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$b \rightarrow s\gamma$ DECAY IN SUPERGRAVITY GRAND UNIFICATION AND DARK MATTER

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Abstract

An analysis of the $b \rightarrow s\gamma$ is given in supergravity grand unification using the framework of the radiative breaking of the electro-weak symmetry under three separate sets of constraints:1) neutralino relic density does not overclose the universe,2)p-stability constraint, and 3) the combined constraints of p-stability and COBE data .For case 1 it is found that the CLEO II data on the branching ratio already imposes very strong further constraints on dark matter analyses. For case2 the branching ratio is found to lie in the range (1.5-6.3)x10^{-4} and thus the data does not at present significantly limit the analyses with p-stability constraint. It is shown that improvements by a factor of 3 in the $p \rightarrow \bar{\nu}K^+$ lifetime will reduce SUSY effects to less than O(30%) of the Standard Model value.For case3,the branching ratio lies in the interval (3.1-5.3)x10^{-4} ,and the SUSY effects lie within (-10%,+50%) of the SM value. Thus as experimental bounds on $B(b \rightarrow s\gamma)$ improve, one would need in cases 2 and 3 the next-to-leading order QCD corrections to disentangle SUSY effects.

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Last year the CLEO Collaboration obtained a new bound on the flavour changing decay mode $b \to s\gamma$ [1]. For the branching ratio $B(b \to s\gamma)$ they find the bound $B(b \to s\gamma) < 5.4 \times 10^{-4}$ at 95% CL. At the same time a definite observation of the exclusive mode $B \to K^*\gamma$ was made with a branching ratio $B(B \to K^*\gamma) = (4.5 \pm 1.5 \pm 0.9) \times 10^{-5}$[1]. These branching ratio measurements are expected to improve in the future, and should provide stringent limits on the Standard Model (SM) prediction. In the SM, $b \to s\gamma$ decay is induced at the one-loop level by a penguin diagram which involves the exchange of a W boson and a t-quark. If a definite discrepancy between the SM prediction and the experimental value is found, it would provide a window to physics beyond the SM. For example, in supersymmetry there are additional penguin diagrams involving the exchange of the charged Higgs, the charginos, the gluino and the neutralinos which contribute to the $b \to s\gamma$ decay [2]. It is already known that significant contributions can arise from the charged Higgs [3]–[5]. In this paper we give a detailed analysis of $b \to s\gamma$ branching ratio within the framework of radiative breaking of the $E - W$ symmetry for the minimal SU(5) supergravity model. The analysis is given under three different sets of constraints: (i) cosmological constraint on SUSY dark matter, (ii) proton stability constraint, and (iii) simultaneous imposition of cosmological and proton stability constraints.

The basic formula for the branching ratio $B(b \to s\gamma)$ including the W, charged Higgs and the sparticle exchange contributions to leading order QCD corrections is given by[2],[4],[6],[7]

$$\frac{B(b \to s\gamma)}{B(b \to ce\nu)} = \frac{6\alpha}{\pi} \frac{\left[\eta^{\frac{16}{32}} A_\gamma + \frac{8}{3}\left(\eta^{\frac{14}{23}} - \eta^{\frac{16}{32}} A_g\right) + C\right]^2}{P\left(\frac{m_c}{m_b}\right)\left[1 - \frac{2}{3\pi}\alpha_s(m_b) f\left(\frac{m_c}{m_b}\right)\right]} \tag{1}$$

where $\eta = \alpha_s(m_Z)/\alpha_s(m_b)$, P is a phase-space factor defined by $P(x) = 1 - 8x^2 + 8x^6 - x^8 - 24x^4 \ln x$ and $f(m_c/m_b)$ is a QCD correction factor to the process $b \to ce\nu$ for which we use the value $f(m_c/m_b) = 2.41$. For $B(b \to ce\nu)$ we use the experimental value 0.107 and $A_{\gamma,g}$ are the contributions from penguin diagrams at scale M_W with photonic or gluonic external legs but including the exchange of W, charged Higgs and the sparticle exchanges. For C, the operator mixing coefficient, we use the valuation of Ref. [8]:

