Simplified models with baryon number violation but no proton decay

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We enumerate the simplest models that have baryon number violation at the classical level but do not give rise to proton decay. These models have scalar fields in two representations of $SU(3) \times SU(2) \times U(1)$ and violate baryon number by two units. Some of the models give rise to $n\bar{n}$ (neutron-antineutron) oscillations, while some also violate lepton number by two units. We discuss the range of scalar masses for which $n\bar{n}$ oscillations are measurable in the next generation of experiments. We give a brief overview of the phenomenology of these models and then focus on one of them for a more quantitative discussion of $n\bar{n}$ oscillations, the generation of the cosmological baryon number, the electric dipole moment of the neutron, and K^0-$\bar{K}^0$ mixing.

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I. INTRODUCTION

The standard model has nonperturbative violation of baryon number (B). This source of baryon number nonconservation also violates lepton number (L); however, it conserves baryon number minus lepton number ($B - L$). The violation of baryon number by nonperturbative weak interactions is important at high temperatures in the early universe but it has negligible impact on laboratory experiments that search for baryon number violation and we neglect it in this paper. If we add massive right-handed neutrinos that have a Majorana mass term and Yukawa couple to the standard model left-handed neutrinos, then lepton number is violated by two units, $|\Delta L| = 2$, at tree level in the standard model.

Motivated by grand unified theories (GUT) there has been an ongoing search for proton decay (and bound neutron decay). The limits on possible decay modes are very strong. For example, the lower limit on the partial mean lifetime for the mode $p \to e^+\pi^0$ is 8.2×10^{33} yr [1]. All proton decays violate baryon number by one unit and lepton number by an odd number of units. See Ref. [2] for a review of proton decay in extensions of the standard model.

There are models where baryon number is violated but proton (and bound neutron) decay does not occur. This paper is devoted to finding the simplest models of this type and discussing some of their phenomenology. We include all renormalizable interactions allowed by the $SU(3) \times SU(2) \times U(1)$ gauge symmetry. In addition to standard model fields these models have scalar fields $X_{1,2}$ that couple to quark bilinear terms or lepton bilinear terms. Baryon number violation either occurs through trilinear scalar interactions of the type (i) $X_2X_1X_1$ or quartic scalar terms of the type (ii) $X_2X_1X_1X_1$. The cubic scalar interaction in (i) is similar in structure to renormalizable terms in the superpotential that give rise to baryon number violation in supersymmetric extensions of the standard model. However, in our case the operator is dimension three and is in the scalar potential. Assuming no right-handed neutrinos there are four models of type (i) where each of the X's couples to quark bilinears and has baryon number $-2/3$. Hence in this case the X's are either color **3** or $\bar{\mathbf{6}}$. There are also five models of type (ii) where X_1 is a color **3** or $\bar{\mathbf{6}}$ with baryon number $-2/3$ that couples to quark bilinears and X_2 is a color singlet with lepton number -2 that couples to lepton bilinears.

We analyze one of the models in more detail. In that model the $SU(3) \times SU(2) \times U(1)$ quantum numbers of the new colored scalars are $X_1 = (\bar{6}, 1, -1/3)$ and $X_2 = (\bar{6}, 1, 2/3)$. The $n\bar{n}$ oscillation frequency is calculated using the vacuum insertion approximation for the required hadronic matrix element and lattice QCD results. For dimensionless coupling constants equal to unity and all mass parameters equal, the present absence of observed $\bar{n}n$ oscillations provides a lower limit on the scalar masses of around 500 TeV. If we consider the limit $M_1 \ll M_2$ then for $M_1 = 5$ TeV the next generation of $n\bar{n}$ oscillation experiments will be sensitive to M_2 masses at the GUT scale.

There are three models that have $n\bar{n}$ mixing at tree level without proton decay. In these models, constraints on flavor changing neutral currents and the electric dipole moment (edm) of the neutron require some very small dimensionless coupling constants if we are to have both observable $n\bar{n}$ oscillations and one of the scalar masses approaching the GUT scale.

In the next section we enumerate the models and discuss their basic features. The phenomenology of one of the models is discussed in more detail in Sec. III. Some concluding remarks are given in Sec. IV.

II. THE MODELS

We are looking for the simplest models which violate baryon number but don't induce proton decay. We don't impose any global symmetries. Hence, all local renormalizable interactions permitted by Lorentz and gauge invariance

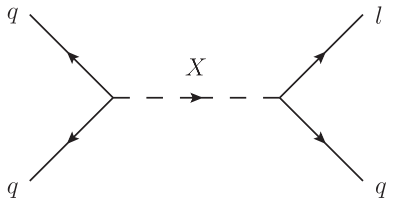

FIG. 1. $\Delta B = 1$ and $\Delta L = 1$ scalar exchange.

