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‘Exotic vector-like pair’ of color-triplet scalars

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Abstract: We propose a minimal extension of Standard Model, generating a Majorana mass for neutron, connected with a mechanism of Post-Sphaleron Baryogenesis. We consider an ‘exotic vector-like pair’ of color-triplet scalars, an extra Majorana fermion ψ, and a scalar field ϕ, giving mass to ψ. The vector-like pair is defined ‘exotic’ because of a peculiar mass term of the color-triplet scalars, violating Baryon number as $\Delta B = 1$. Such a mass term could be generated by exotic instantons in a class of string-inspired completions of the Standard Model: open (un-)oriented strings attached between D-brane stacks and Euclidean D-branes. A Post-Sphaleron Baryogenesis is realized through ϕ-decays into six quarks (antiquarks), or through ψ-decays into three quarks (antiquarks). This model suggests some intriguing B-violating signatures, testable in the next future, in Neutron-Antineutron physics and LHC. We also discuss limits from FCNC. Sterile fermion can also be light as $1 - 100\,\mathrm{GeV}$. In this case, the sterile fermion could be (meta)-stable and $n - \bar{n}$ oscillation can be indirectly generated by two $n - \psi$, $\psi - \bar{n}$ oscillations, without needing of an effective Majorana mass for neutron. Majorana fermion ψ can be a good candidate for WIMP-like dark matter.

Keywords: Supersymmetry Phenomenology, Strings and branes phenomenology

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Contents

1 Introduction

Has the neutron a Majorana mass or not? This is not just an academic question. Majorana himself proposed in '37', that neutron could have a Majorana mass term $\delta m\, nn + h.c$ [1]. We do not know if Majorana understood immediately the depth of his proposal; but today we get that existence of a "Majorana's fermion" is related to baryon or lepton numbers' violations. In particular, a Majorana mass for neutron implies a neutron-antineutron transition, violating baryon number by $\Delta B = 2$ [2–4]. The current limit on $n - \bar{n}$ is $\tau_{n\bar{n}} = 1/\delta m > 0.86 \times 10^{8}\,\mathrm{s}$ with 90% C.L., implying $\delta m < 7.7 \times 10^{-24}\,\mathrm{eV}$ [5]. This corresponds to a constraint $\mathcal{M} >$ 300 TeV on the effective operator $(udd)^2/\mathcal{M}^5$. This limit is particularly loose with respect to other rare processes violating Baryon or Lepton numbers: $\tau_{n\bar{n}} > 3\,yr$ for neutron-antineutron can be compared with $\tau_{p-decay} \sim 10^{34\div 35}\,\mathrm{yr}$ for the Proton decays, $\tau_{0\nu\beta\beta} > 10^{25}\,\mathrm{yr}$ for neutrinoless double beta decays [6]. For these reasons, neutron-antineutron is becoming more and more an interesting challenge for model building [20–26],[1] also considering possibility in the next future to enhance best limit of a factor 100: $\tau_{n\bar{n}} > 10^{10}\,\mathrm{s}$, testing 1000 TeV scale [7]. (For a recent review about phenomenology of Baryon and Lepton violations, see also [27]). In this paper, we would like to suggest a simple minimal model connecting the "Majorana's question" with a mechanism of Baryogenesis. Depending on the particular region of the parameters, this model connects neutron-antineutron physics with LHC, predicting a new peculiar phenomenology in collider physics. This model does not produce proton decay, and FCNC can be sufficiently suppressed.

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[1] See also [42] for a short discussion about Neutron-Antineutron physics as a test of a new fifth force interaction (a more complete version is in preparation [43]).

The main model's feature: we introduce an 'exotic' mixing mass term for a vector-like pair of color scalar triplets, violating baryon number as $\Delta B = 1$, i.e one color-triplet scalar has a different baryon number with respect to the other triplet antiscalar by exactly one unit. One scalar triplet has $B = 1/3$, and the other has $B = 2/3$. We call this an 'exotic vector-like pair'. We propose that existence of a $\Delta B = 2$ Majorana Mass could be connected to a $\Delta B = 1$ exotic mass term! In a broad sense, we have a see-saw mechanism for neutron, involving a non-diagonal mass matrix for scalars rather than fermions.[2,3] This model is inspired by proposals in [28, 29, 53–56]: (NMS-)SM is obtained as a low energy limit of open (un)-oriented strings, attached between D-brane stacks and Euclidean D-branes. Euclidean D-branes are exotic stringy instantons, that can induce new non-perturbative mass terms, violating vector-like U(1)s, rather than axial-ones. In particular, in [28, 29], R-parity is *dynamically* broken by exotic instantons, producing only particular B-violating operators, such as a mass term for a vector-like pair Proton decay is automatically suppressed in this model [28, 29].

An exotic vector-like pairs could be not only indirectly searched in $n - \bar{n}$ physics, but also at LHC, with peculiar processes: $pp \to jj\not{E}_T$, for example, could be a spectacular signature of exotic vector-like pairs and dark matter.

