Observable $N - \bar{N}$ Oscillation in High Scale Seesaw Models

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We discuss a realistic high scale ($v_{BL} \sim 10^{12}$ GeV) supersymmetric seesaw model based on the gauge group $SU(2)_L \times SU(2)_R \times SU(4)_c$, where neutron-anti-neutron oscillation can be in the observable range without fine tuning of parameters. This is contrary to the naive dimensional arguments which say that $\tau_{N-\bar{N}} \propto v_{BL}^2$ and should therefore be unobservable for seesaw scale $v_{BL} \gtrsim 10^5$ GeV. Two reasons for this enhancement are: (i) accidental symmetries which keep some of the diquark Higgs masses at the weak scale and (ii) a new supersymmetric contribution from a lower dimensional operator. The net result is that $\tau_{N-\bar{N}} \propto v_{BL}^2 v_{wk}^3$ rather than $v_{BL}^5$. The model also can explain the origin of matter via the leptogenesis mechanism and predicts light diquark states which can be produced at LHC.

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INTRODUCTION

There are various reasons to suspect that baryon number is not a good symmetry of nature: (i) first is that nonperturbative effects of the standard model lead to $\Delta B \neq 0$, while keeping $\Delta(B-L) = 0$ \[1\]; (ii) understanding the origin of matter in the universe requires $\Delta B \neq 0$ \[2\] and (iii) many theories beyond the standard model lead to interactions that violate baryon number \[3, 4\].

If indeed such interactions are there, the important question is: can we observe them in experiments? Two interesting baryon nonconserving processes of experimental interest are: (a) proton decay e.g. $p \rightarrow e^+ + \pi^0, \bar{\nu} + K^0$ etc \[1, 5\] and (b) $N \leftrightarrow \bar{N}$ oscillation \[2, 5, 6\]. These two classes of processes probe two different selection rules for baryon nonconservation: $\Delta(B-L) = 0$ for proton decay and $\Delta(B-L) = 2$ for $N \leftrightarrow \bar{N}$ oscillation and indicate totally different directions for unification beyond the standard model. For example, observation of proton decay will point strongly towards a grand desert till about the scale of $10^{16}$ GeV whereas $N \leftrightarrow \bar{N}$ oscillation will require new physics at an intermediate scale at or above the TeV scale but much below the GUT scale.

While proton decay goes very naturally with the idea of eventual grand unification of forces and matter, recent discoveries of neutrino oscillations have made $N \leftrightarrow \bar{N}$ oscillation to be quite plausible theoretically if small neutrino masses are to be understood as a consequence of the seesaw mechanism \[5\]. This can be seen as follows: seesaw mechanism implies Majorana neutrinos implying the existence of $\Delta(B-L) = 2$ interactions. In the domain of baryons, it implies the existence of $N \leftrightarrow \bar{N}$ oscillation as noted many years ago \[5\].

An explicit model for $N \leftrightarrow \bar{N}$ oscillation was constructed in \[5\] by implementing the seesaw mechanism within the framework of the Pati-Salam $\mathbb{SU}(2)_L \times \mathbb{SU}(2)_R \times SU(4)_c$ model, where quarks and leptons are unified. It was shown that this process is mediated by the exchange of diquark Higgs bosons with an amplitude ($G_{N \leftrightarrow \bar{N}}$) which scales like $M_{qq}^{-5}$. In the non-supersymmetric version without fine tuning, one expects $M_{qq} \propto v_{BL}$ leading to $G_{N \leftrightarrow \bar{N}} \simeq v_{BL}^{-5}$. So only if $M_{qq} \sim v_{BL} \sim 10 - 100$ TeV, the $\tau_{N \leftrightarrow \bar{N}}$ is in the range of $10^6 - 10^8$ sec and is accessible to experiments. On the other hand, in generic seesaw models for neutrinos, one expects $v_{BL} \sim 10^{11} - 10^{14}$ GeV depending on whether the third generation Dirac mass for the neutrino is 1-100 GeV. An important question therefore is whether in realistic seesaw models, $N \leftrightarrow \bar{N}$ oscillation is at all observable. Another objection to the above nonsupersymmetric model for $N \leftrightarrow \bar{N}$ that was raised in the 80’s was that such interactions will erase any baryon asymmetry created at high scales. It will be therefore important to overcome this objection.

