LIGHT GLUINOS AND *CP* VIOLATION

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It is shown that SUSY models with light gluinos, in contrast to the heavy gluino scenario, have the right amount of flavour mixing in the down-squark mass matrix to explain naturally the observed ϵ parameter even for low top mass ($m_t \approx 40$ GeV) and long bottom lifetime ($\tau_B \gtrsim 1$ ps). Implications for ϵ'/ϵ and $B^0-\bar{B}^0$ mixing are discussed.

The alleged uncertainties [1,2] over the compatibility of the standard $SU(2)\times U(1)$ model with the observed *CP* violation in the neutral kaon system have prompted several authors [3] to examine *CP* violation in the supersymmetric generalisation of the standard model [‡1]. The 6×6 down-squark mass matrix in such models can be conveniently parametrized as

$$M_{\tilde{d}}^2 = \begin{pmatrix} \mu_L^2 \mathbf{1} + M_d M_d^\dagger + C M_u M_u^\dagger & Am & M_d \\ Am & M_d^\dagger & \mu_R^2 \mathbf{1} + M_d M_d^\dagger \end{pmatrix}, \quad (1)$$

where M_d (M_u) is the mass matrix of charge $-1/3$ ($2/3$) quarks. μ_L and μ_R and the flavour-independent SUSY breaking mass terms for the L and R squarks, respectively. The flavour non-diagonal term involving the parameter C arises due to radiative corrections. The off-diagonal block involves the A parameter and the gravitino mass. m is a measure of L–R mixing in the squark sector. If $C \neq 0$ vertices written in terms of mass eigenstate fields will generate flavour-violating couplings (e.g. $\tilde{d}\bar{s}\tilde{g}$) contributing to particle mixing ($K^0 \leftrightarrow \bar{K}^0$, $B^0 \leftrightarrow \bar{B}^0$) and *CP* violation through super-box diagrams [3,4].

The theoretical estimate of the *CP* violation parameter ϵ depends sensitively on the bag parameter $\mathscr{B}$ [1,2] whose theoretical estimates are rather uncertain. It also depends on the Kobayashi–Maskawa (KM) angles θ_2, θ_3 and the KM phase δ which are now somewhat constrained – but not completely determined – by the experimental results on B lifetime (τ_B) [5] and the experimental upper bound: $\bar{R} \equiv \Gamma(b \to u\ell\bar{\nu})/\Gamma(b \to c\ell\bar{\nu}) \lesssim 0.04$ [6]. The situation in the standard model can be summarised as follows: with $\tau_B \gtrsim 1$ ps, relatively smaller estimates of $\mathscr{B}$ (e.g. the bag model

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[‡1] For a review, see ref. [4].

or the current algebraic results $\mathscr{B} = 0.4$ [7] [‡2] or 0.33 [9]) and m_t in the currently favoured range 30–50 GeV, the standard model estimate (ϵ_{std}) turns out to be significantly smaller than the experimental result ϵ_{exp}, even for the optimistic choice $\bar{R} = 0.03$ [1]. If on the other hand one works with large estimates of $\mathscr{B}$ (e.g. the vacuum saturation result $\mathscr{B} = 1.0$ [10]) ϵ can be fitted with $\tau_B \gtrsim 1$ ps *provided* $\bar{R}$ is taken to be nearly equal to its upper bound. A smaller choice ($\bar{R} = 0.01$ say), however, restores the pressure on the standard model [2].

Contributions from the super-box diagrams enhance the theoretical estimate of ϵ. It was shown [10] that with standard choices of the SUSY parameters (see below) $\mathscr{B} = 0.33$, $\bar{R} = 0.03$ and reasonably low m_t ($m_t > 20$ GeV) an agreement with ϵ_{exp} is possible for $C \approx -1.0$, a value indicated by order of magnitude estimates.

Subsequently ϵ was carefully calculated [11,12] in specific $N = 1$ SUGRA models [13]. These calculations, however, revealed that the theoretical estimate C_{th} is indeed much smaller: $C_{th} = -(0.2–0.3)$. This is indeed too small to contribute effectively to ϵ. It was also shown [12] that the minimum value ($|C_{min}|$) required to fit ϵ for $m_t \approx 40$ GeV and a suitable choice of δ, which is not known experimentally, is significantly larger than C_{th}. The SUSY model of CP violation, therefore, loses much of its attractiveness.