This model can connect Neutron-Antineutron oscillations to Dark Matter problem rather than to Baryogenesis. Infact, if ψ is a metastable fermion of mass $1 - 1000\,\mathrm{TeV}$, an exchange of a virtual exotic vector-like pair can generate $n - \psi$ and $\psi - \bar{n}$ oscillations, with $\tau_{n-\psi} \simeq \tau_{\psi-\bar{n}} \simeq \tau_{n-\bar{n}}/2 \simeq 10^8\,\mathrm{s}$. In this case a Neutron-Antineutron transition can be generated as a combination of these two $|\Delta B| = 1$ oscillations, without needing of a Majorana mass for Neutron. ψ can be a good candidate of WIMP Dark Matter.

The paper is organized as follows: in section 2, we describe the model for a Majorana neutron also discuss suppression of FCNCs; in section 3, we discuss implications for LHC physics; in section 4, connections with Baryogenesis; in section 5, we discuss a possible string-inspired scenario for the effective model proposed, in section 6, we present our conclusions.

2 A model for a neutron Majorana mass

We introduce a vector-like pair of (complex) color-triplet scalars $\mathcal{X}_i, \mathcal{Y}^i$ (an their antiparticles) with i, j color indices of $\mathrm{SU}(3)_c$. $\mathcal{X}$ has hypercharge $Y(\mathcal{X}) = -2/3$, $\mathcal{Y}$ has hypercharge $Y(\mathcal{Y}) = +2/3$. Baryon and Lepton numbers are $B(\mathcal{X}) = 1/3$, $B(\mathcal{Y}) = 2/3$ and $L(\mathcal{X}) = L(\mathcal{Y}) = 0$. We also consider a Majorana sterile particle $\psi(1, 1; 0)$, with a mass term $\mu\psi\psi + h.c.$ This is a gauge singlet with zero Baryon number, zero Lepton number, zero hypercharge.

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[2] The see-saw mechanism type I for the neutrino was originally proposed by Minkowski [8], M.Gell-Mann, P.Ramond and R.Slansky [9, 10], by Yanigida [11], R.Mohapatra and G.Senjanovic [12]. Then, other mechanisms called type II [13–17] and type III [14, 15, 18], have been proposed later.

[3] Probably, the most similar mechanism of the one proposed here is in [39–41, 43]. In this case Baryon number is violated by a baryonic 'RH neutron', with a B-violating Majorana mass term.

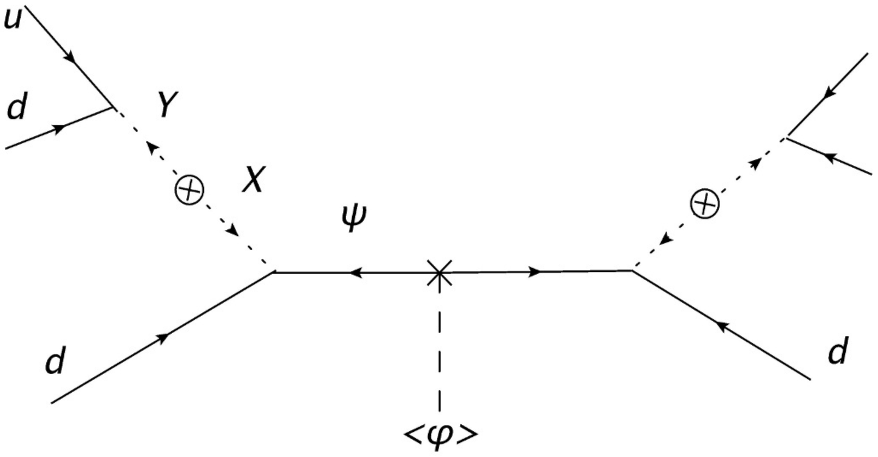

Figure 1. Diagram inducing a Neutron-Antineutron transition. The white blobs indicate the mixing mass term between the vector-like pair of color scalar triplets $\mathcal{X}, \mathcal{Y}$. The central propagator is the Majorana fermion ψ.

Fields	Y	B	L
$\mathcal{X}(3,1;-2/3)$	$-2/3$	$+1/3$	0
$\mathcal{Y}(\bar{3},1;+2/3)$	$+2/3$	$+2/3$	0
$\psi(1,1;0)$	0	0	0
$q_L(3,2;+1/3)$	$+1/3$	$+1/3$	0
$u_R(\bar{3},1;-4/3)$	$-4/3$	$-1/3$	0
$d_R(\bar{3},1;+2/3)$	$+2/3$	$-1/3$	0
$l_L(1,2;-1)$	-1	0	-1
$e_R(1,1;2)$	$+2$	0	$+2$

Table 1. New matter fields introduced with respect to SM. We report their representation with respect to SM gauge group SU(3) × SU(2) × U(1)$_Y$, their hypercharges Y and their Baryon and Lepton numbers B, L. We also report Standard quarks and leptons for a comparison.