are assumed to be present. We begin by considering renormalizable scalar couplings with all possible standard model fermion bilinears. A similar philosophy can be used to construct models involving proton decay [3] or baryon number violating interactions in general [4,5]. We first eliminate any scalars which produce proton decay via tree-level scalar exchange as in Fig. 1. In particular, this eliminates the scalars with $SU(3) \times SU(2) \times U(1)$ quantum numbers $(3, 1, -1/3)$, $(3, 3, -1/3)$, and $(3, 1, -4/3)$. Note that in the case of $(3, 1, -4/3)$ we need an additional W-boson exchange to get proton decay (Fig. 2) since the Yukawa coupling to right-handed charge 2/3 quarks is antisymmetric (for a detailed discussion see Ref. [6]). The remaining possible scalar representations and Yukawa couplings are listed in Table I. We have assumed there are no right-handed neutrinos (ν_R) in the theory.

None of these scalars induce baryon number violation on their own, so we consider minimal models with the requirement that only two unique sets of scalar quantum numbers from Table I are included, though a given set of quantum numbers may come with multiple scalars.

Baryon number violation will arise from terms in the scalar potential, so we need to take into account just the models whose scalar quantum numbers are compatible in the sense that they allow scalar interactions that violate baryon number. For scalars coupling to standard model fermion bilinears there are three types of scalar interactions which may violate baryon number: 3-scalar $X_1X_1X_2$, 4-scalar $X_1X_1X_1X_2$, and 3-scalar with a Higgs $X_1X_1X_1H$ or $X_1X_1X_2H$, where the Higgs gets a vacuum expectation value (Fig. 3).

Actually, the simplest possible model violating baryon number through the interaction $X_1X_1X_1H$ includes just one new scalar $(\bar{3}, 2, -1/6)$, but it gives proton decay via $p \to \pi^+\pi^+e^-\nu\nu$ (Fig. 4). Note that a similar diagram with $\langle H \rangle$

TABLE I. Possible interaction terms between the scalars and fermion bilinears along with the corresponding quantum numbers and B and L charges of the X field. Representations labeled with the subscript "PD" allow for proton decay via either tree-level scalar exchange (Fig. 1) or 3-scalar interactions involving the Higgs vacuum expectation value (Fig. 4).

Operator	$SU(3) \times SU(2) \times U(1)$ rep. of X	B	L
XQQ, Xud	$(\bar{6}, 1, -1/3)$, $(3, 1, -1/3)_{\rm PD}$	$-2/3$	0
XQQ	$(\bar{6}, 3, -1/3)$, $(3, 3, -1/3)_{\rm PD}$	$-2/3$	0
Xdd	$(3, 1, 2/3)$, $(\bar{6}, 1, 2/3)$	$-2/3$	0
Xuu	$(\bar{6}, 1, -4/3)$, $(3, 1, -4/3)_{\rm PD}$	$-2/3$	0
$X\bar{Q}\bar{L}$	$(3, 1, -1/3)_{\rm PD}$, $(3, 3, -1/3)_{\rm PD}$	$1/3$	1
$X\bar{u}\bar{e}$	$(3, 1, -1/3)_{\rm PD}$	$1/3$	1
$X\bar{d}\bar{e}$	$(3, 1, -4/3)_{\rm PD}$	$1/3$	1
$X\bar{Q}e$, $XL\bar{u}$	$(3, 2, 7/6)$	$1/3$	-1
$X\bar{L}d$	$(\bar{3}, 2, -1/6)_{\rm PD}$	$-1/3$	1
XLL	$(1, 1, 1)$, $(1, 3, 1)$	0	-2
Xee	$(1, 1, 2)$	0	-2

replaced by X_2 allows us to ignore scalars with the same electroweak quantum numbers as the Higgs and coupling to $\bar{Q}u$ and $\bar{Q}d$, $X_2 = (1, 2, 1/2)$ and $(8, 2, 1/2)$, as these will produce tree-level proton decay as well. The other two baryon number violating models with an interaction term $X_1X_1X_2H$ are $X_1^* = (3, 1, -1/3)$, $X_2 = (\bar{3}, 2, -7/6)$ and $X_1 = (3, 1, -1/3)$, $X_2^* = (\bar{3}, 2, -1/6)$. As argued earlier, such quantum numbers for X_1 also induce tree-level proton decay, so we disregard them.

