then measurement of several quantities will be necessary in order to determine the phases. A relevant question then is the accuracy with which such phases can be determined. The linear collider is an appropriate instrument for the accurate determination of the phases. Thus, for example, accurate measurements of the chargino and neutralino masses and their pair production cross sections at linear colliders can allow a determination of the CP violating phases to a good accuracy. With the design parameters of the linear colliders a determination of some phases to an accuracy of one tenth of a radian is possible[39].

4 Effects of CP violation in the neutral Higgs sector

At the tree level the Higgs mass matrix in MSSM is block diagonal between the CP even and the CP odd odd states and here one gets two CP even states and one CP odd state. The situation changes when one includes the effects of loop corrections to the effective potential[47]. In the presence of CP violating phases the loop corrections mix the CP even and the CP odd Higgs sectors[32] and the neutral Higgs mass matrix no longer factorizes into CP even and CP odd sectors. Thus in MSSM one has two Higgs doublets (H_1^0, H_1^-) and (H_2^+, H_2^0) where H_2 gives mass to the up quarks and H_1 gives mass to the down quarks and the leptons. We denote the real and imaginary parts of the H_1^0 and H_2^0 by ϕ_1, ψ_1, and ϕ_2 and ψ_2. After spontaneous breaking we go to the basis $\phi_1, \phi_2, \psi_{1D}, \psi_{2D}$ defined by $\psi_{1D} =$

$\sin\beta\psi_1+\cos\beta\psi_2$, $\psi_{2D}=-\cos\beta\psi_1+\sin\beta\psi_2$. In this basis ψ_{2D} decouples and one is left with a 3×3 matrix which mixes the 2 CP even and one CP odd states. It was first shown in Ref.[32] that the effect of top-stop exchange can generate a significant mixing between the CP even and the CP odd states. In Ref.[34] it was extended to include the chargino, W and charged Higgs boson exchange and it was found this exchange could be very significant for large $\tan\beta$[34]. it turns out that that a similar computation to include the CP violation effects from the neutralino, Z and neutral Higgs exchanges is far more difficult. The reason for this is that while the computation of the top-stop and charged Higgs, W and chargino exchange calculation involves diagonalization of only 2x2 mass matrices, the computation of the neutralino exchange contribution involves the diagonalization of a 4x4 neutralino mass matrix. To deal with this problem one needs to use some special techniques. A full analysis of the neutralino exchange corrections with inclusion of CP effects is given in Ref.[35]. Again one finds that the effects of neutralino exchange contributions for large $\tan\beta$ can be quite significant comparable to the contributions from the top-stop exchange contributions. There are a variety of signals associated with the effects of CP violation in the Higgs sector. One interesting signal associated with the CP even -CP odd mixing in the neutral Higgs sector can be seen directly in e^+e^- colliders, e.g., three peaks in the process $e^+e^-, q\bar{q}\to Z^*\to Z+H_i$, and modified rates of $h\to b\bar{b}, c\bar{c}$ etc[32]. Further, a very interesting observation in made in Ref.[48] is 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[14]. Another possible way to detect the existence of CP violation is in polarization asymmetries in the Higgs decays which have been analyzed recently[49]. Specifically in this case one analyzes the spin correlated decays of the Higgs into neutralinos and charginos and one can express the decays in terms of the longitudinal and the transverse polarization of the final charginos and neutralinos. These spin correlated decays show a strong dependence on the CP violating phases. Thus an observation of the spin correlated decays can shed a considerable light on the presence of supersymmetric CP violation in the Higgs sector.

5 CP violation and flavor structure

The contribution of the supersymmetric CP violation to the K and B systems can act as a probe of the flavor structure of supersymmetric models. Specifically one can envision three scenarios: (a) Negligible or small contribution from the supersymmetric phases to the K and B system: In this case essentially all of the CP violation in K and B physics has standard model origin, i.e., arises from δ_{CKM} and K and B physics provides us with no guide to the presence of a new flavor structure beyond what is present in the Yukawa couplings; (b) Sizable contribution from SUSY phases to K and B physics: If it turns out that there is a large contribution to the K and B physics from supersymmetry, then in addition to large supersymmetric CP phases, a new flavor structure beyond the Yukawas is indicated[38, 50]. For example, one needs a non negligible $(\delta_{12})_{LR}(d)=m^2_{LR}(d)/\tilde{m}^2_q$ to get a significant contribution to ϵ'/ϵ from supersymmetry; (c) The entire CP phenomena in K and B system arises from SUSY phases[51, 52]: As in (b) in this case one needs a new flavor structure in addition to large phases. However, there is no compelling reason for this extreme view point. In the latter two scenarios, i.e., in (b) and (c) one can view CP violation as a probe of the flavor structure of the supersymmetric theory.