These fields, compatible with gauge invariances, can interact with quark fields as

$$\mathcal{L}_Y = y_1 \mathcal{X}_i \psi d^i_R + y_2 \mathcal{Y}^i u^j_R d^k_R \epsilon_{ijk} + h.c \tag{2.1}$$

mass terms for $\mathcal{X}$ and $\mathcal{Y}$,

$$\mathcal{L}_{\text{mass}} = m^2_{\mathcal{X}} \mathcal{X}^\dagger \mathcal{X} + m^2_{\mathcal{Y}} \mathcal{Y}^\dagger \mathcal{Y} + h.c \tag{2.2}$$

and $\mathcal{X} - \mathcal{Y}$ has a peculiar mixing mass term

$$\mathcal{L}_{\mathcal{X}-\mathcal{Y}} = \mathcal{M}^2_0 \mathcal{X}^i \mathcal{Y}_i + h.c = \frac{1}{2} \mathcal{M}^2_0 \epsilon_{ijk} \mathcal{X}^i \mathcal{Y}^{[jk]} + h.c \tag{2.3}$$

With these interactions, one can construct a Neutron-Antineutron transitions as shown in figure 1. Note that all interactions terms are B-preserving, exception for mixing term

$\mathcal{M}_0^2\epsilon_{ijk}\mathcal{X}^i\mathcal{Y}^{[jk]}$, violating baryon number as $\Delta B = 1$. Effective operator $(udd)^2/\mathcal{M}^5$ has a mass scale $\mathcal{M} = (\mathcal{M}_0^4\mu)^{1/5}$, times coupling constants $y_{1,2}$, where μ is mass of fermion ψ. Experimental bound on $n - \bar{n}$ implies $\mathcal{M} > 300\,\text{TeV}$. So, one can consider different choices of parameters $\mathcal{M}_0$ and μ in order to satisfy experimental limits. A trivial choice could be $\mathcal{M}_0 = \mu = 300\,\text{TeV}$, automatically saturating the bound. On the other hand, we can also consider for example $\mathcal{M}_0 \simeq 1 - 10\,\text{TeV}$ and $\mu \simeq 10^{6\div 10}\,\text{TeV}$, generating a lot of interesting physics for LHC, as discussed later. Another branch could be $\mu \simeq 1 - 10^3\,\text{GeV}$ corresponding to $\mathcal{M}_0 \simeq 7\times 10^{3\div 2}\text{TeV}$. In this last case, the fermion ψ is a natural candidate for WIMP dark matter, and Feynman diagram in figure 1 can be seen as a combination of two oscillations $n - \psi$ and $\psi - \bar{n}$ with $\tau_{n\psi} \simeq \tau_{\psi\bar{n}} \simeq 10^8\,\text{s}$: ψ is a (meta)stable particle, and not a virtual one in propagator, in this case. Note that actual best limits on $n - \psi$ oscillations are $\tau \geq 414\,\text{s}$, from Ultra Cold Neutron experiments, in condition of suppressed magnetic fields $|\mathcal{B}| < 10^{-4}\,\text{Gauss}$ [35–38].

More precisely, in estimation of $\mathcal{M}$, we have to consider not $\mathcal{M}_0^2$, but the smallest mass eigenvalue of mass matrix of $\mathcal{X}, \mathcal{Y}$. We assume $\mathcal{M}_0$ as a real parameter. We can decompose the color complex scalars as $\mathcal{X} = \frac{1}{\sqrt{2}}(\mathcal{X}_1 + i\mathcal{X}_2)$ and $\mathcal{Y} = \frac{1}{\sqrt{2}}(\mathcal{Y}_1 + i\mathcal{Y}_2)$, and we can write mass matrix, in basis $(\mathcal{X}_1, \mathcal{X}_2, \mathcal{Y}_1, \mathcal{Y}_2)$ as

$$M_{\text{eff}}^2 = \begin{pmatrix} m_{\mathcal{X}}^2 & 0 & \mathcal{M}_0^2 & 0 \\ 0 & m_{\mathcal{X}}^2 & 0 & -\mathcal{M}_0^2 \\ \mathcal{M}_0^2 & 0 & m_{\mathcal{Y}}^2 & 0 \\ 0 & -\mathcal{M}_0^2 & 0 & m_{\mathcal{Y}}^2 \end{pmatrix} \tag{2.4}$$

The eigenvalues are

$$\lambda_{\pm}^2 = \frac{1}{2}\left(m_{\mathcal{X}}^2 + m_{\mathcal{Y}}^2 \pm \sqrt{4\mathcal{M}_0^4 + (m_{\mathcal{X}}^2 - m_{\mathcal{Y}}^2)^2}\right) \tag{2.5}$$

(two-two degeneracies, as manifest in (2.4)).

In this model, we are not generating a proton decay process, if the mass of ψ is higher than proton mass.[4]

2.1 FCNC bounds and the space of the parameters

FCNC in meson physics are generated in our model. The strongest effects can come from a direct exchange of one $\mathcal{Y}$, shown in figure 2. In particular diagrams (b) in figure 2

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[4] We assume that other possible interactions of $\mathcal{X}, \mathcal{Y}, \psi$ with leptonic sector are suppressed, in order to avoid other dangerous effective operators. For example, possible extra operators like $\mathcal{Y}q_\alpha l^\alpha$, leading to a proton decay operator $qqql/\Lambda^2$, can be avoided through opportune discrete symmetry Z_N, compatible with $\Delta B = 1$ operators like $\mathcal{M}_0\mathcal{X}\mathcal{Y}$. Note that $\mathcal{X}, \mathcal{Y}$ are not leptoquarks, they not have Lepton numbers, in our case. We are assuming that our model is not violating lepton number as $\Delta L = 1$; this is simple to realize just with a discrete symmetry Z_2. This can be also compatible with Majorana masses for neutrini $\Delta L = 2$. We also note that ψ is not a Right-handed neutrino, it has a Lepton number equal to zero. For a complete classification of gauge discrete symmetries, protecting the proton by $D = 6$ operators, for string constraints on Discrete symmetries, see [51, 52]. Alternatively, in a string-inspired model like [28], R-parity is dynamically broken by Exotic Instantons, generating (2.1)–(2.2)–(2.3), without other dangerous operators. For instance, $qqql/\Lambda^2$ is automatically avoided! [28].