We now consider models with a 3-scalar interaction $X_1X_1X_2$. A straightforward analysis shows that there are only four models which generate baryon number violation via a 3-scalar interaction without proton decay. We enumerate them and give the corresponding Lagrangians below. All of these models give rise to processes with $\Delta B = 2$ and $\Delta L = 0$, but only the first three models contribute to $n\bar{n}$ oscillations at tree level due to the symmetry properties of the Yukawas. Note that a choice of normalization for the sextet given by

$$(X^{\alpha\beta}) = \begin{pmatrix} \tilde{X}^{11} & \tilde{X}^{12}/\sqrt{2} & \tilde{X}^{13}/\sqrt{2} \\ \tilde{X}^{12}/\sqrt{2} & \tilde{X}^{22} & \tilde{X}^{23}/\sqrt{2} \\ \tilde{X}^{13}/\sqrt{2} & \tilde{X}^{23}/\sqrt{2} & \tilde{X}^{33} \end{pmatrix} \tag{1}$$

leads to canonically normalized kinetic terms for the elements $\tilde{X}^{\alpha\beta}$ and the usual form of the scalar propagator

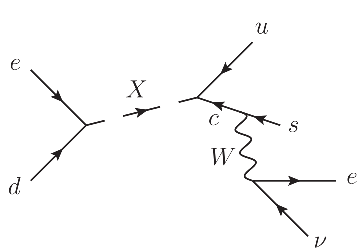

FIG. 2. Feynman diagram that contributes to tree level $p \to K^+e^+e^-\bar{\nu}$ from $(3, 1, -4/3)$ scalar exchange.

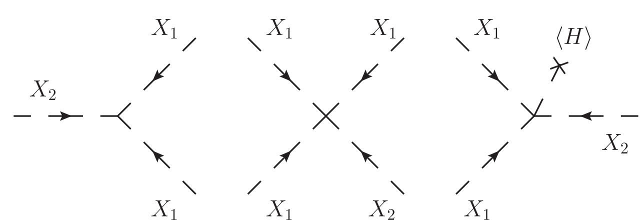

FIG. 3. Scalar interactions which may generate baryon number violation.

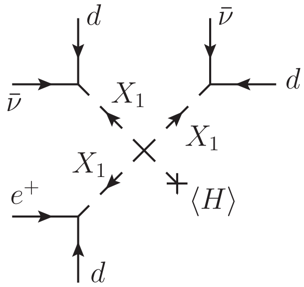

FIG. 4. Interaction which leads to proton decay, $p \rightarrow \pi^+\pi^+e^-\nu\nu$, for $X_1 = (\bar{3}, 2, -1/6)$.

with symmetrized color indices. Unless otherwise stated, we will be using two-component spinor notation. Parentheses indicate contraction of two-component spinor indices to form a Lorentz singlet.

Model 1. $X_1 = (\bar{6}, 1, -1/3)$, $X_2 = (\bar{6}, 1, 2/3)$,

$$\mathcal{L} = -g_1^{ab} X_1^{\alpha\beta}(Q_{L\alpha}^a \epsilon Q_{L\beta}^b) - g_2^{ab} X_2^{\alpha\beta}(d_{R\alpha}^a d_{R\beta}^b) - g_1'^{ab} X_1^{\alpha\beta}(u_{R\alpha}^a d_{R\beta}^b) + \lambda X_1^{\alpha\alpha'} X_1^{\beta\beta'} X_2^{\gamma\gamma'} \epsilon_{\alpha\beta\gamma}\epsilon_{\alpha'\beta'\gamma'}. \tag{2}$$

By virtue of the symmetric color structure of the $\bar{\mathbf{6}}$ representation and the antisymmetric weak structure of the QQ bilinear in the first term, g_1 must be antisymmetric in flavor. However, this antisymmetry is not retained upon rotation into the mass eigenstate basis. Similarly, g_2 must be symmetric because of the symmetric color structure in the second term. In this case, the symmetry character of g_2 will be retained upon rotation into the mass eigenstate basis because it involves quarks of the same charge. Therefore, the interaction involving the Yukawa coupling g_2 gives rise to (and is thus constrained by) K^0-$\bar{K}^0$ mixing through tree-level X_2 exchange. The coupling g_1' has no particular flavor symmetry.

Model 2. $X_1 = (\bar{6}, 3, -1/3)$, $X_2 = (\bar{6}, 1, 2/3)$,

$$\mathcal{L} = -g_1^{ab} X_1^{\alpha\beta A}(Q_{L\alpha}^a \epsilon\tau^A Q_{L\beta}^b) - g_2^{ab} X_2^{\alpha\beta}(d_{R\alpha}^a d_{R\beta}^b) + \lambda X_1^{\alpha\alpha' A} X_1^{\beta\beta' A} X_2^{\gamma\gamma'} \epsilon_{\alpha\beta\gamma}\epsilon_{\alpha'\beta'\gamma'}. \tag{3}$$

Here the matrix $\epsilon\tau^A$ is symmetric. Because the first and second terms have symmetric color structures, g_1 and g_2 must be symmetric in flavor. The weak triplet X_1 has components which introduce both K^0-$\bar{K}^0$ and D^0-$\bar{D}^0$ mixing. As in model 1, the interaction involving g_2 will introduce K^0-$\bar{K}^0$ mixing via X_2 exchange.

