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Baryogenesis and Low Energy CP Violation

Mihir P. Worah
Department of Physics
University of California, Berkeley, California 94720
and
Theoretical Physics Group
Lawrence Berkeley National Laboratory

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Abstract

CP violation is a crucial component in the creation of the matter - anti matter asymmetry of the universe. An important open question is whether the CP violating phenomena observeable in terrestrial experiments have any relation with those responsible for baryogenesis. We discuss two mechanisms of baryogenesis where this question can be meaningfully posed: "electroweak baryogenesis" and "baryogenesis via leptogenesis". We show how these scenarios can be constrained by existing and forthcoming experimental data. We present a specific example of both these scenarios where the CP violating phase in the Cabbibo Kobayashi Maskawa matrix is related in a calculable way to the CP violating phase responsible for baryogenesis.

The world that we observe is manifestly baryon asymmetric. All the stable matter we see is made up of baryons, with anti-baryons being created only in high energy collisions (either in the laboratories or out in the cosmos). There is evidence that this asymmetry persists even at much larger scales. Matter and anti-matter galaxies within the same galactic cluster would result in strong γ ray emission due to annihilations. The absence of these confirms a baryon asymmetric region on the 20 Mpc scale [1]. More recently, a bound on the scale of the observable universe has been obtained by ruling out a contribution to the diffuse γ ray spectrum from particle-antiparticle annihilation [2]. The observed nuclear abundances in the stars, then allows us to estimate that the current baryon to photon ratio, $n_B/n_\gamma = (4-7)\times 10^{-10}$. This corresponds to a baryon-antibaryon asymmetry of 1 part in 10^8 in the early universe.

One possible explanation for the asymmetry is that it is an initial condition, that we cannot hope to understand. The other, more appealing, possibility is that although the universe initially had no net baryon number, microphysical processes that we can hope to understand led it to develop one during its evolution from the big bang to the present epoch. There are three requirements in order for such a baryon asymmetry to develop [3]:

(i) There must be a departure from thermal equilibrium. CPT invariance gaurantees the equality of particle and anti-particle masses. Hence in thermal equilibrium both will have the same number density as dictated by Boltzmann statistics.

(ii) There must be baryon number violation. This requirement is self explanatory.

(iii) There must be C and CP violation. This is required in order for the above baryon number violating interactions to preferentially produce baryons rather than antibaryons.

The discovery of CP violation in the neutral K mesons, thus made possible a meaningful discussion, in terms of physical processes, of why the universe consists of only matter and no anti-matter.

It was later realised that the Standard Model, in fact, contains all of the three ingredients listed above that are required for baryogenesis [4]. At a temperature $T \sim 100$ GeV in the early universe, the electroweak symmetry was broken due to the Higgs field aqquiring a vacuum expectation value. This resulted in a phase transition which, if strong enough, could provide the departure from thermal equilibrium needed for baryogenesis. Although baryon number is conserved in the Standard Model at the classical level, it is broken at the quantum level due to the anomolous coupling of the $B+L$ (baryon number plus lepton number) current to two W bosons. This baryon number violation is unobservably small at zero temperature, but it is enhanced at high temperatures, and could be a viable source for the asymmetric creation of baryons over anti-baryons. Finally, CP violation has been observed in the neutral K's, and is explained by a complex phase in the Cabbibo, Kobayashi, Maskawa (CKM) matrix.

Unfortunately, in the Standard Model, neither is the phase transition strong enough, nor is the CP violation efficient enough to explain the observed baryon asymmetry. The requirement on the strength of the phase transition in order to be able to generate and mantain a baryon asymmetry is given by [5]

$$\frac{H(T_0)}{T_0} \geq 1. \tag{1}$$

Here $T_0 \sim 100$ GeV is the critical temperature for the phase transition, and $H(T_0)$ is the value of the Higgs vacuum expectation value at this temperature. This strength is governed by the ratios of boson masses that are generated by the spontaneous symmetry breaking (SSB) to the mass of the Higgs boson. In the Standard Model, the W and Z bosons get their masses by SSB, and one obtains the approximate relationship

$$\frac{H(T_0)}{T_0} \sim \frac{2M_W^3 + M_Z^3}{2m_H^2 v} \sim \frac{1}{2}. \tag{2}$$

Where we have used $M_W = 80$ GeV, $M_Z = 90GeV$, $m_H = 95GeV$ (which is the current LEP lower bound), and $v = 246$ GeV is the zero temperature Higgs vacuum expectation value.