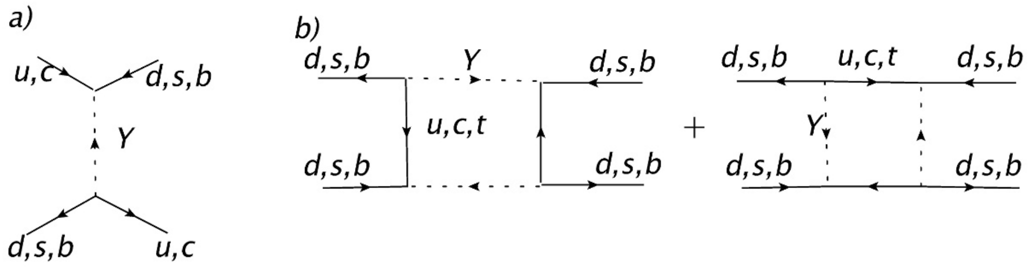

Figure 2. a) FCNCs tree-level diagrams mediated by $\mathcal{Y}$. b) Diagrams of neutral-meson oscillations, mediated by two $\mathcal{Y}$.

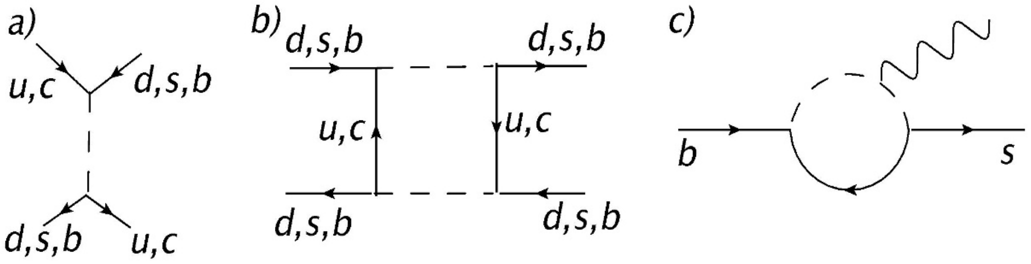

Figure 3. a) Diagram for meson decays into two mesons [28]. This is mediated by two sterile fermions ψ and four $\mathcal{X}-\mathcal{Y}$. b) diagram for neutral meson-antimeson oscillation [28].

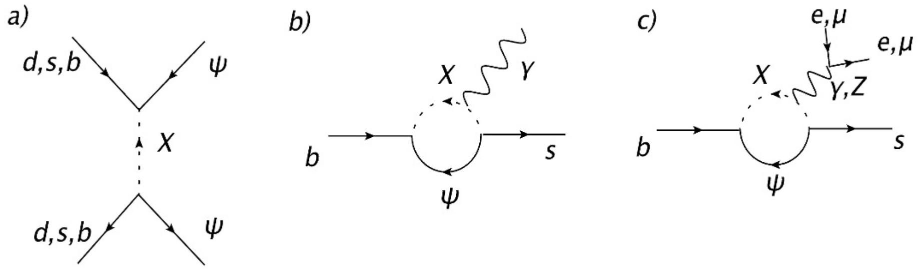

Figure 4. B^0,B^0_s,$\bar{B}^0$,$\bar{B}^0_s \to \psi\psi$ are possible if $2\mu \leq m_B$. b) $b \to s\gamma$ transitions leading to $B \to K\gamma$, $\phi\gamma$. c) $b \to sl^+l^-$ transitions leading to $B \to Kl^+l^-$, ϕl^+l^-.

contribute to neutral meson-antimeson oscillations such as $K_0-\bar{K}_0$, $D_0-\bar{D}_0$, $B_0-\bar{D}_0$ etc. These constrain $\mathcal{Y}$'s mass up to $m_{\mathcal{Y}} \gtrsim 1000\,\text{TeV}$. However, these FCNC are not directly constraining $\mathcal{X}$'s mass. In particular, assuming $m^2_{\mathcal{Y}} \simeq 10^6 m^2_{\mathcal{X}}$ and $\mathcal{M}_0^2 \simeq m^2_{\mathcal{X}}$, we obtain, from (2.5): $\lambda^2_- \simeq m^2_{\mathcal{X}}$ and $\lambda^2_+ \simeq m^2_{\mathcal{Y}}$, with mixing angles $\theta_{13}=\theta_{24}\sim 10^{-6}$. So, mixings between $\mathcal{X}$ and $\mathcal{Y}$ are strongly suppressed in this case, but enough for neutron-antineutron transitions: an prefactor of 10^{-12} in a $n-\bar{n}$ scale $(\mathcal{M}_0^4\mu)^{1/5}$. has to be considered. This strongly afflicts estimations of parameters: for $\mathcal{M}_0 = 1-10\,\text{TeV}$, it is enough a light ψ of $\mu = 1 \div 100\,\text{GeV}$! As a consequence, the lightest eigenstate of mass matrix (2.5) can elude FCNC's constraints of figure 2 and it can stay also near TeV scale. Other FCNC's contributions, directly involving $\mathcal{X}$, are suppressed, practically avoiding any current observations as shown in figure 3. In neutral mesons' oscillations $K_0-\bar{K}_0$, $D_0-\bar{D}_0$, $B_0-\bar{D}_0$ etc. any effects are suppressed as $\mathcal{M}_0^{-8}\mu^{-2}$. This strongly motivates a direct research of exotic color scalar triplets (the lightest eigenstate) at LHC. In next