$$C = \sum_{i=1}^{8} q_i \eta^{p_i} \tag{2}$$

where q_i (obeying $\sum_{i=1}^{8} q_i = 0$) and p_i are given by $\{q_i; i = 1, ..., 8\} = (2.2996, -1.088, -0.4286, -0.0714, -0.6494, -0.038, -0.186, -0.0057)$; $\{p_i; i = 1, ..., 8\} = (0.6087, 0.6957, 0.2609, -0.5217, 0.4086, -0.423, -0.8994, 0.1456)$. The (q_i, p_i) of Eq. (3) are computed using an $O(g^2)$ calculation of an 8×8 anomalous dimension matrix which enters in the evolution of the current-current, QCD and "magnetic penguin" operators as one uses the renormalization group to evolve from the weak scale M_W to the scale $\mu = O(m_b)$. (There is a disagreement in the literature on the numerical evaluation of (q_i, p_i) (see papers of Ref.[9]) but this disagreement only leads to O(1%) differences and thus is not of measurable significance at this stage).

The evaluation of $B(b \to s\gamma)$ from Eq. (1) suffers in general from several uncertainties. There are uncertainties generated due to experimental errors in the quark masses and α_s. However, potentially the largest error is due to the renormalization point μ dependence of

Eq. (1). For example a variation of μ by a factor of 2 in each direction from its mean value m_b (i.e. in the range $m_b/2$ to $2m_b$) can generate a $\pm 25\%$ variation, in the branching ratio [10],[11]. This μ-dependence is expected to be diluted by a significant amount [11] by inclusion of the next-to-leading order QCD corrections, analogous to what has been observed in other FCNC processes [12]. Presently, only partial analyses of the next-to-leading order QCD corrections exist, and the full analysis appears very involved requiring analysis of three loop mixings in some sectors [11]. These next-to-leading order corrections are likely to become more significant as experimental measurements of $B(b \rightarrow s\gamma)$ improve.

In this paper we analyze Eq. (1) within the framework of the supergravity unified models [13], [14] with an SU(5) type embedding. In this model supersymmetry is broken spontaneously via a hidden sector, and the effective potential contains the following supersymmetry breaking terms below the GUT scales [13]–[17]: $m_0, m_{1/2}, A_0$ and B_0, where m_0 is the universal scalar mass, $m_{1/2}$ is the universal gaugino mass and A_0 and B_0, are the cubic and quadratic soft SUSY breaking constants that appear in the effective theory below the GUT scale. Further, one finds for the effective superpotential of the theory the form $W_{eff} = W^{(2)} + W^{(3)} + M_{H_3}^{-1} W^{(4)}$, where $W^{(2)} = \mu_0 H_2 H_1$, and $H_2(H_1)$ are the Higgs doublets that give mass to the up (down) quarks, $W^{(3)}$ contains the usual cubic interactions of the quarks (and of the leptons) to the Higgs, and $W^{(4)}$ contains baryon number violating dimension four operators which are responsible for proton decay via dimension five operators. The $W^{(4)}$ interactions are suppressed by the superheavy Higgsino triplet mass M_{H_3}. We use the renormalization group analysis to break the electroweak symmetry [18], and after radiative breaking of the symmetry one can determine the parameter μ_0 by fixing the Z-mass, and determine B_0 in terms of $\tan\beta = \langle H_2 \rangle / \langle H_1 \rangle$. The model is then completely specified by four parameters

$$m_0,\ m_{1/2},\ A_t, \tan\beta \tag{3}$$

and the sign of μ. Here A_t is the value of A_0 at the electroweak scale. There are 32 new particles in this model (12 squarks, 9 sleptons, 2 charginos, 4 neutralinos, 1 gluino, 2CP even neutral Higgs, 1 CP odd neutral Higgs and 1 charged Higgs). These 32 new particles and all their interactions, can be determined in terms of the four parameters of Eq. (3). Thus the theory makes many predictions. A general analysis of $b \rightarrow s\gamma$ in supergravity unification is given in Ref. [19]. Here we discuss $b \rightarrow s\gamma$ decay under constraints of cosmology and proton stability.

