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SUPERSYMMETRIC BARYOGENESIS AND FLAVOR PHYSICS

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Abstract

We study the flavor physics implications of baryogenesis in the Minimal Supersymmetric Standard Model. Enhanced $B-\bar{B}$ mixing and $b \to s\gamma$ rates are generic to all scenarios. Depending on the origin of the CP violating phase responsible for baryogenesis there could be a large neutron electric dipole moment, large CP violating $D-\bar{D}$ mixing or CP violation in top quark production. We discuss how the combination of these measurements with the requirement of baryogenesis shed light on the MSSM parameter space and the source of CP violation.

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In order to account for the observed baryon asymmetry of the universe, $n_B/s = 4-6\times10^{-11}$, using electroweak baryon number violation one needs more effective CP violation and a stronger electroweak phase transition than present in the Standard Model [1]. Both of these are possible in the Minimal Supersymmetric Standard Model (MSSM) [2]. Although there are large uncertainties related to the many non-perturbative processes involved, it is still possible to obtain a broad brush picture of the circumstances under which sufficient baryogenesis may be acheived in the MSSM.

There has been much recent work relating to this issue [3, 4, 5] including the interesting possibility, further explored in this letter, of baryogenesis in the MSSM using just the one explicit CP violating phase present in the quark mixing matrix [5]. In this letter we present a simple, unified description of the different mechanisms proposed above. It is interesting that when one puts all of it together, a coherent picture emerges resulting in a few favored scenarios for baryogenesis in the MSSM. Remarkably, these scenarios all have distinct experimental predictions that can be tested at the next generation of particle physics experiments: LHC, the B factories, and improved measurements of d_N, the neutron electric dipole moment (EDM). Thus, in the next few years experiments will not only determine the possibility of baryogenesis in the MSSM, but also ascertain the specific mechanism by which it occurs.

The strength of the electroweak phase transition in the MSSM could be enhanced due to the large coupling of a light *stop* to the Higgs boson. The possibility of a strong enough phase transition was demonstrated using a one-loop effective Higgs potential whenever [6]

$$m_h \lesssim 80 \text{ GeV}; \quad m_A \gtrsim 200 \text{ GeV}; \quad \tan\beta \lesssim 2.5; \quad m_{\tilde{t}_R} \lesssim 175 \text{ GeV}; \quad \tilde{A}_t \simeq 0. \quad (1)$$

Here m_h is the mass of the lightest (Standard Model-like) Higgs boson, m_A is that of the pseudoscalar Higgs boson, $\tan\beta$ is the ratio of the two Higgs vevs, and $\tilde{A}_t = A_t + \mu/\tan\beta$ is the effective $\tilde{t}_L - \tilde{t}_R$ mixing parameter. These limits are slightly relaxed if one includes two-loop QCD effects [7].

In order to have rapid interconversion between particles and sparticles at the phase transition, the gluinos and/or some of the charginos are required to have masses of $\mathcal{O}(T_0) \sim 100$ GeV, where T_0 is the critical temperature for the electroweak phase transition. Besides the obvious direct search implications of these light sparticles and Higgs boson [4], the light $\tilde{t}_R$ and charginos also result in large contributions to $B-\bar{B}$ mixing independently of the rest of the squark masses [8]. This is because the $b_L - \tilde{t}_R - \tilde{h}$ coupling proportional to the top quark mass removes the possibility of any GIM cancellation.

Thus we see that the requirement of a first order phase transition coupled to the existence of light charginos predicts large new contributions to $B-\bar{B}$ mixing.

This new contribution to $B - \bar{B}$ mixing may be hard to detect because of the hadronic uncertainties in the Standard Model predictions. It could, however, be resolved at the B factories by combining the measured value of $x_d \equiv \Delta m/\Gamma$ with several CP violating B decay asymmetries [9].

The most effective way to generate a cosmological particle number asymmetry for some species is to arrange that, during the electroweak phase transition, a CP violating space-time dependent phase appears in the mass matrix for that species. If this phase cannot be rotated away at subsequent points by the same unitary transformation, it leads to different propagation probabilities for particles and anti-particles, thus resulting in a particle number asymmetry. The existence of such phases is possible in the MSSM if $\tan\beta$ changes as one traverses the bubble wall separating the symmetric phase from the broken one.* Particle number asymmetries will then be proportional to $\Delta\beta$, the change in β across the bubble wall [3].