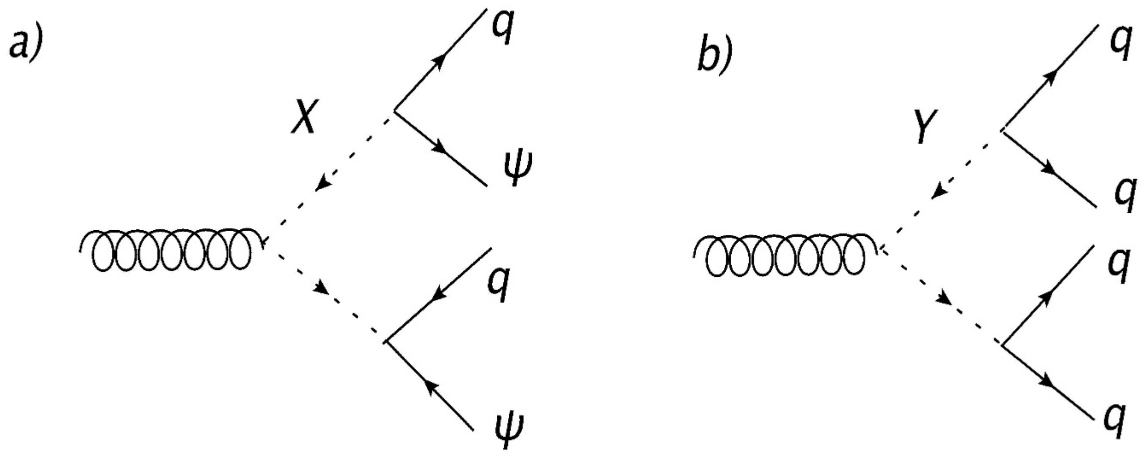

Figure 5. a) Missing energy channel $jj\not{E}_T$ at LHC; b) Diagram leading to $4j$ and $t\bar{t}jj$ channels.

section, we will discuss these aspects. We also note that possible decays as $D^0, B^0 \to \psi\psi$, shown in figure 4, can be generated if $2\mu \leq m_{D^0,B^0}$. Suppose $2\mu \leq m_B$: in order to satisfy $n-\bar{n}$ limits, $\mathcal{X}$ may have $m_{\mathcal{X}} \gg 1\,\text{TeV}$, strongly suppressing decays in figure 4, or colliders' processes. In the following discussion, we will assume $\mu > m_B/2 \simeq 2.5\,\text{GeV}$.

Other effects generated in our model are $b \to s\gamma$ and $b \to sl^+l^-$, shown in (b)-(c) figure 4. Possible deviations in these are predicted in our model, with similar limits of supersymmetric models [50], compatible with limits from the other channels discussed above.

3 LHC physics

As discussed in section 2, a direct production of the e.v.l.p is possible: bounds from neutron-antineutron physics allow $\mathcal{M}_0 \sim 1-10\,\text{TeV}$. A possible diagram of direct production of the lightest mass eigenstate of $\mathcal{X}-\mathcal{Y}$ is represented in figure 5-(a). Compatible with FCNCs discussed above, We call two mass eigenstates as $\mathcal{Z}_{\pm}$, with mass eigenvalues $\lambda_{\pm}^2$. We can reach the lowest eigenstate $\mathcal{Z}_-$, with eigenvalue $\lambda_- \simeq \mathcal{M}_0$, compatible with FCNCs' bounds. For LHC physics, practically $\mathcal{Z}_- \simeq \mathcal{X}$. An interesting signature for LHC is $pp \to jj\not{E}_T$. From this channel, we can put limit on $(m_{\mathcal{X}}, m_{\psi})$; essentially the same of squarks $\tilde{q}\tilde{q} \to jj\not{E}_T$ [47, 48]. For $m_{\mathcal{X}} > 200\,\text{GeV} \to \mu > 200\,\text{GeV}$; $m_{\mathcal{X}} > 500\,\text{GeV} \to \mu > 400\,\text{GeV}$; $m_{\mathcal{X}} > 1000\,\text{GeV} \to \mu$ is unbounded from below. As a consequence, ψ could be a (meta)stable particle visible at LHC as transverse missing energy and Dark Matter Direct Detection. In this scenario, Neutron-Antineutron physics is directly connected to the Dark Matter question.[5]

We also mention limits from top-jet and di-jets channels, in figure 3-(b), around 1 TeV (top-jet 900 GeV, di-jets 1.2 TeV) [49], but these are not lower than FCNC ones cited above.

