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Supersymmetric (S)Neutrino-Mass Induced Baryogenesis

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Abstract

We propose a new mechanism for baryogenesis in supersymmetric extensions of the standard model, that does not depend on (super)GUT interactions. It occurs by the non-perturbative electroweak reprocessing of a lepton asymmetry. This lepton asymmetry is generated by the effects of lepton number violating induced operators, arising from "see-saw" (s)neutrino masses, which act on scalar condensate oscillations along flat directions of the supersymmetric standard model.

The baryon asymmetry of the universe represents one of the basic facts of cosmology, which must be addressed by any theory of the fundamental interactions. This is most emphatically the case in the context of inflationary models of the universe [1], where any preexisting baryon asymmetry would have been inflated away, and we are forced to rely on the microphysics of elementary particle interactions to generate the observed BAU. The conditions necessary for this to occur as enunciated by Sakharov [2] are: Non-conservation of baryon number; violation of C and CP symmetry, and out of equilibrium dynamics.

The first realizations of the Sakharov conditions were in the context of Grand Unified Theories (GUTs). In these theories, quarks and leptons were unified into multiplets of a larger simple gauge symmetry, which contained the Standard Model gauge group as a subgroup. Gauge and Higgs interactions of the larger simple group then violated baryon (B) and lepton (L) number at the high energy scales where grand unification occurred. During the thermal history of the Universe, heavy gauge and Higgs particles could, via their out-of-equilibrium decays, generate cosmological baryon and lepton asymmetries [3]. The constraints on such a scenario derive from two conflicting requirements. To generate a BAU after inflation requires that the relevant dynamics occur at energy scales below either the inflaton mass scale, or the reheating temperature. On the other hand, GUT reactions of the type responsible for generation of the BAU are generally the same interactions that cause proton decay; the non-observation of the latter puts lower limits on the energy scale at which this dynamics can occur. In many models, proton stability considerations are difficult to reconcile with baryogenesis after inflation.

New possibilities arose after the realization [4] that at temperatures above the electroweak transition temperature baryon number violating nonperturbative electroweak interactions (sphalerons) would be in equilibrium. Since these interactions conserve B-L, it would suffice to produce a net lepton asymmetry, and then rely on the sphaleron effects to (partially) convert it to a BAU. The great advantage here is that one no longer needs GUT dynamics, and the concomitant problems of proton stability. Fukugita and Yanagida proposed a scenario [5] where the lepton asymmetry is generated in the out of equilibrium decay of a heavy right handed neutrino ν_R , as arises in the see-saw [6] mass matrix that gauge symmetries permit for models with a ν_R . The Fukugita-Yanagida mechanism is similar to the standard GUT scenario in that it utilizes out of equilibrium decay as its dynamical mechanism; it is distinct and original in that it utilizes neutrino Majorana masses,

not GUT interactions, as its source of B-L violation, producing only a lepton asymmetry for later sphaleron reprocessing.

In supersymmetric Grand Unified Theories (susyGUTs) the baryon number violating GUT interactions can also effect a BAU by their effects on scalar superpartner fields [7, 8, 9, 10, 11]. As Affleck and Dine [7] first proposed, GUT interactions induce an effective contribution to the scalar potential (after supersymmetry breaking) which could act on the oscillations of coherent sfermion condensates so as to generate a BAU. The dynamics are entirely different, but the underlying interaction is still that of GUT violation of baryon number.

In this paper we propose a new mechanism of baryogenesis, arising from the presence of see-saw neutrino masses in supersymmetric theories; no GUT interactions are required. We first derive the contributions induced after supersymmetry breaking, in the low energy effective potential of a supersymmetric theory, from the effects of see-saw neutrino mass generation. We then examine the effect of these interactions on slepton and squark condensates oscillating along “flat directions” (before supersymmetry breaking) of the low-energy supersymmetric standard model. We show that these interactions act on the condensate oscillations to produce a net lepton asymmetry. Sphaleron reprocessing of the lepton asymmetry to baryons then completes our scenario. Our mechanism resembles that of Fukugita and Yanagida in that the only “non-standard” interaction required is the see-saw neutrino mass, and in that the dynamical mechanism only generates a lepton asymmetry at first, with sphalerons responsible for partially reprocessing that into baryons.

On the other hand, unlike the proposal of Fukugita and Yanagida, the dynamics of our mechanism involves the oscillations of sfermion condensates along susy flat directions, and hence unlike theirs can only occur in supersymmetric extensions of the standard model. Furthermore, in our mechanism the CP violation necessary for the production of the asymmetry may arise spontaneously from the phase of the condensate, and hence is naturally of order unity, whereas in the Fukugita-Yanagida scenario one needs hard CP violation in the neutrino-Higgs Yukawa couplings. Finally, as our mechanism depends on the effective low energy interactions induced by the right handed see-saw neutrinos, it can be operative even when the ν_R masses are too large for them to be physically produced in the post inflationary epoch, whereas in the Fukugita-Yanagida mechanism they must be copiously produced, thus bounding their mass by the inflaton mass scale, which COBE results give as $\leq 10^{11} GeV$ for typical inflationary models [12].