It has been recently estimated that $\Delta\beta \propto m_h^2/m_A^2 \sim 0.01$ for the pseudoscalar Higgs boson mass $m_A = 200 - 300$ GeV [4]. This can actually be turned into an upper bound for $\Delta\beta$ using the relation $m_{h_+}^2 = m_A^2 + m_W^2$, where m_{h_+} is the charged Higgs boson mass. Charged Higgs bosons make large positive contributions to the $b \to s\gamma$ decay rate. Although there is a partial cancellation of this effect due to the contribution from light charginos and *stops* this requires fine-tuning to be completely effective in the range of parameters considered here. The current experimental value for $Br(b \to s\gamma)$ already sets the limit $m_{h_+} \gtrsim 300$ GeV at the 2σ level [10]. This then implies $\Delta\beta \lesssim 0.01$ through the relations above.

Thus we see that the requirement of CP violation in the propagation of particles through the bubble wall requires a light charged Higgs and subsequently enhanced $b \to s\gamma$ decay rate [3, 4, 5]. This scenario will be significantly constrained at the next round of measurements at CLEO III and at the asymmetric B factories.

Baryogenesis in the MSSM proceeds most efficiently through the generation of higgsino number or axial squark number in the bubble wall, which then diffuses to the symmetric phase where it is processed into baryon number. The origin of the CP violation responsible for baryogenesis, and consequent flavor physics effects can be understood by studying the structure of the up-type squark mass matrix. This is justified because for $\tan\beta \sim 1$ the effects due to the down-type squarks are suppressed by $\sim m_b^2/m_t^2$. Further, as we will discuss below, the CP violation responsible for higgsino production can be considered a special case of the ways CP violation manifests itself in the up-type squark mass matrix and

*This is strictly true only for the leading term in an expansion in powers of the particle mass matrices.

does not lead to independent flavor physics effects.

Consider the mass squared matrix for the up-type squarks:

$$M_{\tilde{u}}^2 = \begin{pmatrix} M_{\tilde{u}_{LL}}^2 & M_{\tilde{u}_{LR}}^2 \\ M_{\tilde{u}_{LR}}^{2\dagger} & M_{\tilde{u}_{RR}}^2 \end{pmatrix} \quad (2)$$

where

$$\begin{aligned} M_{\tilde{u}_{LL}}^2 &= m_Q^2 A_{U_{LL}} + (F,\ D) \text{ terms}, \\ M_{\tilde{u}_{RR}}^2 &= m_U^2 A_{U_{RR}} + (F,\ D) \text{ terms}, \\ M_{\tilde{u}_{LR}}^2 &= m_A v_2 \lambda_U A_{U_{LR}} + \mu v_1 \lambda_U. \end{aligned} \quad (3)$$

λ_U is the Yukawa coupling matrix for up-type quarks, and the A_U's are dimensionless matrices. The CP violating invariant responsible for producing an asymmetry in the right-handed up-type squark number (and hence baryon number) is [3]

$$J_{CP} = m_A|\mu|\Delta\beta Im Tr[e^{i\phi_B} A_{U_{LR}}^\dagger \lambda_U^\dagger \lambda_U \rho(\tilde{u}_R)] \quad (4)$$

where m_A is real (the phase information is in $A_{U_{LR}}$), $e^{i\phi_B}$ comes from the phase of the μ parameter, and $\rho(\tilde{u}_R)$ can be approximated by the density matrix for the right-handed up-type squarks in the symmetric phase. Similar formulae obtain for the other squark species.

Finally, we concentrate only on the production of $\tilde{t}_R$ since it is required to be light in order to enhance the phase transition strength. Unless they are also light, effects on the other squark species will be Boltzmann suppressed. For $m_{\tilde{t}_R} = 175$ GeV, $m_{\tilde{t}_L} = 300$ GeV, and $\tan\beta \sim 1$ we obtain the result

$$\frac{n_B}{s} \simeq 10^{-8} \frac{\kappa\Delta\beta}{v_w} \frac{m_A}{T_0} \frac{|\mu|}{T_0} Im[e^{i\phi_B} A_{U_{LR}}^\dagger \lambda_U^\dagger \lambda_U]_{(3,3)} \quad (5)$$

κ is related to the weak sphaleron rate, $\Gamma_{ws} = \kappa\alpha_w^4 T$. There is a large uncertainty in its precise value, with current estimates giving $\kappa = 1 - 0.03$ [13]. $v_w \simeq 0.1$ is the wall velocity, $\Delta\beta \lesssim 0.01$, and $T_0 \sim m_A \sim |\mu| \sim 100$ GeV is the phase transition temperature. The approximations made in deriving Eq. (5) and their validity our outlined in [3]. If $\tilde{t}_L$ and $\tilde{t}_R$ have very different masses there is a suppression of the baryon asymmetry by $m_{\tilde{t}_R}^2/m_{\tilde{t}_L}^2$ that is not explicit in their work. Thus the estimate of Eq. (5) would be modified if $m_{\tilde{t}_L} \gg 300$ GeV.