In this note we point out that in a class of supersymmetric $SU(2)_L \times SU(2)_R \times SU(4)_c$ models (called SUSY $G_{224}$), an interesting combination of circumstances improves the $v_{BL}$ dependence of the $G_{\Delta B=2}$ to $v_{BL}^{-5} v_{wk}^3$ instead of $v_{BL}^{-5}$ making $N \leftrightarrow \bar{N}$ oscillation observable. Further more the same model also allows us to overcome the difficulty with high scale baryogenesis. An example of such a theory was presented in \[10\] where it was shown that in the minimal version of the model, there exist accidental symmetries that imply that some of the $M_{qq}$’s are in the TeV range even though $v_{BL} \simeq 10^{11}$ GeV. We discuss this class of theories in this letter. The new results in this paper are: (i) a new diagram which enhances the $N \leftrightarrow \bar{N}$ oscillation amplitude; (ii) a realistic example which is in agreement with the observed neutrino oscillation parameters while predicting observable $N \leftrightarrow \bar{N}$ oscillation amplitude and (iii) adequate leptogenesis mechanism \[11\] for understanding the origin of matter via the quasi-degenerate leptogenesis \[12\] with right-handed neutrinos at $\sim 10^7$ GeV.

At present, the best lower bound on $\tau_{N \leftrightarrow \bar{N}}$ comes from
ILL reactor experiment and is $10^8$ sec. There are also comparable bounds from nucleon decay search experiments. There are proposals to improve the precision of this search by at least two orders of magnitude. We feel that the results of this paper should give new impetus to a search for neutron-antineutron oscillation.

\[ SU(2)_L \times SU(2)_R \times SU(4), \text{ MODEL WITH LIGHT DIQUARKS} \]

The quarks and leptons in this model are unified and transform as $\psi : (2, 1, 4) \oplus \psi^c : (1, 2, 4)$ representations of $SU(2)_L \times SU(2)_R \times SU(4)_c$. For the Higgs sector, we choose, $\phi_1 : (2, 2, 1)$ and $\phi_{15} : (2, 2, 15)$ to give mass to the fermions. The $\Delta^c : (1, 3, 10) \oplus \Delta_{\overline{c}}^c : (1, 3, \overline{10})$ break to the $B - L$ symmetry. The diquarks mentioned above which lead to $B(\Delta^c) = 2$ processes are contained in the $\Delta^c : (1, 3, 10)$ multiplet. We also add a $B - L$ neutral triplet $\Omega : (1, 3, 1)$ which helps to reduce the number of light diquark states and a gauge singlet field $S$. The superpotential of this model is given by:

\[ W = W_Y + W_H \]

\[ W_H = \lambda_1 S(\Delta^c \Delta^c - M^2) + \lambda_5 \frac{(\Delta^c \Delta^c)^2}{M_{P}} + \lambda_6 \frac{(\Delta^c \Delta^c)(\Delta_{\overline{c}}^c \Delta_{\overline{c}}^c)}{M_{P}} + \lambda_7 \Delta^c \Delta_{\overline{c}}^c \Omega \]

\[ W_Y = h_1 \psi \phi_1 \psi^c + h_{15} \psi \phi_{15} \psi^c + f \psi^c \Delta^c \psi^c \]

Note that since we do not have parity symmetry in the model, the Yukawa couplings $h_1$ and $h_{15}$ are not symmetric with respect to $L \leftrightarrow R$. When $\lambda_B = 0$, this superpotential has an accidental global symmetry much larger than the gauge group $SU(4)$: as a result, vacuum breaking of the $B - L$ symmetry leads to the existence of light diquark states that mediate $N \leftrightarrow \bar{N}$ oscillation and enhance the amplitude.