An interesting result of supergravity unification with R-invariance is that over much of the parameter space the lightest neutralino is also the lightest supersymmetric particle (LSP) and is a natural candidate for dark matter [20]–[23]. Thus at the very least one must impose the constraint that the neutralino dark matter not overclose the Universe, i.e., one has

$$\Omega_{\tilde{Z}_1}\ h^2 < 1\ . \tag{4}$$

Here $\Omega_{\tilde{Z}_1} = \rho_{\tilde{Z}_1}/\rho_c$ where $\rho_{\tilde{Z}_1}$ is the neutralino mass density, ρ_c is the critical mass density needed to close the Universe, and h is the Hubble constant in units of 100 km/sec Mpc. Current measurements give h the range $0.5 < h < 0.75$. Under additional assumptions one can obtain a more stringent bound than (4). Thus assuming the inflationary scenario which requires $\Omega = 1$, and a mix of cold dark matter (CDM) and hot dark matter (HDM) in the ratio 2:1 which is consistent with COBE data, one finds $0.1 < \Omega_{\tilde{Z}_1} h^2 < 0.35$ where we have used the estimate $\Omega_{NB} \approx 0.9$ for non-baryonic matter. In our computation of the neutralino relic density we have used the accurate method which integrates over the Higgs and the Z poles in the neutralino annihilation [22-24].

Next we discuss the p-stability constraint. In the minimal model the most dominant decay mode of the nucleon is $p \rightarrow \bar{\nu} K^+ (n \rightarrow \bar{\nu} K^0)$ which proceeds via dimension five operators generated from the exchange of the Higgsino triplet field, i.e., the $W^{(4)}$ term in W_{eff} discussed earlier. The proton decay lifetime for this mode is [25],[26].

$$\tau(p \rightarrow \bar{\nu} K^+) = Const \left(\frac{M_{H_3}}{\beta_p}\right)^2 |B|^{-2} \tag{5}$$

where the front factor is determined using chiral Lagrangian technique, β_p is the three-quark matrix element of the proton which is determined via lattice gauge theory computations, and B is the dressing loop function which depends on masses of the SUSY particles that enter in the dressing loop. A reasonable upper bound on M_{H_3} without the Planck scale effects becoming dominant is $M_{H_3} < 10\ M_G$ [22] which replaces the more stringent condition of $M_{H_3} < 3M_G$ imposed in previous analyses [20],[21],[29]. The most recent lattice gauge determination of β_p gives $\beta_p = (5.6 \pm 0.8) \times 10^{-3}\ GeV^{-3}$ [27].

We can now use Eq. (5) to obtain an upper bound on (B) using the experimental lower bound on $\tau(p \rightarrow \bar{\nu} K^+)$ of 1.0×10^{32} yr [28]. One finds that $B < 100(M_{H3}/M_G) GeV^{-1}$. The allowed range of $p \rightarrow \bar{\nu} K^+$ lifetime then is

$$\tau(p \rightarrow \bar{\nu} K^+) \gtrsim 10^{32} \left(\frac{M_{H_3}}{M_G}\right)^2 \left(\frac{100\ GeV^{-1}}{B}\right)^2 yr \tag{6}$$

We proceed as follows: we use renormalization group evolution of gauge, Yukawa and soft SUSY breaking terms with supergravity boundary conditions imposed at the GUT scale M_G. After the breaking of electroweak symmetry, the SUSY spectrum is computed in terms of the allowed values of the parameter space defined in Eq. (3). As discussed in Refs. [21],[29], it is found that over much of the parameter space $|\mu| \gg M_Z$ and this leads to certain scaling relations on the mass spectra. For example, for the chargino and neutralino masses one finds

$$m_{\tilde{W}_1} \simeq m_{\tilde{Z}_2} \simeq 2m_{\tilde{Z}_1} \tag{7a}$$

$$m_{\tilde{W}_1} \simeq \frac{1}{3} m_{\tilde{g}}\ (\mu < 0)\ ;\quad m_{\tilde{W}_1} \simeq \frac{1}{4} m_{\tilde{g}}\ (\mu > 0) \tag{7b}$$

Also one finds in the same domain of the parameter space that the heavier CP even Higgs, the CP odd Higgs and the charged Higgs are essentially degenerate in mass, i.e.,

$$m_{H^0} \simeq m_A \simeq m_{H+} \tag{8}$$

The analysis of Eq. (1) is carried out using the spectrum that emerges from the radiative electroweak breaking. In the evaluation of $B(b \rightarrow s\gamma)$ we shall include the contributions of