4 Post-sphaleron baryogenesis

In the proposed mode, one can envisage two simple mechanisms for post-sphaleron baryogenesis: i) ϕ-decays into six-quarks (antiquarks), ii) ψ-decays into three-quarks (antiquarks).

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[5] If ψ compose all Dark Matter, from WIMP relic abundance $\mu > 7\,\text{GeV}$ [44, 45].

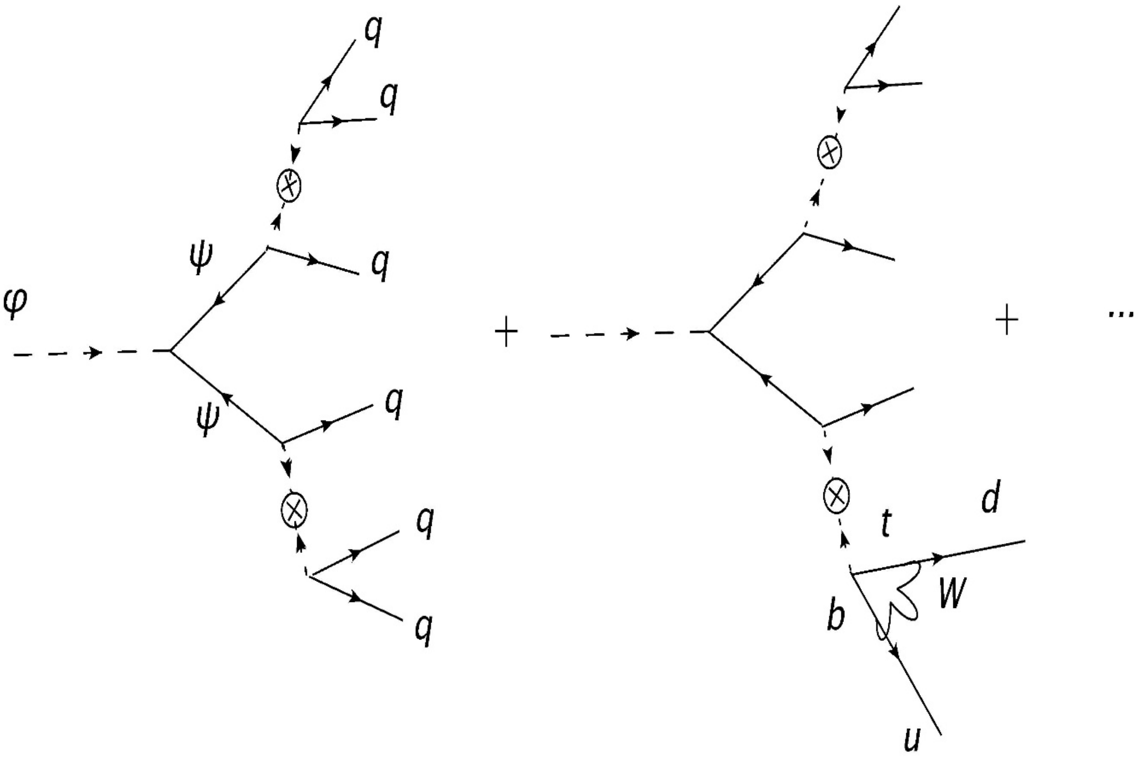

Figure 6. Decay $\phi \to 6q$: the first is a tree level contribution, but also one loops contributions, as the one shown, have to be considered. One-loop contribution in figure is an example of electroweak CKM correction to decay amplitude through an exchange of a W boson, converting *top* − *down* and *bottom* − *up*. Because of Majorana particle ψ, we can revert all arrows in Feynman diagrams, obtaining $\phi \to 6\bar{q}$.

We discuss these two in the following.

4.1 Scalar-decays into six quarks (antiquarks)

We can reverse diagram in figure 1, considering the mass parameter of ψ as generated by a scalar field ϕ, acquiring a vev scale v, with $\mu = y_\psi v$. For the moment, the mass of ϕ is a free parameter, M_ϕ.[6] In figure 6 we show decay diagrams, at tree level and one-loop. We can evaluate the amplitude $\mathcal{M}$, at tree level, as

$$\mathcal{M}^{\rm tree} \simeq \frac{y_\psi < \phi > Tr[y_1^\dagger y_1]Tr[y_2^\dagger y_2]\mathcal{V}^*\mathcal{V}}{\mathcal{M}_0^4\mu^2} = \frac{Tr[y_1^\dagger y_1]Tr[y_2^\dagger y_2]\mathcal{V}^*\mathcal{V}}{\mathcal{M}_0^4\mu} \tag{4.1}$$

where $\mathcal{V}$ is the diagonalizing matrix of masses (2.4), suppressing the amplitude as $\mathcal{V}^*\mathcal{V} \sim 10^{-12}$, as cited above. under the assumption $\lambda_+ \gg \lambda_- \simeq \mathcal{M}_0$, where $\lambda_\pm$ are the mass eigenvalues in (2.5).