The CP violating phases responsible for baryogenesis could then logically be divided into three separate possibilities:

- There is a universal supersymmetric phase, ϕ_B, coming from the μ term. Since the μ parameter also appears in the higgsino mass matrix, this possibility also results in the production of higgsino number, which contributes to the baryogenesis an amount similar to that of the axial *stop* number when the higgsino mass parameters are all $\sim T_0 \simeq 100$ GeV [3].†

- There are flavor dependent supersymmetric phases present in $A_{U_{LR}}$. Note that a universal phase in $A_{U_{LR}}$ can be rotated into the higgsino mass, and so is not distinct from the previous scenario.
- The supersymmetric parameters are all real, and the only phases are in the quark mass matrix, λ_U. This allows the possibility that there is only one large fundamental phase, that of the CKM matrix, that is reponsible for both the baryon asymmetry and the CP violating $K - \bar{K}$ mixing [5].

We will now consider these three possibilities separately. One should realise, however, that in the most general case phases from all three sources could contribute.

The presence of a phase, ϕ_B, for the μ term leads to a neutron EDM. The experimental bound $d_N \leq 1 \times 10^{-25}$ e-cm [11] tells us that either $\phi_B \lesssim 10^{-2}$ or $m_{\tilde{u}} \gtrsim 1$ TeV [12] where $m_{\tilde{u}}$ is the average first generation squark mass. Using a diagonal and real $A_{U_{LR}}$, and top quark Yukawa coupling $\lambda_t = 1$, one obtains from Eq. (5) the requirement $\phi_B \gtrsim 10^{-2}$ for $\kappa = 1$, $\Delta\beta = 0.01$. Thus, either the neutron EDM will be discovered soon or the first generation squarks are heavy [4]. Any reduction in the values of some of the parameters used to evaluate Eq. (5) would force ϕ_B to be larger, and hence the first generation squarks to be heavier. In particular if, $\kappa \ll 1$ or $\Delta\beta \ll 0.01$, one would require $\phi_B \sim 1$ to get a large enough baryon asymmetry. The constraint coming from d_N would then lead us to the particular realization of supersymmetry known as Effective Supersymmetry [14], where the first (two) generations of squarks have masses larger than 1 TeV while the third generation is light. Some of the flavor physics implications of this model have been studied in [15, 16].

If $\phi_B \sim 1$, an additional signal of its presence in the $\tilde{t}_L - \tilde{t}_R$ mixing would be large CP violating asymmetries in $t\bar{t}$ production at hadron colliders. This manifests itself as an asymmetry in the transverse energy distribution of the lepton and antilepton decay products of the $t\bar{t}$ pair which could be large enough to observe at the LHC [17].

The possibility that the phase arises in $A_{U_{LR}}$ allows us to evade the constraint from the neutron EDM because in this case the phase in the $\tilde{t}_L - \tilde{t}_R$ mixing is independent of that of $\tilde{u}_L - \tilde{u}_R$ mixing. Using $\kappa = 1$, $\Delta\beta = 0.01$, and a

†This possibility was recently studied in detail [4]. They conclude that baryogenesis from higgsino production is possible only for very specific choices of the mass parameters, and that it is not possible at all from axial *stop* production. We feel this conclusion is too strong given the inherent uncertainties in baryogenesis calculations.

diagonal $A_{U_{LR}}$ in Eq. (5), the requirement of baryogenesis implies $\phi_t \gtrsim 10^{-2}$ for the phase of $A_t \equiv A_{U_{LR}}(3,3)$. If however $\kappa \ll 1$ or $\Delta\beta \ll 0.01$, we would require $\phi_t \sim 1$, leading to the possibility of CP violating $t\bar{t}$ production mentioned above. The absence of a large neutron EDM even in the presence of light first generation squarks would distinguish this scenario from the previous one. The supersymmetry breaking scale in this case cannot be too high, else one would generate too large a neutron EDM due to RGE effects [18].