Model 3. $X_1 = (\bar{6}, 1, 2/3)$, $X_2 = (\bar{6}, 1, -4/3)$,

$$\mathcal{L} = -g_1^{ab} X_1^{\alpha\beta}(d_{R\alpha}^a d_{R\beta}^b) - g_2^{ab} X_2^{\alpha\beta}(u_{R\alpha}^a u_{R\beta}^b) + \lambda X_1^{\alpha\alpha'} X_1^{\beta\beta'} X_2^{\gamma\gamma'} \epsilon_{\alpha\beta\gamma}\epsilon_{\alpha'\beta'\gamma'}. \tag{4}$$

Both terms have symmetric color structures and no weak structure, so g_1 and g_2 must be symmetric in flavor. In this model, the interactions involving g_1 and g_2 each have the potential to introduce neutral meson-antimeson mixing. For example, the g_1 interaction will induce K^0-$\bar{K}^0$ mixing while g_2 will induce D^0-$\bar{D}^0$ mixing.

Model 4. $X_1 = (3, 1, 2/3)$, $X_2 = (\bar{6}, 1, -4/3)$,

$$\mathcal{L} = -g_1^{ab} X_{1\alpha}(d_{R\beta}^a d_{R\gamma}^b)\epsilon^{\alpha\beta\gamma} - g_2^{ab} X_2^{\alpha\beta}(u_{R\alpha}^a u_{R\beta}^b) + \lambda X_{1\alpha} X_{1\beta} X_2^{\alpha\beta}. \tag{5}$$

Because of the antisymmetric color structure in the first term, g_1 must be antisymmetric in flavor which prevents it from introducing meson-antimeson mixing. The antisymmetric structure of g_1 also prevents the existence of six-quark operators involving all first-generation quarks, and thus prevents $n\bar{n}$ oscillations. As in previous models, g_2 is symmetric and so we will get D^0-$\bar{D}^0$ mixing as in model 3. Although this model does not have $n\bar{n}$ oscillations, there are still baryon number violating processes which would constrain this model—for example, the process $pp \rightarrow K^+K^+$. This has been searched using the Super-Kamiokande detector looking for the nucleus decay $^{16}O \rightarrow {}^{14}CK^+K^+$ [7]. Had we included ν_R, model 4 would have been excluded by tree-level scalar exchange.

Now, a similar line of reasoning applies to the case where we have a quartic scalar interaction term $X_1X_1X_1X_2$. The only models violating baryon number which don't generate proton decay (or bound neutron decay) are discussed briefly below. These last five models have dinucleon decay to leptons, but don't contribute to tree-level $n\bar{n}$ oscillations by virtue of their coupling to leptons.

Model 5. $X_1 = (\bar{6}, 1, -1/3)$, $X_2 = (1, 1, 1)$,

$$\mathcal{L} = -g_1^{ab} X_1^{\alpha\beta}(Q_{L\alpha}^a \epsilon Q_{L\beta}^b) - g_2^{ab} X_2(L_L^a \epsilon L_L^b) - g_1'^{ab} X_1^{\alpha\beta}(u_{R\alpha}^a d_{R\beta}^b) + \lambda X_1^{\alpha\alpha'} X_1^{\beta\beta'} X_1^{\gamma\gamma'} X_2 \epsilon_{\alpha\beta\gamma}\epsilon_{\alpha'\beta'\gamma'}. \tag{6}$$

Similar arguments to those for the previous models tell us that g_1 and g_2 must be antisymmetric in flavor.

Model 6. $X_1 = (\bar{6}, 3, -1/3)$, $X_2 = (1, 1, 1)$

$$\mathcal{L} = -g_1^{ab} X_1^{\alpha\beta A}(Q_{L\alpha}^a \epsilon\tau^A Q_{L\beta}^b) - g_2^{ab} X_2(L_L^a \epsilon L_L^b) + \lambda X_1^{\alpha\alpha' A} X_1^{\beta\beta' B} X_1^{\gamma\gamma' C} X_2 \epsilon^{ABC} \epsilon_{\alpha\beta\gamma}\epsilon_{\alpha'\beta'\gamma'}. \tag{7}$$

By comparison with model 2, we see that g_1 is symmetric in flavor while g_2 is antisymmetric.

Model 7. $X_1 = (\bar{6}, 3, -1/3)$, $X_2 = (1, 3, 1)$,

$$\mathcal{L} = -g_1^{ab} X_1^{\alpha\beta A}(Q_{L\alpha}^a \epsilon\tau^A Q_{L\beta}^b) - g_2^{ab} X_2^A(L_L^a \epsilon\tau^A L_L^b) + \lambda X_1^{\alpha\alpha' A} X_1^{\beta\beta' B} X_1^{\gamma\gamma' C} X_2^D \epsilon_{\alpha\beta\gamma}\epsilon_{\alpha'\beta'\gamma'} \times (\delta^{AB}\delta^{CD} + \delta^{AC}\delta^{BD} + \delta^{AD}\delta^{BC}). \tag{8}$$

Once again, as in model 2, we have a symmetric g_1. The coupling g_2 must be symmetric in flavor as well.