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[6] More precisely we can rewrite $\phi = (v + \phi_r + \phi_i)/\sqrt{2}$, and the dynamical scalar decaying is ϕ_r. In the following discussions, for ϕ-decays we will always mean ϕ_r-decays, and for M_ϕ we will mean M_{ϕ_r}.

One-loop corrections from the electroweak sector can be evaluated as (assuming all the couplings in $\lambda_1 \sim \lambda_2 \sim 10^{-3} \div 1$)

$$\mathcal{M}^{1-loop} \simeq c\mathcal{V}^*\mathcal{V}V^*_{ub}V_{td}\Phi_{1-loop}\bar{\mathcal{O}}^2_{n\bar{n}}\left(\frac{\mu m_t m_b}{m_W^2}\right) \tag{4.2}$$

where $c \simeq (10^{-3} \div 1)^4/128\pi^2$, and $\bar{\mathcal{O}}^2_{n\bar{n}} \equiv< \bar{n}|\mathcal{O}^2|n >\simeq -0.3 \times 10^{-5}\,\mathrm{GeV}^6$ from MIT bag model [30] (confirmed also by recent lattice calculations [31]). Φ^{1-loop} (with dimension mass $[\Phi^{1-loop}] = M^{-4}$) is a function depending on the mass of the quarks closing the one-loop in figure 6 (the the top and bottom masses, in dominant contribution). However, there are also other possible contributions, closing 1-loops involving the vector-like pairs, in which Φ^{1-loop} is depending also on vector-like pair. A precise evaluation of such a formula is not necessary for our purposes. It is a good approximation to compare directly (4.1) with the present bounds on neutron-antineutron physics. In principle, we have also to consider running prefactors connecting high energy physics of baryogenesis with low energy neutron-antineutron physics. This prefactor is around 10^{-2} [32].

At three level, the decay rate of ϕ is the square modulus of the amplitude (4.1), times a phase space factor for a $6q$ (or $6\bar{q}$) final state:

$$\Gamma_\phi = \Gamma(\phi \to 6q) + \Gamma(\phi \to 6\bar{q}) = \mathcal{I}\mathcal{V}^*\mathcal{V}Tr[y_1^\dagger y_1]^2 Tr[y_2^\dagger y_2]^2\left(\frac{M_\phi^{13}}{\mu^4\mathcal{M}_0^8}\right) \tag{4.3}$$

with $\mathcal{I} \simeq 7 \times 10^{-18}$ a numerical factor coming from a numerical integration in the phase space times combinatoric factors (practically independent from the ratios of mass parameters, the variations on this integration are of the order of 1 %, not important for our purposes).

Considering the case of a Post-sphaleron baryogenesis: the rate (4.3) has to be smaller than the Hubble rate at a temperature near the electroweak phase transition epoch: $\Gamma_S < H(T_{ew})$. We consider a decay temperature indicatively between $100\,GeV \div 200\,\mathrm{MeV}$, between electroweak phase transition and the QCD phase transition ($\Lambda_{QCD} \simeq 200\,\mathrm{MeV}$). The decay temperature $\bar{T}$ can be found solving the equation

$$\Gamma_S(\bar{T}) \simeq H(\bar{T}) \simeq 1.66 g_*^{1/2}\frac{\bar{T}^2}{M_{Pl}} \tag{4.4}$$

where g_* is the number of degrees of freedom at $\bar{T}$. From this we can get

$$\bar{T} \simeq \sqrt{\frac{M_{Pl}M_\phi^{13}}{(2\pi)^9\mu^4\mathcal{M}_0^8}} \tag{4.5}$$

So, a post sphaleron scenario impose limits on the masses' ratios. For example, supposing $\bar{T} \sim 100 \div 200\,\mathrm{GeV}$ and $M_\phi \simeq 0.5\,\mathrm{TeV}$: we can get bounds on the vector-like pair mixing mass $\mathcal{M}_0$ and Majorana fermion mass, well compatible with the ones coming from neutron-antineutron physics.

Finally, we can evaluate the primordial baryon asymmetry parameter, directly related to the observed baryon asymmetry:

$$\epsilon \simeq \frac{n_\phi}{n_\gamma}\frac{\Gamma(\phi \to 6q) - \Gamma(\phi \to 6\bar{q})}{\Gamma_\phi} \tag{4.6}$$

It is necessary to evaluate this including 1-loop CP-violating contributions coming from the electroweak sector, i.e CKM CP violating contributions. The contribution from 1-loop vertices[7] as the one shown in figure 6 are (considering (4.2))

$$\epsilon^{V} \simeq \frac{g_2^2}{32\pi}\frac{\mathcal{V}^{*}\mathcal{V}y_2^{\dagger}V_{td}^{*}V_{ub}y_2}{Tr[y_2^{\dagger}y_2]}\frac{m_t m_b}{m_W^2}\left[1+\frac{9m_W^2}{M_\phi^2}\ln\left(1+\frac{\mathrm{M}_\phi^2}{3\mathrm{m}_\mathrm{W}^2}\right)\right] \tag{4.7}$$

With ϵ^V one-loop vertex contribution. So the asymmetry is controlled by M_ϕ. As a consequence, $M_\phi \gg 500 \div 1000\,\mathrm{GeV}$ suppresses the contribution from the vertex. Cimparing this bound with the other one coming from (4.5), the region of the parameters discussed in section 2 are well compatible. As a consequence, a Post-sphaleron baryogenesis is possible and naturally predicts a neutron-antineutron oscillation of $\tau_{n\bar{n}} \simeq 10^8 - 10^{10}\,\mathrm{s}$.