Finally we come to the third possibility that the supersymmetric parameters $A_{U_{LR}}$ and μ are real, with all the CP violation being in the quark mass matrix [5]. Notice that $\lambda_U^\dagger \lambda_U$ in Eq. (5) is Hermitian, hence the phase is on one of the off-diagonal terms. One then requires $A_{U_{LR}}$ to have off diagonal entries in order to move this phase to the (3,3) element of the product $A_{U_{LR}}^\dagger \lambda_U^\dagger \lambda_U$.[‡] Given the reasonable assumption that at least part of θ_C, the Cabbibo angle, is generated in the up-type quark mass matrix [19], off-diagonal terms in $A_{U_{LR}}$ always lead to large $D-\bar{D}$ mixing due to gluino mediated box diagrams. The magnitude of the mixing is generically within an order of magnitude of the current experimental bound $\Delta(m_D) < 1.3 \times 10^{-13}$ GeV [11]. Further, given the hierarchical structure of the quark masses and mixings, one expects the largest off-diagonal entry in $\lambda_U^\dagger \lambda_U$ to be $\sim \theta_C^2 \sim 0.04$. For example the ansatz $\lambda_U = V_{CKM}^\dagger \hat{\lambda}_U V_{CKM}$ where V_{CKM} is the CKM matrix, and $\hat{\lambda}_U$ is the diagonal matrix of up-type Yukawa couplings can lead to

$$Im[A_{U_{LR}}^\dagger \lambda_U^\dagger \lambda_U]_{(3,3)} = \lambda_t^2 |V_{cb}| \sin\gamma \tag{6}$$

for

$$A_{U_{LR}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}, \tag{7}$$

where $\gamma \sim 1$ is the phase in the CKM matrix, that is measured in $K-\bar{K}$ mixing. This leads to a large enough baryon asymmetry [*cf.* Eq. (5)] for $\kappa = 1$, $\Delta\beta = 0.01$, but is ruled out if $\kappa \ll 1$ or $\Delta\beta \ll 0.01$. Thus we see that the three different ways in which the CP violation required for baryogenesis can manifest itself in the up-type squark mass matrix all result in experimentally distinguishable scenarios.

To summarize the effects on flavor physics imposed by the requirement of electroweak baryogenesis in the MSSM:

A sufficiently first order phase transition requires a light Higgs boson and $\tilde{t}_R$. The light $\tilde{t}_R$ coupled with the existence of light charginos required to convert

[‡]A scenario where the lightest squark is an admixture of $\tilde{c}_R$ and $\tilde{t}_R$ was considered in [5] as a way to motivate large off-diagonal entries in $A_{U_{LR}}$. The predictions for low energy flavor physics in that scenario are not very different from those obtained here.

sfermions to fermions implies large new contributions to $B - \bar{B}$ mixing. These could be observed at the asymmetric B factories.

In order to get a CP violating asymmetry in the propagation of particles through the bubble wall, one requires a non-trivial variation in the ratio of the Higgs vevs. This implies that the second Higgs doublet cannot be much heavier than the first. This scenario will be significantly constrained by improvements in the experimental accuracy for the $b \to s\gamma$ decay rate.

The CP violating phase responsible for baryogenesis resides in the up-type squark mass matrix. It could be a universal supersymmetric phase in which case either the neutron EDM will be discovered soon, or the first generation squarks are heavy. This scenario will be most significantly tested by improvements in the measurement of d_N combined with direct searches for first generation squarks.

The CP violation could also come from a flavor dependent phase in $A_{U_{LR}}$. This scenario could be distinguished from the one above if light first generation squarks were discovered, but not the neutron EDM.

Alternatively the supersymmetric parameters could be real, and the phase could come from the quark mixing matrix. This scenario predicts $D - \bar{D}$ mixing at a level that should be discovered soon. This scenario is the most constrained of the three, since the size of the CP violating invariant can be estimated from our knowledge of the quark masses and mixings, and is suppressed by the small angle V_{cb}.

Thus we see that the possibility of baryogenesis in the MSSM significantly constrains its parameter space. Experiments planned for the next few years will shed light on this picture. Direct searches for the light particles required are the first step towards determining the possibility of baryogenesis in the MSSM. If these particles are discovered, there are currently three different scenarios for the source of the CP violating phase that allow baryogenesis, all having distinct and testable experimental consequences. The flavor physics effects discussed here will then serve to elucidate the mechanism for baryogenesis in the MSSM.

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conservation. The constrained MSSM includes the assumptions of coupling constant unification, universal scalar and gaugino masses and universal trilinear terms at a high "unification" scale.

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