Model 8. $X_1 = (\bar{6}, 1, 2/3)$, $X_2 = (1, 1, -2)$,

$$\mathcal{L} = -g_1^{ab} X_1^{\alpha\beta}(d^a_{R\alpha} d^b_{R\beta}) - g_2^{ab} X_2 (e^a_R e^b_R) + \lambda X_1^{\alpha\alpha'} X_1^{\beta\beta'} X_1^{\gamma\gamma'} X_2 \epsilon_{\alpha\beta\gamma}\epsilon_{\alpha'\beta'\gamma'}. \tag{9}$$

As in model 1, g_1 must be symmetric. The coupling g_2 must also be symmetric in flavor.

Model 9. $X_1 = (3, 1, 2/3)$, $X_2 = (1, 1, -2)$,

$$\mathcal{L} = -g_1^{ab} X_{1\alpha}(d^a_{R\beta} d^b_{R\gamma})\epsilon^{\alpha\beta\gamma} - g_2^{ab} X_2 (e^a_R e^b_R) + \lambda X_{1\alpha} X_{1\beta} X_{1\gamma} X_2 \epsilon^{\alpha\beta\gamma}. \tag{10}$$

By comparison with model 4, we see that g_1 must be antisymmetric in flavor. The coupling g_2 is symmetric. Note that the antisymmetric color structure of the scalar interaction requires the existence of at least three different kinds of X_1 scalars for this coupling to exist. Including ν_R would eliminate model 9 for the same reason as model 4.

III. PHENOMENOLOGY OF MODEL 1

In this section we present a detailed analysis of model 1. The corresponding calculations for the other models can be performed in a similar manner. Our work is partly motivated by the recently proposed $n\bar{n}$ oscillation experiment with increased sensitivity [8]. In addition to $n\bar{n}$ oscillations, we analyze also the cosmological baryon asymmetry generation in model 1 as well as flavor and electric dipole moment constraints. A brief comment on LHC phenomenology is made.

A. Neutron-antineutron oscillations

The topic of $n\bar{n}$ oscillations has been explored in the literature in various contexts. For some of the early works on the subject see Refs. [9–12]. Recently, a preliminary study of the required hadronic matrix elements using lattice QCD has been carried out [13]. Reference [14] claims that a signal of $n\bar{n}$ oscillations has been observed.

The scalar content of model 1 we are considering is similar to the content of a unified model explored in Ref. [15]. The transition matrix element,

$$\Delta m = \langle \bar{n} | \mathcal{H}_{\rm eff} | n \rangle, \tag{11}$$

leads to a transition probability for a neutron at rest to change into an antineutron after time t equal to $P_{n\to\bar{n}}(t) = \sin^2(|\Delta m| t)$.

Neglecting the coupling g_1 in the Lagrangian (2) (for simplicity) the effective $|\Delta B| = 2$ Hamiltonian that causes $n\bar{n}$ oscillations is

$$\mathcal{H}_{\rm eff} = -\frac{(g_1'^{11})^2 g_2^{11}\lambda}{4M_1^4 M_2^2} d^{\dot\alpha}_{Ri} d^{\dot\beta}_{Ri'} u^{\dot\gamma}_{Rj} d^{\dot\delta}_{Rj'} u^{\dot\lambda}_{Rk} d^{\dot\chi}_{Rk'} \epsilon_{\dot\alpha\dot\beta}\epsilon_{\dot\gamma\dot\delta}\epsilon_{\dot\lambda\dot\chi} \times (\epsilon_{ijk}\epsilon_{i'j'k'} + \epsilon_{i'jk}\epsilon_{ij'k'} + \epsilon_{ij'k}\epsilon_{i'jk'} + \epsilon_{ijk'}\epsilon_{i'j'k}) + \text{H.c.}, \tag{12}$$

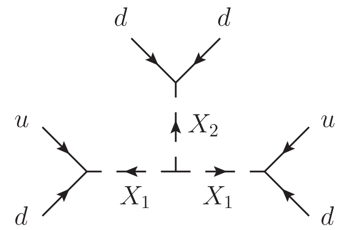

FIG. 5. Interaction which leads to neutron-antineutron oscillations.

where Latin indices are color and Greek indices are spinor. It arises from the tree-level diagram in Fig. 5 (see, for example Ref. [16]). We have rotated the couplings g_1' and g_2 to the quark mass eigenstate basis and adopted a phase convention where λ is real and positive. We estimate Δm using the vacuum insertion approximation [17]. This relates the required $n\bar{n}$ six-quark matrix element to a matrix element from the neutron to the vacuum of a three quark operator. The later matrix element is relevant for proton decay and has been determined using lattice QCD methods. The general form of the required hadronic matrix elements is

$$\langle 0 | d^{\dot\alpha}_{Ri} d^{\dot\beta}_{Rj} u^{\dot\gamma}_{Rk} | n(p,s)\rangle = -\frac{1}{18}\beta\epsilon_{ijk}(\epsilon^{\dot\alpha\dot\gamma} u^{\dot\beta}_R(p,s) + \epsilon^{\dot\beta\dot\gamma} u^{\dot\alpha}_R(p,s)). \tag{13}$$