In fact it was shown that for $\langle \Delta^c \rangle \neq 0 \neq \langle \Omega \rangle$ and all VEVs in the range of $10^{11}$ GeV, the light states are those with quantum numbers: $\Delta_{u \leftrightarrow c}$. The symmetry argument behind is that for $\lambda_B = 0$, the above superpotential is invariant under $U(10, c) \times U(2, c)$ symmetry which breaks down to $U(9, c) \times U(1)$ when $\langle \Delta_{u \leftrightarrow c} \rangle \neq 0$. This results in 21 complex massless states; on the other hand these vevs also breaks the gauge symmetry down from $SU(2)_R \times SU(4)_c$, to $SU(3)_c \times U(1)_Y$. This allows nine of the above states to pick up masses of order $g_{BL} v_{BL}$ leaving 12 massless complex states which are the six $\Delta_{u \leftrightarrow c}$ plus six $\Delta_{c \leftrightarrow u}$ states. Once $\lambda_B \neq 0$, they pick up mass (call $M_{u \leftrightarrow c}$) of order of the electroweak scale.

\[ N \leftrightarrow \bar{N} \text{ OSCILLATION- A NEW DIAGRAM} \]

To discuss $N \leftrightarrow \bar{N}$ oscillation, we introduce a new term in the superpotential of the form:

\[ W_{\Delta_B=2} = \frac{1}{M_s} \epsilon^\mu \epsilon^\nu \epsilon^\lambda \epsilon^\sigma \lambda \epsilon^\mu \epsilon^\nu \epsilon^\lambda \epsilon^\sigma \Omega \]

where the $\mu, \nu$ etc stand for $SU(4)$, and we have suppressed the $SU(2)_R$ indices. We choose $M_s \ll M_{P}$. This does not affect the masses of the Higgs fields. When $\Delta_{u \leftrightarrow c}$ acquires a VEV, $\Delta_B = 2$ interaction are induced from the superpotential. The contribution to neutron antineutron oscillation in this model comes from the diagram in Fig. 1, which gives

\[ G_{N \leftrightarrow \bar{N}} \simeq \frac{g_3^2}{16 \pi^2} \frac{M_{SUSY} M_s}{f_{11}^2 v_{BL}^2} \]

which scales like $v_{BL}^{-3}$. There is also another pure Higgs diagram that involves the vertex $\bar{d}^c \bar{d}^c \Delta_{u \leftrightarrow c} \Delta_{c \leftrightarrow u}$ which also scales the same way and gives an identical contribution. This graph is the supersymmetric partner of Fig. 1. Note that for high scale seesaw models, these contributions to $G_{N \leftrightarrow \bar{N}}$ are considerably enhanced over that from the non-supersymmetric theory which goes like $v_{BL}^{-5}$.

In order to estimate the rate for $N \leftrightarrow \bar{N}$ oscillation, we need not only the different mass values for which we now have an order of magnitude, we also need the Yukawa coupling $f_{11}$. Now $f_{11}$ is a small number since its value is associated with the lightest right-handed neutrino mass. However, in the calculation we need its value in the basis where quark masses are diagonal. We note that the $N \leftrightarrow \bar{N}$ diagrams involve only the right-handed quarks, the rotation matrix need not be the CKM matrix. The right-handed rotations need to be large e.g. in order to involve $f_{33}$ (which is $O(1)$), we need $(V_{R}^{(u,c)})_{11}$ to be large,
where $V_L^{(u,d)} Y_{u,d} V_R^{(u,d)} = Y_{u,d}$. The left-handed rotation matrices $V_L^{(u,d)}$ contribute to the CKM matrix, but right-handed rotation matrices $V_R^{(u,d)}$ are unphysical in the standard model. In this model, however, we get to see its contribution since we have a left-right gauge symmetry as we will see later.