Assuming a strong enough phase transition and perfectly efficient baryon number violation one can obtain the estimate $n_B/n_\gamma \sim 10^{-2}\delta$ where δ is a dimensionless measure of CP violation [6]. However, the CKM mecahnism of CP violation in the Standard Model requires the participation of all three fermion families, and δ will be proportional to $Det\ \mathcal{C}/T_0^{12} \sim 10^{-21}$, where $Det\ \mathcal{C}$ is the Jarlskog determinant [7], and we have used $T_0 = 100$ GeV. There is a further suppression since the time scale needed for such interactions is so large that finite temperature plasma effects cause the participating particle wave functions to decohere before they can interfere enough to generate a significant CP asymmetry [8]. Thus, it is clear that one needs to invoke physics beyond the Standard Model in order to explain the baryon asymmetry of the universe.

In this talk we give an overview of baryogenesis in two extensions of the Standard Model. These models are motivated by the fact that they offer explanations for observed phenomena other than the baryon asymmetry that cannot be explained by the Standard Model and, most importantly, have low energy experimental consequences. We will demonstrate that in these models it is possible to relate the CP violation responsible for baryogenesis with the CP violation observed in the neutral Kaons.

One obvious possibility is to augment the Standard Model with new particles in the 100 GeV mass range that would remedy the deficiencies pointed out above [9]. Additional bosons that get their masses by the Higgs mechanism could enhance the strength of the electroweak phase transition. Moreover, the richer particle content could make CP violation more efficient. The most attractive such extension is the Minimal Supersymmetric Standard Model (MSSM), which we consider here. This model has its primary motivations in the facts that it stabilizes the hierarchy between the electroweak scale and the Planck scale, and that it provides a natural explanation of electro weak symmetry breaking.

The other distinct possibility is to use the baryon and/or lepton number, and CP violating decays of some super-heavy particle. The departure from

thermal equilibrium typically occurs because the decay rate of the particle is slower than the expansion rate of the universe [10]. These processes must occur in the very early history of the universe because it is only then that the expansion rate was rapid enough to provide the out of equilibrium conditions needed for baryogenesis. The situation we will consider is where the Standard Model is augmented with massive ($\sim 10^{10}$ GeV) right-handed Majorana neutrinos which have lepton number and CP violating mass matrices. Their out of equilibrium decays generate a net lepton number, which is then processed by the anomolous $B+L$ violation in the Standard Model into a net baryon number. The primary motivation for this extension lies in the fact that it provides, via the see-saw mechanism, a framework for understanding the smallness of the left-handed neutrino masses suggested by the atmospheric and solar neutrino data.

1 Baryogenesis in the MSSM

The squarks (scalar partners of the quarks) present in the MSSM get contributions to their masses from supersymmetry breaking, as well as from electroweak symmetry breaking via the Higgs mechanism. In particular, $\tilde{t}_L$ and $\tilde{t}_R$ the scalar partners of the top quark get a large contribution from the Higgs mechanism due to the size of the top quark Yukawa coupling to the Higgs boson. If the supersymmetry breaking mass of the $\tilde{t}_R$ is negligible, and there is no $\tilde{t}_L$- $\tilde{t}_R$ mixing, (the $\tilde{t}_R$ is chosen to be light in order to avoid conflicts with the ρ parameter if the $\tilde{t}_L$ were light), Eq. (2) gets modified to

$$\frac{H(T_0)}{T_0} \sim \frac{2M_W^3 + M_Z^3 + 2m_t^3}{2m_H^2 v} \sim 3 \tag{3}$$

for $m_t = 175$ GeV. Thus we see, the condition of Eq. (1) can be satisfied and we have a strongly first order phase transition. This simple relation is modified by the presence of supersymmetry breaking masses, $\tilde{t}_L - \tilde{t}_R$ mixing, and finite temperature effects. A detailed analysis [11] shows that an electroweak phase transition strong enough to allow baryogenesis is possible if $m_{\tilde{t}_R} \leq 175$ GeV and $m_H \leq 115$ GeV. Moreover, efficient baryogenesis requires rapid intraconversion between the particles and their supersymmetric partners. This means that most of the supersymmetric particles and especially the gauginos (fermionic partners of the gauge bosons) must also have masses of order $T_0 \sim 100$ 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, the light $\tilde{t}_R$ and charginos also result in large contributions to $B-\bar{B}$ mixing 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 of its contribution [12].