Here u_R is the right-handed neutron two-component spinor and the Dirac equation was used to remove the term proportional to the left-handed neutron spinor. The constant β was determined using lattice methods in Ref. [18] to have the value $\beta \simeq 0.01\ \text{GeV}^3$. In the vacuum insertion approximation to Eq. (11) we find

$$|\Delta m| = 2\lambda\beta^2 \frac{|(g_1'^{11})^2 g_2^{11}|}{3M_1^4 M_2^2}. \tag{14}$$

We note that an analogous calculation using the MIT bag model was performed in Ref. [19] and yields a similar result. The current experimental limit on Δm is [20]

$$|\Delta m| < 2\times 10^{-33}\ \text{GeV}. \tag{15}$$

For scalars of equal mass, $M_1 = M_2 \equiv M$, and the values of the couplings $g_1'^{11} = g_2^{11} = 1$, $\lambda = M$, one obtains

$$M \gtrsim 500\ \text{TeV}. \tag{16}$$

If, instead, the masses form a hierarchy, the effect on $n\bar{n}$ oscillations is maximized if we choose $M_2 > M_1$. Assuming $M_1 = 5$ TeV (above the current LHC reach) and $\lambda = M_2$ this yields

$$M_2 \gtrsim 5\times 10^{13}\ \text{GeV}. \tag{17}$$

Note that $\lambda = M_2$ is a reasonable value for this coupling since integrating out M_2 then gives a quartic X_1 interaction term with a coupling on the order of one. Of course, this model does have a hierarchy problem so having the Higgs scalar and the X_1 light compared with X_2 requires fine-tuning.

Experiments in the future [8] may be able to probe $n\bar{n}$ oscillations with increased sensitivity of $|\Delta m| \simeq 7 \times 10^{-35}$ GeV. If no oscillations are observed, the new limit in the case of equal masses will be

$$M \gtrsim 1000 \text{ TeV}. \tag{18}$$

On the other hand, having $M_1 = 5$ TeV would push the mass of the heavier scalar up to the GUT scale, leading to the following constraint on the second scalar mass:

$$M_2 \gtrsim 1.5 \times 10^{15} \text{ GeV}. \tag{19}$$

We note, however, that in Sec. III B we show that M_1 on the order of a few TeV is disfavored by the electric dipole moment constraints.

B. LHC, flavor and electric dipole moment constraints

If the mass of the scalar X_1 is small enough, it can be produced at the LHC through both single and pair production. Detailed analyses have been performed setting limits on the mass of X_1 from such processes [21–23]. A recent simulation [21] shows that 100 fb^{-1} of data from the LHC running at 14 TeV center of mass energy can be used to rule out or claim a discovery of X_1 scalars with masses only up to approximately 1 TeV, even when the couplings to quarks are of order 1. Our earlier choice of $M_1 = 5$ TeV used to estimate the constraint on M_2 from $n\bar{n}$ oscillations lies well within the allowed mass region.

Some of the most stringent flavor constraints on new scalars come from neutral meson mixing and electric dipole moments. The fact that in model 1 X_1 couples directly to both left- and right-handed quarks means that at one loop the top quark mass can induce the chirality flip necessary to give a light quark edm, putting strong constraints on this model even when X_1 is at the 100 TeV scale. The diagram contributing to the edm of the down quark is given in Fig. 6. We find

$$|d_d| \simeq \frac{m_t}{6\pi^2 M_1^2} \log\left(\frac{M_1^2}{m_t^2}\right) |\mathrm{Im}[g_1^{31}(g_1'^{31})^*]| e \text{ cm}. \tag{20}$$

Here we have neglected pieces not logarithmically enhanced. This will give the largest contribution to the neutron edm because of the top quark mass factor. All Yukawa couplings in this section are in the mass eigenstate basis.

Using $SU(6)$ wave functions, this can be related to the neutron edm via $d_n = \frac{4}{3} d_d - \frac{1}{3} d_u \simeq \frac{4}{3} d_d$. The present experimental limit is [24]

$$d_n^{\text{exp}} < 2.9 \times 10^{-26} e \text{ cm}. \tag{21}$$

Assuming $M_1 = 500$ TeV, neutron edm measurements imply the bound $|\mathrm{Im}[g_1^{31}(g_1'^{31})^*]| \lesssim 6 \times 10^{-3}$. Furthermore, for observable $n\bar{n}$ oscillation effects with M_2 being close to the GUT scale we need $M_1 \approx 5$ TeV. In such a scenario the edm constraint requires $|\mathrm{Im}[g_1^{31}(g_1'^{31})^*]| \lesssim 10^{-6}$.