Let us now estimate the time of oscillation. When we start on a $f$-diagonal basis (call the diagonal matrix $f$), the Majorana coupling $f_{11}$ in the diagonal basis of up-and down-type quark matrices can be written as $(V_{qu}^q F V_{qu}^\dagger)_{11} \sim (V_{qu}^q)^2 f_{33}$. Now $f_{33}$ is $O(1)$ and $V_{qu}^q$ can be $\sim 0.6$, so $f_{11}$ is about 0.4 in the diagonal basis of the quark matrices. We use $M_{\text{SUSY}}, M_{\nu_{e}} \sim 350$ GeV and $v_{BL} \sim 10^{12}$ GeV. Due to the presence of the colored field the couplings become non-perturbative very soon beyond the $v_{BL}$, we therefore take $M_s \simeq 10^{13}$ GeV. The mass of $\Delta_{\pi-\nu}$ i.e. $M_{\pi-\nu}$ is $10^5$ GeV which is obtained from the VEV of $\Omega : (1,3,1)$. Putting all the above the numbers together, we get $G_{N \leftrightarrow \tilde{N}} \sim 1 \times 10^{-30}$ GeV$^{-5}$. Along with the hadronic matrix element $\tilde{H}$, the $N - \tilde{N}$ oscillation time is found to be about $2.5 \times 10^{10}$ sec which is within the reach of possible next generation measurements.

We also note that as noted in [3] the model is invariant under the hidden discrete symmetry under which a field $X \rightarrow e^{i \pi B_X} X$, where $B_X$ is the baryon number of the field $X$. As a result, proton is absolutely stable in the model.

**LEPTOGENESIS AND $N \leftrightarrow \tilde{N}$**

Since $N \leftrightarrow \tilde{N}$ oscillation is a low intermediate scale phenomenon, it is necessary to see how it affects the baryogenesis discussion. One could of course invoke weak scale baryogenesis, which would remain unaffected since it happen at the weak scale. Instead here we focus on lepto-ogenesis mechanism for origin of matter. The obvious problem here is that if leptoogenesis takes place at a scale where the $\Delta B = 2$ process is in thermal equilibrium, then the matter-antimatter asymmetry generated will be erased. So two questions must be answered within our model: (i) what is the temperature $T_D$ below which the $\Delta B = 2$ processes are out of equilibrium? and (ii) what constraints must be obeyed by the right-handed neutrino spectrum in the theory so that it will be possible to generate the lepton asymmetry below $T_D$? Clearly, $T_D$ must be above the weak scale so that the sphalerons can be effective in converting leptons to baryons.

To answer the first question, we compare the $\Delta B = 2$ reaction rate with the Hubble expansion. The diquark Higgs field $\Delta_{\mu \nu}$ remains at weak scale in the thermal bath, while $\Delta_{\nu e}$ decouple at high scale. The $\Delta B = 2$ process surviving till lowest temperature is $\Delta_{\mu \nu} \leftrightarrow b^c d^c b d$. The coupling of the interaction can be estimated as $G_{\Delta B = 2} = \frac{m_{\mu \nu}}{M_{\text{SUSY}}} \simeq 10^{-19}$ GeV$^{-2}$. The out of equilibrium condition of this process would be: $G_{\Delta B = 2} T^5 < g_s^{1/2} T^2 \frac{\Gamma_D}{3 M_{\nu}}$ which gives $T_D \simeq 10^7$ GeV. This implies that for leptoogenesis to work, at least one right-handed neutrino should be lighter than $10^7$ GeV. In fact in view of the low scale, we will need to invoke quasi-degenerate leptoogenesis [12], in the case of thermal leptoogenesis or one can also have the inflaton decaying into the two light right-handed neutrinos and the decay of the right-handed neutrinos would generate the required lepton asymmetry. In both these cases, the lighter right-handed neutrinos are almost degenerate to produce the correct amount of baryon asymmetry. Below, we give an example of the heavy right-handed neutrino as well as the Dirac neutrino mass texture as an example that leads to the correct neutrino mixings as well as a correct amount of baryons. We choose the Majorana neutrino coupling to the $\Delta s$ as:

$$f = \begin{pmatrix} 0 & x & 0 \\ x & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