The most effective way to generate a 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 two Higgs fields in the MSSM makes this possible. If $\tan\beta$ (the ratio of the expectation values of the two Higgs fields) changes as one traverses the bubble wall separating the symmetric phase from the broken one, particle number asymmetries can be generated, which will be proportional to $\Delta\beta$, the change in β across the bubble wall [13].

It has been 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 [14]. 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. The current experimental value for $Br(b \to s\gamma)$ already sets the limit $m_{h_+} \gtrsim 300$ GeV at the 2σ level [16]. This then implies $\Delta\beta \lesssim 0.01$ through the relations above.

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. Here, they bias the Standard Model $B+L$ violation to produce a net baryon number [13, 14, 15]. In this paper we present the special case of baryogenesis through the production of axial squark number, where the CKM phase responsible for kaon CP violation is also directly responsible for baryogenesis [15].

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

$$M_{\tilde{u}}^2 = \begin{pmatrix} M_{\tilde{u}_{LL}}^2 & M_{\tilde{u}_{LR}}^2 \\ M_{\tilde{u}_{LR}}^{2\dagger} & M_{\tilde{u}_{RR}}^2 \end{pmatrix} \tag{4}$$

where

$$\begin{aligned} M_{\tilde{u}_{LL}}^2 &= m_Q^2 A_{U_{LL}} + (F,\ D) \text{ terms}, \\ M_{\tilde{u}_{RR}}^2 &= m_U^2 A_{U_{RR}} + (F,\ D) \text{ terms}, \\ M_{\tilde{u}_{LR}}^2 &= m_A v_2 \lambda_U A_{U_{LR}} + \mu v_1 \lambda_U. \end{aligned} \tag{5}$$

where M_Q, M_U, and M_A are supersymmetry breaking masses λ_U is the Yukawa coupling matrix for up-type quarks, and the A_U's are dimensionless matrices. Concentrating only on the production of $\tilde{t}_R$, and using $m_{\tilde{t}_R} = 175$ GeV, $m_{\tilde{t}_L} = 300$ GeV, and $\tan\beta \sim 1$ we obtain the result

$$\frac{n_B}{s} \simeq 10^{-8} \frac{\kappa\Delta\beta}{v_w} \frac{m_A}{T_0} \frac{|\mu|}{T_0} Im[e^{i\phi_B} A_{U_{LR}}^\dagger \lambda_U^\dagger \lambda_U]_{(3,3)} \tag{6}$$

κ is related to the rate of anomolous $B+L$ violation, $\Gamma_{B+L} = \kappa\alpha_w^4 T$. There is a large uncertainty in its precise value, with current estimates giving $\kappa = 1 - 0.03$ [17]. $v_w \simeq 0.1$ is the velocity of the wall separating the phase where electroweak symmetry is broken (the Higgs field has an expectation value) from where it is unbroken (the Higgs field has no expectation value). $\Delta\beta \lesssim 0.01$, and $T_0 \sim m_A \sim |\mu| \sim 100$ GeV. The approximations made in deriving Eq. (6) and their validity our outlined in [13]. If $\tilde{t}_L$ and $\tilde{t}_R$ have very different masses there is a suppression of the baryon asymmetry by $m^2_{\tilde{t}_R}/m^2_{\tilde{t}_L}$ that is not explicit in their work. Thus the estimate of Eq. (6) would be modified if $m_{\tilde{t}_L} \gg 300$ GeV.

Consider the possibility that the supersymmetric parameters $A_{U_{LR}}$ and μ are real, with all the CP violation being in the quark mass matrix [15]. Notice that $\lambda_U^\dagger \lambda_U$ in Eq. (6) 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 $A^\dagger_{U_{LR}} \lambda_U^\dagger \lambda_U$. These large 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 about an order of magnitude lower than the current experimental bound $\Delta(m_D) < 1.3 \times 10^{-13}$ GeV. 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 $\lambda_U = V^\dagger_{CKM} \hat{\lambda}_U V_{CKM}$ where V_{CKM} is the CKM matrix, and $\hat{\lambda}_U$ is the diagonal matrix of up-type Yukawa couplings can lead to

$$Im[A^\dagger_{U_{LR}} \lambda_U^\dagger \lambda_U]_{(3,3)} = \lambda_t^2 |V_{cb}| \sin\gamma \tag{7}$$

for

$$A_{U_{LR}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}, \tag{8}$$

where $\gamma \sim 1$ is the phase in the CKM matrix. Thus, we see that the baryon asymmetry is directly related to the phase responsible for CP violation in $K - \bar{K}$ mixing. We can obtain a large enough baryon asymmetry [*cf* Eq. (6)] for $\kappa = 1,\ \Delta\beta = 0.01$.