$W, H^{\pm}$ and $\tilde{W}_i (i = 1, 2)$ and neglect the (small) contributions from the gluino and neutralino states. The chargino contributions involve the exchange of all the three generation of squark states. Of specific interest are the exchanges of the third generation of squarks (i.e. stops) which can make large contributions over certain regions of the parameter space. To fix notation the stop-(mass)^2 matrix is given by

$$\begin{pmatrix} m_{\tilde{t}_L}^2 & m_t(A_t + \mu \cot\beta) \\ m_t(A_t + \mu \cot\beta) & m_{\tilde{t}_R}^2 \end{pmatrix} \tag{9}$$

where

$$m_{\tilde{t}_L}^2 = m_Q^2 + m_t^2 + \left[\left(-\frac{1}{2}\right) + \left(\frac{2}{3}\right) \sin^2\theta_W\right] M_Z^2 \cos 2\beta \tag{10a}$$

$$m_{\tilde{t}_R}^2 = m_U^2 + m_t^2 - \left(\frac{2}{3}\right) \sin^2\theta_W M_Z^2 \cos 2\beta \tag{10b}$$

and m_Q^2, m_U^2 are as defined in Ibañez et al. Ref. [18].

We find in general that for the supersymmetric case there are significant regions of the parameter space where $B(b \to s\gamma)$ can be either larger or smaller than the corresponding SM value. An interesting phenomenon for some specific points in the parameter space is the almost perfect cancellation of the branching ratio because of contributions from the chargino exchange. Although supersymmetry is certainly at the root of these almost perfect cancellations, the points in the parameter space where such cancellations occur are far from the exact supersymmetric limit where one expects a perfect cancellation [30].

We discuss next details of the analysis. As expected the charged Higgs makes a positive contribution and increases the $b \to s\gamma$ branching ratio. However, the contribution of the chargino can be either positive or negative depending on the point in the parameter space and the sign of μ. This conclusion agrees with previous analyses of Refs. [4], [5], and [31] that chargino contributions can be either constructive or destructive. In general the domain where the cosmological constraint of Eq.(4) is satisfied is quite large (see Figs. 1a and 2a), while the domain where the p-stability constraint of Eq.(6), is satisfied is generally smaller (see Figs. 1b and 2b). The stringent constraint of p-stability arises in part due to the fact that p-stability limits $\tan\beta$ so that $\tan\beta \leq 10$. The parameter space where constraints of eqs. (4) and (6) are simultaneously satisfied is the smallest (see Figs. 1c, 1d, 2c and 2d).

The recent experimental measurements suggest a top mass value of 174±16 GeV [32]. At the same time precision electro-weak data predicts m_t=162±9 GeV [33]. We have carried out an analysis over the full top mass range consistent with the above analyses. In the following we discuss specifically the case when the running top mass M_Z =160 GeV. Since the running top mass at M_Z is about 5 % lower than the physical top mass [34], this case corresponds to a physical top mass of about 168 GeV. The analysis is carried out over the full parameter space including both signs on the value of μ. The result of this analysis is then found to be valid within 10% for other top masses in the range consistent with the CDF [32], LEP and SLC [33] data.

The result for the case $\mu < 0$ is exhibited in figs 1a-1d, and for $\mu > 0$ is exhibited in Figs 2a-2d. Fig1a gives the branching ratio as a funtion of $\Omega_{\tilde{Z}_1} h^2$ for $\mu < 0$ in the interval consistent with the cosmological constraint of eq(4) but without imposition of p-stability constraint of eq(5).Since the branching ratio is plotted as a function of $\Omega_{\tilde{Z}_1}h^2$ it is straightforward to further impose the COBE constraint by limiting the value of $\Omega_{\tilde{Z}_1}h^2$ to the range (0.1-0.35). Fig1a shows that cosmological constraint with or without the COBE constraint does not limit the current experiment. However, the current experiment significantly constrains the dark matter analysis, since the analysis with dark matter constraints alone allow for $B(b \to s\gamma)$ branching ratios which can exceed the current experimental bounds by a significant amount. Fig1b gives the branching ratio as a function of the $p \to \bar{\nu}K^+$ lifetime consistent with the current experimental limits on this decay[28] but without the imposition of the cosmological consraint of eq(4). One finds that the branching ratio lies in the range (1.5-5.7) x 10^{-4}. Thus the current experimental limits do not significantly constrain the model when the p-stability constraint is included. Fig1c is identical to Fig1b except that it also includes the cosmological constraint of eq(4).Fig1d exhibits the branching ratio as a function of $\Omega_{\tilde{Z}_1}h^2$ with inclusion of p-stabilty constraint. From Fig1d one finds that the branching ratio in the domain consistent with p-stability and COBE data lies in the range (3.1-5.0)x 10^{-4}. An analysis similar to that for Figs1a-1d for $\mu > 0$ is carried out for Figs2a-2d. From Fig2b one finds that the branching ratio with p-stabilty constraint lies in the interval (2.6-5.3)x10^{-4}, and from fig1d one finds that the branching ratio under the combined constraint of p-stability and COBE data lies in the interval (3.1-5.3)x 10^{-4}. Together from Fig1 and Fig2 we find that with p-stability constaint alone the branching ratio lies in the interval (1.5-5.7)x10^{-4}, and with the combined constraints of p-stability and COBE data the branching ratio lies in the interval (3.1-5.3)x 10^{-4}. To see the variation with the top mass we give below the ranges of the branching ratios for $m_t(M_Z) = 166$ GeV which correspond to the physical top mass of 174 GeV. Here with p-stability constraint the branching ratio lies in the interval (2.2-6.3) x 10^{-4}, and with the combined constraints of p-stability and COBE data the range of the branching ratio is (3.5-5.0)x 10^{-4}. Thus the variation in the predicted range of the branching ratio in each case is within 10%, and thus the ranges are found to be insensitive to small changes of m_t. For comparison the Standard Model branching ratio in this domain is about 3.5x10^{-4}.