(5)

where $x \sim 10^{-5}$ to have two right-handed neutrino around $10^7$ GeV, where the heaviest neutrino mass is $10^{12}$ GeV. The degeneracy has to be broken, however, since we need $|M_{N_1} - M_{N_2}| \geq \Gamma_{N_1} + \Gamma_{N_2}$, where $M_{N_1}$ and $\Gamma_N$ are masses and decay widths of right-handed neutrinos, respectively. Thus, we need small perturbation in 11 and 22 elements. The formula for lepton asymmetry is:

$$\epsilon_i \simeq \frac{1}{8 \pi} \frac{1}{(\lambda^D_{\nu} \lambda^D_{\nu'})_{ii}} \sum_{k \neq i} \text{Im} (\lambda^D_{\nu} \lambda^D_{\nu'})_{ik} F \left( \frac{M_{N_k}}{M_{N_i}} \right),$$

(6)

where the neutrino Dirac Yukawa coupling $\lambda^D_{\nu}$ in this expression is given in the basis where the right-handed Majorana neutrino mass matrix is diagonal. We choose the following Dirac neutrino coupling (which generates the correct neutrino masses using type I seesaw)

$$\lambda^D_{\nu} = \begin{pmatrix} 1 \times 10^{-6} & 3 \times 10^{-5} & 0.026 \\ 5 \times 10^{-6} & 5 \times 10^{-6} & 0.026 \\ 0.00031 & 0.00031 & -0.013 \end{pmatrix},$$

where we have omitted phases of order one. The asymmetry generated by this texture needs to be multiplied by the efficiency factor $\epsilon_i$. For quasi degenerate right-handed neutrinos, one gets $F \left( \frac{M_{N_k}}{M_{N_i}} \right) \simeq \frac{M_{N_k}}{M_{N_1} - M_{N_2}}$. As a result, there is an enhancement factor for the lepton asymmetry depending on the mass difference which is a parameter in this model. The decay parameter $K_{i} (\equiv \Gamma_{i}/2\hbar)$, where $\Gamma_i$ is the decay width of the heavy Majorana neutrino, is large; for example, $K_{i} \propto (\lambda^D_{\nu} \lambda^D_{\nu'})_{ii}/M_{N_{1,2}}$ for above choice of $\lambda^D$ and $M_{N_{1,2}}$ around $10^7$ GeV, $K_{i} \simeq 10^2$ or smaller.

Our model has several interesting phenomenological consequences both for colliders and rare decays for up-type quarks. For instance, since our diquark Higgs
bosons and their superpartners have masses in the few hundred GeV range, they should be produced at LHC, possibly at Tevatron. The production can happen singly or in pairs via parton processes such as $\bar{q} + q \to \Delta_{u'}^c u$, $q + \bar{q} \to \Delta_{u'}^c \Delta_{u'}^c etc.$ These new Higgs boson and its superpartners can decay into two charm, up quarks, top quarks should provide a good signal. At the LHC, the signal from a pair production may contain the following final states: 4 charm quarks, 2 top-2 charm quarks, 4 top quarks etc. The fermionic partner of these diquark Higgs, however, would produce missing energy in the final states. The single production will produce a change in the top quark pair production. A detailed study is underway. A second interesting consequence is that in the mass eigenstate basis for quarks, the light $\Delta_{u'}^c$ will mediate flavor changing processes such as $D \to \pi\pi$, $t \to c + G$ etc. The present bounds on charm changing processes is consistent with the value of the diquark Higgs boson mass that has been used in the paper.

**CONCLUSION**

In conclusion, we have presented a quark-lepton unified model where despite the high seesaw ($v_{BL}$) scale in the range of $\sim 10^{12}$ GeV, the $N - \bar{N}$ oscillation time is around $10^{10}$ sec. due to the presence of a new supersymmetric graph and accidental symmetries of the Higgs potential (also connected to supersymmetry). No unnatural fine tuning of diquark masses is needed to get such an enhanced effect. Our predicted oscillation time is within the reach of possible future experiments. We believe that this work should provide a new motivation to conduct a new round of search for $N - \bar{N}$ oscillation. To show that this is a completely realistic model, we note that (i) the proton is absolutely stable in this model; (ii) the model can provide a realistic description of known quark and lepton physics as well as (iii) a way to generate an adequate lepton asymmetry via the mechanism of quasi-degenerate leptogenesis.

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