2 Baryogenesis via Leptogenesis

The idea that one can obtain a baryon asymmetry by first generating a lepton asymmetry was first proposed in [18], and subsequently explored in several papers [19]. As mentioned earlier, $B+L$ is anomously violated in the Standard Model, and the rate for this process is large at high temperatures. However, $B-L$ is conserved. Thus given enough time for the $B+L$ violating

processes to act, we obtain the relations:

$$\begin{aligned}(B-L)_f &= (B-L)_i \\ (B+L)_f &= 0\end{aligned} \tag{9}$$

where the subscripts f and i stand for final and initial respectively. Thus if one started with zero initial baryon number, but non-zero initial lepton number one would obtain the final condition $B_f = -L_i$ (this relationship is slightly modified by a careful consideration of all the Standard Model interactions [20]. The initial lepton number asymmetry is obtained by the CP and lepton number violating decay of heavy right-handed Majorana neutrinos.

Consider a model with right-handed Majorana neutrinos N_R. By definition these fields are self conjugate, $N_R^c = N_R$ where the superscript c denotes the charge conjugated field. Thus given the Yukawa interaction

$$\mathcal{L}_Y = -h_{ij}\bar{l}_L^i N_R^j H + h.c. \tag{10}$$

where h_{ij} is the matrix of Yukawa couplings, the l_L are left-handed Standard Model leptons and H is the Higgs field one finds that N_R can decay into both light leptons and anti-leptons. If these decays are CP violating they will generate an excess of one over the other. Let us define an asymmetry

$$\delta = \frac{\Gamma - \Gamma^{CP}}{\Gamma + \Gamma^{CP}} \tag{11}$$

where Γ is the decay rate into leptons, and Γ^{CP} into anti-leptons. In the case that the heavy neutrinos are not degenerate in mass, which is the case we study here, it is sufficient to consider only CP violation in the decays of the heavy neutrinos (direct CP violation). One then obtains the result [18]

$$\delta = \frac{1}{2\pi(h^\dagger h)_{11}} \sum_{j=1}^{6} \mathrm{Im}[(h^\dagger h)_{1j}]^2 f(m_j^2/m_1^2), \tag{12}$$

where $f(x)$ is a kinematic function of order one for reasonable choices of the masses [18]. The subscript 1 in the terms above is due to the fact that the lepton asymmetry is generated by the decay of the lightest of the right-handed neutrinos (any asymmetry generated by the heavier right-handed neutrinos will be washed out by the decays of the lightest).

The first constraint on the mass scale of the N_R is obtained by insisting that it be out of thermal equilibrium with the rest of the universe when it decays. This will hold if it lives till the universe has cooled to a temperature below the mass of the particle. This condition is encoded in the requirement that

$$\Gamma_R \leq H(T = m_R) \tag{13}$$

where Γ_R is the decay rate of the right-handed neutrino with mass m_R, and H is the Hubble constant. This translates to

$$\frac{(h^\dagger h)_{11} m_R}{8\pi} \lesssim \frac{20 m_R^2}{M_P} \Rightarrow \frac{(h^\dagger h)_{11}}{m_R} \lesssim 10^{-16}\ \mathrm{GeV}^{-1} \tag{14}$$

if the dominant decay is via the Yukawa coupling of Eq. (10). The second constraint is obtained by insisting that the heavy Majorana mass scale explain the solar and atmospheric neutrino data. If we assume that the observed deficit in ν_e's from the sun is due to $\nu_e - \nu_\mu$ mixing, then the mass squared difference $\Delta m^2 \sim 10^{-6}$ eV^2, preferred by the data, implies $m_{\nu_\mu} \sim 10^{-3}$ eV. Similarly, assuming the deficit in atmospheric ν_μ's is due to $\nu_\mu - \nu_\tau$ mixing, then the preferred mass squared difference, $\Delta m^2 \sim 10^{-3}$ eV^2, implies $m_{\nu_\tau} \sim 3 \times 10^{-2}$ eV. The see-saw mass relations

$$m_{\nu_\mu} \sim \frac{m_\mu^2}{m_R}; \quad m_{\nu_\tau} \sim \frac{m_\tau^2}{m_R} \tag{15}$$