6 CP violation, $g_\mu - 2$ and the Muon EDM

As mentioned already the muon anomalous moment is a very sensitive function of CP phases and this effect has been analysed theoretically at considerable length in Ref.[31]. It turns out that an experimental determination of the deviation of $g_\mu - 2$ from the standard model also has strong implications on constraining the CP phases. These constraints were also analyzed in Ref.[31]. One very interesting result of the CP phases is that the usual hierarchy between the chargino-sneutrino and the neutralino-smuon exchange contributions to $g_\mu - 2$ no longer applies when phases exist. Thus in the absence of CP phases one finds that the chargino-sneutrino exchange contribution to $g_\mu - 2$ is typically much larger than the neutralino-smuon exchange contribution. However, in the presence of phases this does not necessarily hold. Thus while the chargino-sneutrino exchange contribution depends only on the phase combination $\xi_2+\mu$, the neutralino-smuon exchange contribution depends on the phases ξ_1, ξ_2, μ and α_{A_μ}. Thus in this case depending on the numerical value of the phases one finds that the neutralino-smuon exchange contributions can become comparable to and even exceed the chargino-sneutrino exchange contribution. The large sensitivity of a_μ^{SUSY} on the phases implies that a constraint on a_μ^{SUSY} can be turned into a constraint on the phases and this constraint turns out to be quite significant if $a_\mu^{SUSY} \geq 10^{-10}$[31]. Of course in the presence of CP phases there will be an EDM associated with the muon and it is interesting to ask what the size of this EDM is. This question is interesting in view of the fact that there is a recent proposal by BNL to probe the muon EDM (d_μ) with a sensitivity of $d_\mu \sim O(10^{-24})ecm$[53]. This proposed limit will be six orders of magnitude more sensitive that the current limit of $\sim 10^{-18}$ ecm, Now for wide class of models one finds that a so called scaling holds so that the EDMs scale by the masses, i.e., $d_\mu/d_e \simeq m_\mu/m_e$. Since the electron EDM has an experimental upper limit of $d_e < 4.3 \times 10^{-27} ecm$ scaling implies $d_\mu < 10^{-25} ecm$ which lies below the sensitivity (i.e., $d_\mu < 10^{-24} ecm$) that will be accessible in the proposed BNL experiment. The question then is if there are any models which could produce a muon EDM sensitive to the proposed BNL experiment. Clearly this can happen only by a violation of scaling. Such scaling violations can occur in some Left-Right symmetric models[54]. More recently it was proposed that slepton nonuniversalities can generate such violations[55, 56], These slepton non-universalities can easily arise from the soft trilinear couplings, either in the magnitude or in phase. It is found that such nonuniversalities can easily generate a muon EDM in excess of $10^{-24} ecm$ which is the sensitivity limit of the BNL experiment.

7 Conclusions

In this paper we have given a brief overview of the current status of CP violation in supersymmetric theories. We argued that CP violation arising from supersymmetric phases can influence a wide range of low energy phenomena. These include masses and decays of sparticles, the neutral Higgs system, flavor changing processes such as $b \to s + \gamma$, the trileptonic signal, the process $B^0_{s,d} \to \mu^+\mu^-$, dark matter, proton decay and many other processes. Clearly, the CP phases then have an important impact on SUSY and Higgs searches. On a theoretical level, the origin of CP violation can be traced back to string compactification and to the spontaneous breaking of supersymmetry. The CP violation associated with Yukawa couplings that arise as a consequence of string compactification largely affects the CKM matrix, while phenomena such as the EDMs, low energy SUSY phenomenology and the baryon asymmetry of the universe are largely governed by the CP phases that are associated with the spontaneous breaking of supersymmetry. Assuming K and B physics is largely controlled by the CP violation in the CKM matrix, such physics gives us a glimpse into the nature of string compactification, while CP violation in low energy SUSY and Higgs phenomena which we expect to observe in collider experiments will reveal the nature of CP violation associated with soft parameters, and such physics will give us a glimpse into the nature of spontaneous breaking of supersymmetry.

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