In the above analysis the SUSY masses used were motivated by a class of analysis [14] of the CERN monojet events of 1983 based on the hypothesis of two-gluino production, which favoured the choice $\tilde{m} = 40$ GeV, $\mu_L = 50$ GeV, where $\tilde{m}$ is the gluino mass. Several authors [15] have, however, claimed that $\tilde{q}$ production via $q\tilde{g}$ fusion is also a viable mechanism for producing monojets + missing momentum. This model favour the light gluino ($\tilde{m} \sim 3–10$ GeV) heavy squark ($m_{\tilde{q}} > 100$ GeV) scenario [‡3]. It should, however, be noted that there is a lower bound on $\tilde{m}$ from a beam-dump experiment [18]: $\tilde{m} > 4$ GeV for $m_{\tilde{q}} \approx M_W$.

‡2 For a different point of view, see ref. [8].

‡3 Several authors [16,17] have criticised this idea since its predictions depend sensitively on model-dependent assumptions about gluino fragmentation, etc.

Table 1

C_{min}, A_{th} (the theoretical value of the A parameter corresponding to C_{min}), and the predicted ϵ'/ϵ for different τ_B. A blank entry for ϵ'/ϵ implies that A_{th} is inconsistent with other theoretical requirements (see text). Case (i) $\bar{R} = 0.03$, $\mathscr{B} = 0.33$, $\cos\delta = -0.6$. Case (ii) $\bar{R} = 0.01$, $\mathscr{B} = 1.00$, $\cos\delta = -0.4$.

Case	τ_B	C_{min}	A_{th}	ϵ'/ϵ
(i)	1.0	−0.8	3.1	0.011
	1.2	−1.15	3.88	0.009
	1.4	−1.42	4.4	–
	1.6	−1.65	4.8	–
	1.8	−1.85	5.13	–
	2.0	−2.03	5.4	–
(ii)	1.2	−0.26	0.93	0.007
	1.4	−0.73	2.9	0.005
	1.6	−1.01	3.6	0.004
	1.8	−1.23	4.04	–
	2.0	−1.41	4.4	–

The purpose of this note is to analyze *CP* violation in the light gluino scenario which was ignored in earlier works [3,11,12]. This appears to be promising since for a given μ_L, SUSY contribution ϵ_{SUSY} is considerably enhanced in this scenario. As a result a *smaller* $|C_{min}|$ serves the purpose. The theoretical estimate C_{th}, on the other hand, *increases in magnitude* as $\tilde{m}$ decreases (see below for an elaboration). The chance of accommodating the phenomenologically required $|C_{min}|$ in the theory is indeed brighter in the light gluino scenario. Our numerical results for C_{min} and corresponding $\cos\gamma$ for different τ_B are shown in table 1 [‡4]. We have used $\tilde{m} = 6$ GeV, $\mu_L \approx \mu_R = 100$ GeV, $m = 100$ GeV. ϵ_{SUSY} is fairly insensitive to the choice of A. The other CP violation parameter ϵ'/ϵ however, depends crucially on A (see below). To highlight the role of SUSY as an alternative to the standard model for explaining *CP* violation we have restricted ourselves to the following choices of $\mathscr{B}$ and $\bar{R}$ strongly disfavoured by the standard model:

(i) $\mathscr{B} = 0.33$, $\bar{R} = 0.03$,

(ii) $\mathscr{B} = 1.0$, $\bar{R} = 0.01$.

‡4 Throughout this paper we have used the relevant formulae given in refs. [3,11,12,19]. We have also used the same non-SUSY parameters as given in the above references, unless otherwise stated.