Finally, we discuss the constraints on the parameter space that emerge from imposition of the CLEO II bounds. For the dark matter analysis of case1, the current experimental limits put very strong constraints for the case $\mu > 0$. Here one finds that if the top mass lies in the range 165-175 GeV, then 60-70% of the parameter space allowed by the constraint that neutralino relic density not overclose the universe, is eliminated. For the case $\mu < 0$, the fraction of the parameter space consistent with the cosmological constraint and in violation of the CLEO II bound is much smaller, i.e., 15-20% of the parameter space consistent with Eq(4) is eliminated. The constraints on the parameter space from CLEO II bounds in cases 2 and 3 are negligible.

CONCLUSIONS

We have analysed the inclusive $B(b \to s\gamma)$ decay branching ratio under three different sets of constraints: cosmological constraint, p-stability constraint, and the combined constraints of p-stability and COBE data. An important result that emerges from the analysis is that the current experimental limits on the $B(b \to s\gamma)$ branching ratio put significant constraints on dark matter analyses for $\mu > 0$. The constraints on the parameter space would become even more severe as the experimental bounds on the branching ratio improve. The theoretical analysis under the p-stability constraint gives a branching ratio in the range (1.5-6.3)x10^{-4} Thus the current CLEO bounds do not significantly constrain the model in this case. The analysis under the combined constraints of p-stabilty and COBE data give a branching ratio in the range (3.1-5.3)x10^{-4}. Thus the result of the analysis with the combined constraints of p-stability and COBE data is totally unconstrained by current experiment.The analysis with p-stability also shows (see Figs 1b and 2b) that when lifetime measurements on $p \rightarrow \bar{\nu}K^{+}$ decay mode improve by a factor of about 3, the allowed theoretical variations in the branching ratio will fall within O(30%) of the Standard Model prediction, and consequently the next-to-leading order effects will become relevant. However, the analysis under the constraints of p-stability and COBE data gives a result for the branching ratio at the level of the leading order calculation, which has a variation of O(-10%,+50%) from the SM value and a variation of only O(30%) around its mean .Thus the next-to-leading order effects are already relevant in this case if one wants to disentangle the SUSY effects when experimental measurements improve.

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FIGURE CAPTIONS

Fig. 1a: Plot of the branching ratio $BR(b \to s\gamma)$ as a function of $\Omega_{\tilde{Z}_1} h^2$ for the domain $\Omega_{\tilde{Z}_1} h^2 < 1$ when no p-stability constraint is imposed. The analysis is for $m_t(M_Z) = 160$ GeV and $\mu < 0$. All other parameters are integrated out.

Fig. 1b: $BR(b \to s\gamma)$ vs. the proton lifetime $\tau(p \to \bar{\nu}K)$ without imposition of dark matter constraints. All other parameters are the same as in Fig. 1a.

Fig. 1c: Same as Fig. 1b except the cosmological constraint $\Omega_{\tilde{Z}_1} h^2 < 1$ is imposed.

Fig. 1d: Same as Fig. 1a except that p-stability constraint is imposed.

Fig. 2a : Same as Fig. 1a except $\mu > 0$.

Fig. 2b: Same as Fig. 1b except $\mu > 0$.

Fig. 2c: Same as Fig. 1c except $\mu > 0$.

Fig. 2d: Same as Fig. 1d except $\mu > 0$.