In order to demonstrate our mechanism of baryogenesis we need the following elements. First we need to show the existence of flat (before supersymmetry breaking) directions in the potential of our model, including the potential contributions coming from the see-saw neutrino mass generation F-terms. It is the scalar condensates (squark, slepton, and Higgs) along these directions whose motion, after supersymmetry breaking potentials turn on, drives the lepton asymmetry generation. Second, we need to establish the existence of slepton number violating potential interactions, induced after supersymmetry breaking by the neutrino mass see-saw superpotential terms, which pick up a non-zero contribution along the flat direction, and which act during the course of the scalar oscillations to build up a net slepton density. Third, we must follow the evolution of the condensate to calculate the lepton asymmetry produced, and its subsequent dilution by inflaton decay, to get the final lepton asymmetry for sphaleron reprocessing.

To begin our demonstration example, we need to exhibit flat directions in the supersymmetric standard model, extended to include neutrino see-saw masses. The superpotential terms contributing to the potential are:

$$W = g_u^{ij}(H_1 Q^i u^{cj}) + g_d^{ij}(H_2 Q^i d^{cj}) + g_e^{ij}(H_2 L^i e^{cj}) + g_\nu^{ij}(H_1 L^i \nu^{cj}) + M^{ij} \nu^c i \nu^{cj} \quad (1)$$

where the left chiral supermultiplets are labeled by their particles, and H_1 and H_2 are the two Higgs doublet supermultiplets. The potential resulting from these F-terms (plus the $SU(3) \times SU(2) \times U(1)$ D-terms) has the following useful flat direction (which is a generation permuted version of one appearing in reference [11], and which may be shown to acquire no new contributions from F-terms associated with the neutrino mass see-saw); it depends on three arbitrary complex parameters a, v, c , and four phases α, β, ϕ , and γ . We work in a generation basis in which the g_e^{ij} and the g_d^{ij} have been diagonalized; the quark indices denote quark colour.

$$\begin{aligned} \tilde{t}_3^c &= a & \tilde{t}^1 &= v & \tilde{\nu}_e &= e^{i\gamma} c \\ \tilde{b}_3^c &= c & \tilde{s}_2^c &= e^{i\alpha} \sqrt{|a|^2 + |c|^2} & & \\ \tilde{\mu}^- &= e^{i\beta} \sqrt{|v|^2 + |c|^2} & \tilde{d}_1^c &= e^{i\phi} \sqrt{|a|^2 + |v|^2 + |c|^2} & & \end{aligned} \quad (2)$$

This particular flat direction has the virtue that its vev produces a non-zero value for the effective scalar operator

$$\langle \tilde{\mu}^- \tilde{\nu}_e \tilde{b}_3^c (\tilde{t}_3^c)^* \rangle = e^{i(\beta+\gamma)} a^* c^2 \sqrt{|v|^2 + |c|^2} \quad (3)$$

which violates lepton number by two units.

After supersymmetry breaking, this scalar operator will be induced by the neutrino see-saw couplings via the diagram of Figure 1. In the diagram the insertions on the gluino line are the supersymmetry breaking gaugino Majorana mass terms m_δ . The resulting potential term coupling is of order $V = \lambda\phi\phi\phi^*$, where $\phi\phi\phi^*$ corresponds to the quartic scalar operator of equation (3) and

$$\lambda \simeq \alpha_s g_\nu^c g_\nu^\mu g_t g_b \frac{m_\delta^2}{M^2} \quad (4)$$

where g_ν^c and g_ν^μ are the (experimentally undetermined) neutrino see-saw Dirac mass Yukawas, and M is the scale of the large singlet ν^c Majorana mass term. The estimate for the scale of the induced quartic scalar coupling agrees with the general arguments of [11] for operators of the form $\phi\phi\phi\phi^*$.

So we have: a flat direction; a see-saw generated lepton number violating quartic scalar potential interaction, which is induced along the flat direction after supersymmetry breaking; and an arbitrary phase for the flat direction vevs which breaks CP spontaneously and is generically of order unity. It remains only to calculate the net lepton (and baryon) asymmetry produced by the the decay of the sfermion oscillations.