It was shown in ref. [11] that $C_{th} = \frac{1}{3}(\mu_2^2 - \mu_1^2)/m_t^2$, where $\mu_{1(2)}^2$ are the mass squared parameters (evaluated at the scale M_W) of the Higgs field $H_{1(2)}$ which couples to charge $-1/3$ (2/3) quark fields. Using μ_1^2 and μ_2^2 as given in ref. [20] (derived with a top Yukawa coupling leading to $m_t \approx 40$ GeV) one obtains

$$C_{th} = -m^2(0.1 + 0.03A^2)/3m_t^2. \quad (2)$$

In writing the above equation the gaugino mass term, which is indeed small (≈ 2 GeV for $\tilde{m} \approx 6$ GeV) in this case, has been neglected. Moreover, $m^2 \approx \mu_L^2$ in this scenario. We wish to emphasise that for significantly larger gluino masses m^2 is much smaller. For a given A, therefore, C_{th} turns out to be much larger in this scenario. This feature enables one to accommodate the phenomenologically required $|C_{min}|$ in the theory without requiring A to be larger than the bound [16,20] imposed by the requirement of charge and color invariance of the vacuum. In contrast, the required A in the heavy gluino scenario always violates the above bound [12] [‡5]. The required value of A for $|C_{th}| = |C_{min}|$ for each τ_B is also included in table 1.

As discussed above for large A the vacuum might break both SU $(3)_c$ and $U(1)_{EM}$. In fact if the higgsino mass parameter (μ_0) at the GUT scale is taken to be zero then A (at GUT scale) is restricted by the upper bound $A \lesssim 3$. A at the scale M_W is not very different in the light gluino scenario [13,20] and it is clear from table 1 that a consistent model CP violation with $\mu_0 = 0$ is not possible for choice (i) given above. For choice (ii) this is possible for $\tau_B \lesssim 1.4$ ps.

For $\mu_0 \neq 0$ one has the following situations: choice (i): we have explicitly checked that both the constraints [20] of charge–color symmetric vacuum and $SU(2)_L \times U(1)$ breaking at the right scale are satisfied with $\mu_0 = 53.85$ (142.21), $\mu_3(0) = 95.87$ (176.5) (all masses in GeV), $\omega = 1.25$ (1.12) for $A = 3.1$ (3.88) corresponding to $\tau_B = 1.0$ (1.2) ps. For $\tau_B = 1.2$ ps, however, the condition ($m^2 + \mu_0^2 > \mu_3(0)^2$) that the Higgs potential be bounded from below [13,20] is barely violated. A consistent model of CP violation is, therefore, possible for $\tau_B < 1.2$ ps only. Choice (ii): satisfactory models can be built for $\tau_B \lesssim 1.6$ ps. The choices for the SUSY parameters are (a) $\tau_B = 1.2$ ps, $\mu_0 = 16.16$, $\mu_3(0) = 82.34$, $\omega = 1.05$; (b) $\tau_B = 1.4$ ps, $\mu_0 = 38.73$, $\mu_3(0) = 86.99$, $\omega = 1.12$; (c) $\tau_B = 1.6$ ps, $\mu_0 = 112.94$, $\mu_3(0) = 146.10$, $\omega = 1.16$. It should, however, be noted that in none of the above cases the relation $\mu_3^2(0) = (1 - A)\mu_0 m$ arising in *minimal* supergravity is satisfied.

We now turn to the predictions of this model for ϵ'/ϵ and observables of B^0–$\bar{B}^0$ mixing. It was pointed out in refs. [1,2] that two types of operators contribute to ϵ'/ϵ in this model. One of them is the usual penguin operator while the other one – a tensor operator – is induced by L–R mixing. The contribution of the second operator increases for large values of the relevant parameter A. As discussed above, A is expected to be large. Moreover, m is constrained to be rather large ($\approx \mu_L$) in the light gluino scenario. One would, therefore, expect significant enhancement in ϵ'/ϵ – a feature not very welcome in view of the present experimental situation. It is, however, gratifying to note that the enhancement is somewhat compensated by the small gluino mass which also multiplies the operator under consideration [19]. The results for ϵ'/ϵ are shown in table 1 for the cases where a satisfactory explanation of C_{min} is allowed by the theory. This should be compared with the data (quoted errors have been combined quadratically): $\epsilon'/\epsilon = 0.0017 \pm 0.0082$ [22]; $\epsilon'/\epsilon = -0.0046 \pm 0.0058$ [23]. There is, however, a general feeling that models with $\epsilon'/\epsilon > 0.005$ are vulnerable [24]. In view of this choice, (i) does not appear to be attractive. Choice (ii) appears to be a borderline case. The fact that a negative ϵ'/ϵ, which arises naturally in models with $A = 0$ [19], can not be accommodated in this model also causes some uneasiness.