then imply that $m_R \sim 10^{10} - 10^{11}$ GeV. Eq. (14) then tells us that $h_{11} \sim 10^{-2} - 10^{-3}$ (assuming a hierarchical matrix of Yukawa couplings). Note, that if the electron gets its mass at tree level from the Yukawa coupling h as in the Standard Model, one would obtain $m_e = h_{11} v = 1$ GeV, for $v = 246$ GeV, which is too large by several orders of magnitude. In order for this model to work, one has to impose symmetries such that the Standard Model fermions only get their masses at the loop level. In such a case the fermion masses would be proportional to the squares of the Yukawa coupling constants, and one obtains $m_e = h_{11}^2 v = 0.2$ MeV for $h_{11} = 10^{-3}$ which is the correct order of magnitude. It is indeed possible to construct a model that incorporates all these requirements [21]. Moreover, in this model, the CP violation responsible for baryogenesis is related in a calculable way to the CP violation present in the CKM matrix.

The model is based on the $SU(4) \times SU(2)_L \times SU(2)_R$ group. The Standard Model fermions transform in the usual representations:

$$\Psi_L^i \sim (4,2,1)^i \equiv \begin{pmatrix} u_1 & u_2 & u_3 & \nu \\ d_1 & d_2 & d_3 & e^- \end{pmatrix}_L^i \tag{16}$$

$$\Psi_R^i \sim (4,1,2)^i \equiv \begin{pmatrix} u_1 & u_2 & u_3 & N \\ d_1 & d_2 & d_3 & e^- \end{pmatrix}_R^i \tag{17}$$

where $i = 1,2,3$ is a generation index, and we have included a right handed neutrino N. We add to this three generations of (right-handed) sterile neutrinos

$$s^i \sim (1,1,1)^i. \tag{18}$$

The matter spectrum is supersymmetric, so the scalars $\tilde{\Psi}^i_L$, $\tilde{\Psi}^i_R$, and $\tilde{s}^i$ in the model transform in exactly the same way. We will impose a discrete Z_3 symmetry on the gauge singlets (broken by the interactions of the Standard Model particles) under which $s^j \to e^{-i(j\pi)/3} s^j$ and $\tilde{s}^j \to e^{i(2j\pi)/3}\tilde{s}^j$. This permits us to make the Lagrangian CP invariant, with the vacuum expectation values of the $\tilde{s}^j$ breaking CP spontaneously. We can choose parameters for the scalar potential such that it is minimized when

$$\langle \tilde{s} \rangle_j = \frac{v_0}{\sqrt{2}} e^{i\alpha_j}; \quad \langle \tilde{N} \rangle_j = \frac{v_R}{\sqrt{2}} \delta_{1j}; \quad \langle \tilde{\nu} \rangle_j = \frac{v_L}{\sqrt{2}} \delta_{1j} \tag{19}$$

with $|v_0| > |v_R| \gg |v_L|$. This provides the correct pattern of symmetry breaking.

The Yukawa interactions are given by

$$\mathcal{L}_{\mathcal{Y}} = -y_i (\bar{s}^c)^i s^i \tilde{s}^i - (\kappa^a_L)_{ij} \bar{\Psi}^i_L s^j \tilde{\Psi}^a_L - (\kappa^a_R)^T_{ij} \bar{\Psi}^i_R (s^c)^j \tilde{\Psi}^a_R + \text{h.c.}, \tag{20}$$

with all of the coupling constants real. However, the mass matrix of the s_i will contain the phases α due to the spontaneous breaking of CP invariance when the $\tilde{s}_i$ obtain a vacuum expectation value. Note that since $\bar{\Psi}_L \Psi_R$ transforms as $(1, 2, 2)$ and there are no scalars in this representation, none of the Standard Model fermions get masses at tree level. Their masses are generated at one loop by diagrams involving the (s_i) on the internal lines. The CP violating phases in the quark mass matrices and hence in the CKM matrix are a function of the phases α in the masses of the s_i.

The out of equilibrium decays of the s_i generate the lepton (and hence baryon) asymmetry. It is this same phase α that is responsible for the CP violation in these decays. Thus one obtains a relationship between the CKM phase and the phase responsible for the baryon asymmetry.

3 Conclusions

We have presented an overview of two models of baryogenesis that also have other low energy experimental consequences. Baryogenesis in the MSSM is possible if the Higgs and $\tilde{t}_R$ are light. Moreover, one expects large contributions to the $b \to s\gamma$ rate, and the $B - \bar{B}$ mixing amplitude. Baryogenesis via the decay of heavy neutrinos can be constrained by insisting that they be at the see-saw scale implied by the solar and atmospheric neutrino data. We have presented specific implementations of these models where the CKM phase responsible for CP violation in the neutral kaons is related to the phase responsible for the baryogenesis.

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