Another important constraint on the parameters of model 1 is provided by K^0-$\bar{K}^0$ mixing. Integrating out X_2 generates an effective Hamiltonian,

$$\begin{aligned} \mathcal{H}_{\text{eff}} &= \frac{g_2^{22}(g_2^{11})^*}{M_2^2} (s_{R\alpha} s_{R\beta})(d_R^{*\alpha} d_R^{*\beta}) \\ &\to \frac{g_2^{22}(g_2^{11})^*}{2M_2^2} (\bar{d}_R^{\alpha} \gamma^\mu s_{R\alpha})(\bar{d}_R^{\alpha} \gamma_\mu s_{R\alpha}), \end{aligned} \tag{22}$$

where in the second line we have gone from two- to four-component spinor notation. This gives the following constraints on the couplings [25]:

$$|\mathrm{Re}[g_2^{22}(g_2^{11})^*]| < 1.8 \times 10^{-6} \left(\frac{M_2}{1 \text{ TeV}}\right)^2, \tag{23}$$

$$|\mathrm{Im}[g_2^{22}(g_2^{11})^*]| < 6.8 \times 10^{-9} \left(\frac{M_2}{1 \text{ TeV}}\right)^2. \tag{24}$$

If we set M_2 to 500 TeV, this corresponds to an upper bound on the real and imaginary parts of $g_2^{22}(g_2^{11})^*$ of 0.45 and 1.7×10^{-3}, respectively.

C. Baryon asymmetry

We now investigate baryon number generation in model 1. B and L violating processes in cosmology have

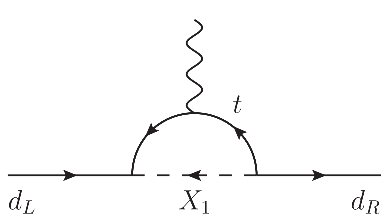

FIG. 6. Diagrams contributing to the electric dipole moment of the down quark.

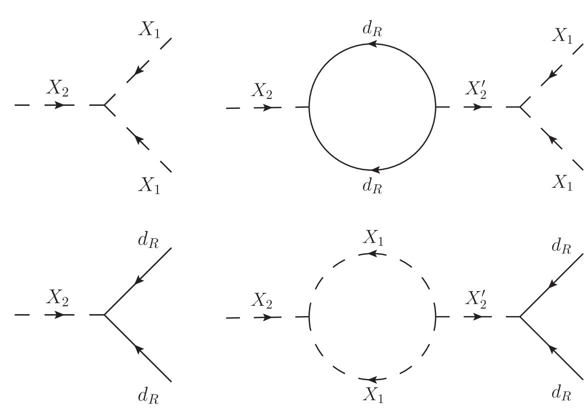

FIG. 7. Diagrams corresponding to the decay of X_2. The diagrams on top contribute to the $\Delta B = 2$ decays, while the diagrams on bottom contribute to $\Delta B = 0$.

been studied in the literature in great detail (for early works, see Refs. [26,27]). We treat X_2 as much heavier than X_1 and use two different X_2's to get a CP violating phase in the one-loop diagrams that generate the baryon asymmetry. For this calculation X_1 is treated as stable with baryon number $-2/3$ as each will eventually decay via baryon number conserving processes to two antiquarks. To simplify our discussion, let's consider the case in which the couplings satisfy the hierarchy λ, $\tilde{\lambda} \ll g_2$, $\tilde{g}_2$. The top line of Fig. 7 shows the dominant tree-level and one-loop diagrams contributing to the baryon number violating decays of X_2. Rotating the X fields to make the couplings λ and $\tilde{\lambda}$ real we find

$$\begin{aligned}\Gamma(X_2 \to \bar{X}_1\bar{X}_1) &= \frac{3\lambda}{8\pi M_2}\left[\lambda - \tilde{\lambda}\frac{M_2^2}{4\pi(M_2^2 - \tilde{M}_2^2)}\,\mathrm{Im}(\mathrm{Tr}(g_2^\dagger \tilde{g}_2))\right],\\ \Gamma(\bar{X}_2 \to X_1X_1) &= \frac{3\lambda}{8\pi M_2}\left[\lambda + \tilde{\lambda}\frac{M_2^2}{4\pi(M_2^2 - \tilde{M}_2^2)}\,\mathrm{Im}(\mathrm{Tr}(g_2^\dagger \tilde{g}_2))\right]. \end{aligned} \quad (25)$$

The net baryon number produced per $X_2\bar{X}_2$ pair is (see, Table II)

$$\begin{aligned}\Delta n_B &= 2(r - \bar{r})\\ &= \frac{6}{\pi\,\mathrm{Tr}(g_2^\dagger g_2)}\,\frac{1}{\tilde{M}_2^2 - M_2^2}\,\mathrm{Im}[\lambda\tilde{\lambda}^*\,\mathrm{Tr}(g_2^\dagger \tilde{g}_2)], \end{aligned} \quad (26)$$

where we have used the fact that CPT invariance guarantees the total width of X_2 and $\bar{X}_2$ are the same. Given our choice of hierarchy for the couplings, we have approximated the total width as coming from the tree-level decay of X_2 to antiquarks. A similar result in the context of $SO(10)$ models was obtained in Ref. [15].