For $C \neq 0$ SUSY also contributes to B_s^0–$\bar{B}_s^0$ and to B_d^0–$\bar{B}_d^0$ mixings [11,12]. The Pais–Treiman parameter, which is a convenient measure of mix-

‡5 One can of course argue that we live on a "false" vacuum [21] which is charge and colour symmetric and which will eventually decay into the "true" vacuum which violates charge–color conservation. This possibility, though allowed in principle (provided the lifetime of the false vacuum is larger than the age of the universe!), does not appear to be very natural.

ing, is given by

$$r_q = (\Delta M_q/\Gamma_q)^2/\left[2 + (\Delta M_q/\Gamma_q)^2\right], \quad (3)$$

where $q = d$, s, ΔM_q is the mass difference between the neutral B_q^0 meson mass eigenstates and Γ_q is the corresponding width. As an illustration we give our results for the two entries in choice (ii) which yields $\epsilon'/\epsilon \lesssim 0.005$. We obtain [3] (a) $r_d = 0.02$, $r_s = 0.83$ for $\tau_B = 1.4$ ps and (b) $r_d = 0.03$, $r_s = 0.87$ for $\tau_B = 1.6$ ps. Our results are consistent with the CLEO upper bound [25] $r_d \lesssim 0.3$ obtained from the absence of like-sign dilepton signature in the decay $\Upsilon(4S) \to B_d^0 - \bar{B}_d^0$. The wide gap between the prediction and the sensitivity of the present experiment, however, is not very encouraging from the point of view of testing SUSY in the near future. A MARK II $e^+ - e^-$ continuum experiment [26] has constrained r_d and r_s simultaneously. Unfortunately, for small r_d, their result does not have enough sensitivity to constrain r_s meaningfully.

It has recently been pointed out [27] that the observed forward–backward asymmetry in $e^+e^- \to b\bar{b}$ jets should be somewhat smaller than the theoretical result A_{FB}^b due to B^0–$\bar{B}^0$ mixing:

$$A_{FB}^B = (1 + R_{FB})^{-1} A_{FB}^b, \quad (4)$$

where R_{FB} is a parameter depending on r_d and r_s. Using the formulas of ref. [27] and the non-SUSY parameter quoted there, we obtain in case (ii) $R_{FB} = 0.24$ (0.26) for $\tau_B = 1.4$ (1.6) ps. This should be compared with the bound [27] $R_{FB} \lesssim 0.35$ extracted from the present data.

In view of the large production cross section of $b\bar{b}$ pairs at the present $\bar{p}p$ collider energies, some authors [28] have observed that the detection of like-sign dileptons in this experiment appears to be the easiest test of B^0–$\bar{B}^0$ mixing. The UA1 group has already reported a preliminary result: R = number of like-sign dileptons/number of unlike-sign dileptons = 0.47 ± 0.1 [29]. Two processes, however, can contribute significantly to R: B^0–$\bar{B}^0$ mixing and the cascade decay $b \to c$ + hadrons $\to \ell^+ + \nu$ + hadrons. Using the Monte Carlo estimate of the cascade contribution ($R = 0.35$ for no B^0–$\bar{B}^0$ mixing) it was claimed in ref. [28] that $R^{b\bar{b}} = 0.18$ seems to be consistent with the data. Using the formula given in ref. [28] and r_s as given above we estimate $R^{b\bar{b}} = 0.21$ (0.23) for $\tau_B = 1.4$ (1.6) ps. SUSY, therefore, predicts observable B^0–$\bar{B}^0$ mixing and is fairly consistent with the present data. Due to the large error bar in the present data the no-mixing case is not completely ruled out. If future experiments with better statistics fail to establish B^0–$\bar{B}^0$ mixing unambiguously, SUSY, the model of particle mixing, and *CP* violation will be strongly disfavoured.

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