After inflation denote the expectation values of scalars parametrizing the flat directions as $\phi_o = \langle o|\phi|o\rangle$, producing $V_o = \langle o|V|o\rangle$. We can then write the net lepton number per scalar particle associated with the oscillations of ϕ as

$$L \sim \frac{ImV_o}{m_\delta^2 \phi_o^2} \quad (5)$$

From equations (3) and (4) we see that

$$ImV_o \sim \theta \lambda \phi_o^4 \quad (6)$$

where $\theta \sim 1$ is the degree of CP violation in (3). Thus we can write the net lepton number per particle as

$$L \sim O(10^{-3}) \theta g_\nu^c g_\nu^\mu \frac{\phi_o^2}{M^2} \quad (7)$$

where we have assumed that $\alpha_s \sim 10^{-1}$, $g_t \sim 1$ and $g_b \sim O(10^{-2})$. The net lepton number density (\sim the net baryon density after shaleron reprocessing) is then given by

$$n_B \sim n_L \sim L m_\delta \phi_o^2 (R_\phi/R)^3 \quad (8)$$

where R is the cosmological scale factor and R_ϕ is the value of the scale factor when the sfermion oscillations begin.

In the absence of inflation, the final baryon asymmetry is easily found using [7]

$$\frac{n_B}{n_\gamma} \sim O(10^{-3}) \theta \frac{\phi_o^2}{M^2} (g_\nu^c g_\nu^\mu \frac{M_P}{m_\delta})^{1/6} \quad (9)$$

which as one can see may be quite large. In the context of inflation, it is known that the final asymmetry is generally much smaller [10, 12]. First, the initial value of ϕ_o is determined by quantum fluctuations during inflation, and second there is the dilution of the asymmetry due to inflaton decays. If we assume a single mass scale μ to be associated with inflation (as can be done for most simple inflationary models), then recent COBE observations of the microwave background anisotropies [13] indicate that $\mu^2 = f e \nu \times 10^{-9} M_P^2$ [12]. The initial value for the sfermion expectation value is $\phi_o^2 = H^3 \tau / 4\pi$ where the Hubble parameter $H \simeq \mu^2 / M_P$ and the duration of inflation is $\tau \simeq M_P^3 / \mu^4$ so that $\phi_o \simeq \mu$ [12]. The final baryon asymmetry can then be found from [10] to be

$$\frac{n_B}{n_\gamma} \simeq O(10^{-3}) \frac{\theta g_\nu^c g_\nu^\mu \phi_o^4 m_\eta^{3/2}}{M^2 M_P^{5/2} m_\delta} \simeq O(10^{-3}) \frac{\theta g_\nu^c g_\nu^\mu \mu^7}{M^2 M_P^4 m_\delta} \quad (10)$$

where $m_\eta \simeq \mu^2 / M_P$ is the inflaton mass. Equation (10) will yield a required value of $\simeq 10^{-10}$ for $\theta g_\nu^c g_\nu^\mu M_P^2 / M^2 \simeq 10^3$.

We can now see clearly the difference between this scenario and previous scenarios for generating the baryon asymmetry. First as we stressed earlier this scenario does not depend in any way upon grand unification as does the original mechanism proposed by Affleck and Dine [7]. It works in the absence of any GUT baryon or lepton number violation. It also differs significantly from the heavy lepton decay scenario of Fukugita and Yanagida [5]. In their scenario, the baryon asymmetry is a reprocessed lepton asymmetry due to the decay of the heavy right-handed neutrino with mass $\simeq M$. The mass scale M must be small enough so that the right handed neutrino is produced in inflaton decays $M \leq m_\eta \simeq 10^{11} GeV$ [12], yet not too small so that the lepton asymmetry is actually erased due to induced dimension-five operators [14]. This leaves only a small window for the scenario to be realized. In our case, there is little restriction beyond that due to the dimension-five operator which in this case is $M \geq 10^{11} GeV$ [12].

In summary, we have proposed a new mechanism for baryogenesis in supersymmetric extensions of the standard model, that does not depend on (super)GUT interactions. It depends on non-perturbative electroweak reprocessing of a lepton asymmetry. The lepton asymmetry is generated by the effects of lepton number violating induced operators, acting on scalar condensate oscillations along flat directions of the standard model. In our realization of the mechanism we have shown that lepton number violating operators of this type can be induced, after supersymmetry breaking, by see-saw neutrino mass terms in the theory. But the idea is quite a general feature of supersymmetric extensions of the standard model. Any source of violation of either baryon or lepton number has, in principle, the potential to induce baryogenesis via sfermion condensate dynamics, coupled with sphaleron reprocessing, in a manner similar to that of the example we have presented. As such, we expect that in supersymmetric models, whatever the sources of lepton or baryon number violation, GUT or otherwise, their effects on flat direction sfermion oscillations may quite generally yield a possible mechanism for generating the lepton and baryon asymmetries of the universe.

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Figure Captions

Figure 1: Diagram inducing lepton number violation in the low energy effective potential, after supersymmetry breaking.