Even with just one generation of quarks, the CP violating phase cannot be removed from the couplings λ, $\tilde{\lambda}$, g_2, $\tilde{g}_2$ and a baryon asymmetry can be generated at one loop. At first glance this is surprising since there are four fields, X_2, $\tilde{X}_2$, X_1 and d_R whose phases can be redefined and four relevant couplings. However, this can be understood by looking at the relevant Lagrangian terms, g_2X_2dd, $\tilde{g}_2\tilde{X}_2dd$, $\lambda X_1X_1X_2$ and $\tilde{\lambda}X_1X_1\tilde{X}_2$. The problem reduces to finding solutions to the following matrix equation:

TABLE II. Branching ratios and final state baryon numbers for the decays of X_2 and $\bar{X}_2$ which contribute to the baryon asymmetry in the coupling hierarchy λ, $\tilde{\lambda} \ll g_2$, $\tilde{g}_2$.

Decay	Br	B_f
$X_2 \to \bar{X}_1\bar{X}_1$	r	$4/3$
$X_2 \to \bar{d}_R\bar{d}_R$	$1 - r$	$-2/3$
$\bar{X}_2 \to X_1X_1$	$\bar{r}$	$-4/3$
$\bar{X}_2 \to d_Rd_R$	$1 - \bar{r}$	$2/3$

$$\begin{pmatrix} 2 & 1 & 0 & 0\\ 2 & 0 & 1 & 0\\ 0 & 1 & 0 & 2\\ 0 & 0 & 1 & 2\end{pmatrix}\begin{pmatrix}\phi_{X_1}\\ \phi_{X_2}\\ \phi_{\tilde{X}_2}\\ \phi_d\end{pmatrix} = \begin{pmatrix}\phi_\lambda\\ \phi_{\tilde{\lambda}}\\ \phi_{g_2}\\ \phi_{\tilde{g}_2}\end{pmatrix}, \quad (27)$$

where the phases on the right-hand side are arbitrary. Let us take the difference of the first two equations to remove phases for the couplings λ and $\tilde{\lambda}$, and the difference of the last two equations to remove phases for the coupling g_2, $\tilde{g}_2$. We therefore obtain $\phi_{\tilde{\lambda}_2} - \phi_{\lambda_2} = \phi_{\tilde{X}_2} - \phi_{X_2}$ and $\phi_{\tilde{g}_2} - \phi_{g_2} = \phi_{\tilde{X}_2} - \phi_{X_2}$. Those two equations cannot be simultaneously fulfilled for arbitrary ϕ_λ, $\phi_{\tilde{\lambda}}$, ϕ_{g_2}, $\phi_{\tilde{g}_2}$.

The baryon number generated in the early universe can be calculated from Eq. (26) by following the usual steps (see, for example, Ref. [28]). Out of equilibrium decay of X_2 and $\bar{X}_2$ is most plausible if they are very heavy (e.g., $\sim 10^{12}$ GeV). However, to get measurable $n\bar{n}$ oscillation in this case, X_1 would have to be light—a case that is disfavored by neutron edm constraints, since it requires some very small dimensionless couplings.

IV. CONCLUSIONS

We have investigated a set of minimal models which violate baryon number at tree-level without inducing proton decay. We have looked in detail at the phenomenological aspects of one of these models (model 1) which can have $n\bar{n}$ oscillations within the reach of future experiments. When all the mass parameters in model 1 have the same value, M, and the magnitudes of the Yukawa couplings $g_1'^{11}$ and g_2^{11} are unity, the present limit on $n\bar{n}$ oscillations implies that M is greater than 500 TeV. For $M = 500$ TeV, the neutron edm and flavor constraints give $\mathrm{Im}[g_1^{31}(g_1'^{31})^*] < 6\times10^{-6}$, $\mathrm{Re}[g_2^{22}(g_2^{11})^*] < 0.45$, and $\mathrm{Im}[g_2^{22}(g_2^{11})^*] < 1.7\times10^{-3}$ which indicates that some of the Yukawa couplings and/or their phases must be small if $n\bar{n}$ oscillations are to be observed in the next generation of experiments. Of course even in the standard model some of the Yukawa couplings are small.

There are two other models (model 2 and model 3) that have $n\bar{n}$ oscillations at tree level. Similar conclusions can be drawn for them, although the details are different. In models 2 and 3, exchange of a single X_1 does not give rise to a one-loop edm of the neutron. However, K^0-$\bar{K}^0$ mixing can occur from tree-level X_1 exchange.

Observable $n\bar{n}$ oscillations can occur for $M_2 \gg M_1$ with M_2 at/near the GUT scale. This requires $M_1 \simeq 5$ TeV, and flavor and electric dipole constraints require some very small Yukawa couplings in that case.

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