Finally, we also have to consider the dilution of the baryon asymmetry: $\bar{T} \simeq M_\phi/5 \div M_\phi/10$, the decay of ϕ generated entropy into the primordial plasma. The dilution can be evaluate as the ratio of entropy density before and after ϕ-decay:

$$\mathcal{D} = \frac{s_{\text{initial}}}{s_{\text{final}}} \simeq \frac{0.6\sqrt{\Gamma_\phi M_{Pl}}}{g_*^{1/4}M_\phi r_\phi} \tag{4.8}$$

where $r_\phi = n_\phi/s$ is at the decays' epoch. This can be estimated as

$$\mathcal{D} \sim k\frac{\bar{T}}{M_\phi} \sim k(10\% \div 20\%) \tag{4.9}$$

(where k parametrize also extra suppressions from the couplings). From (4.7), we can find $\epsilon \sim 10^{-8\div 9}$, but this has to be normalized with the dilution factor. We obtain (assuming all couplings near one i.e $k \sim 1$), $\eta_B \sim \mathcal{D}\epsilon \sim 10^{-9\div 10}$, where $\eta_B = (n_b - n_{\bar{b}})/n_\gamma$, as requeired observations ($\eta_B^{exp} = (6.04 \pm 0.08) \times 10^{-10}$ [33]).

So, we can conclude that this mechanism can generate baryon asymmetry in our Universe, during a Post-Sphaleron epoch, satisfying all Sakharov's conditions i.e i) out of thermal equilibrium; ii) CP-violating processes iii) B-violating processes [46].

4.2 Majorana fermion decays in three quarks (antiquarks)

Alternatively, we can consider directly $\psi \to u_i d_j d_k, \bar{u}_i \bar{d}_j \bar{d}_k$, in which μ is below electroweak scale. In this scenario, color triplets cannot be detected at LHC. The decay rate can be evaluated as

$$\Gamma_{\psi\to qqq,\bar{q}\bar{q}\bar{q}} = ck\mu^5\left(\frac{1}{\lambda_+^2}-\frac{1}{\lambda_-^2}\right)^2 \tag{4.10}$$

where $\lambda_\pm$ are mass eigenvalues in (2.5), and

$$c = 1/4096\pi^3, \quad k = \mathcal{V}^{*}\mathcal{V}y_1^{\dagger}y_1\mathrm{Tr}[\mathrm{y}_2^{\dagger}\mathrm{y}_2]$$

---

[7] One can consider also 1-loop contributions coming involving also $\mathcal{X}, \mathcal{Y}, \psi$ in the propagators. However, one can numerically evaluates these contributions and discover that they are subdominant with respect to the contributions in (4.6). Also Self-energy contributions (or wave-function renormalizations) give not important contributions for our estimations.

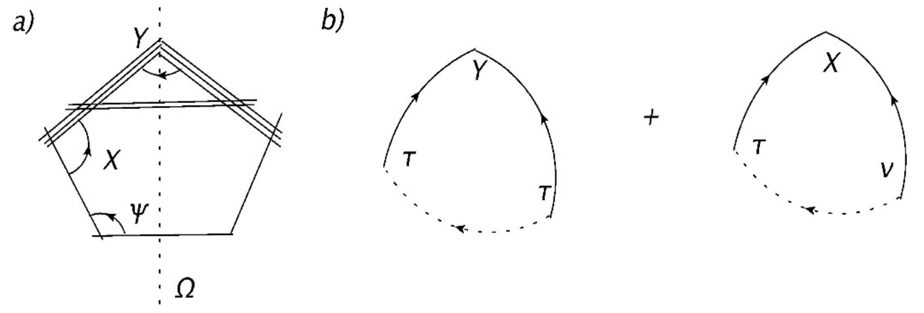

Figure 7. a) (Sub)-system of D-branes stacks generating our toy-model content of fields at low energy limit. b) Mixed-Disk amplitudes generating an Exotic mass term for $\mathcal{X}, \mathcal{Y}$.

(c contains also color factor 6 in numerator). We are assuming $\lambda_{\pm} \gg \mu$. Under the assumption $\lambda_{+} \gg \lambda_{-} \simeq \mathcal{M}_0$, (4.10) is simplified as

$$\Gamma_{\psi \to qqq, \bar{q}\bar{q}\bar{q}} = ck\mu^5 \frac{1}{\mathcal{M}_0^4} \tag{4.11}$$

However, we have also to consider scattering processes. $q + \psi \to \bar{q}\bar{q}$: they go-out of equilibrium at the same temperature $\bar{T}$ of $\psi \to 3q(\bar{q})$ decays. For $\bar{T} < \mu$, ψ cannot be produced, for lack of phase space. So, one has also to consider $\psi\psi \to q\bar{q}$ contributions to baryon asymmetry generation. Extra one-loop electroweak corrections ($W^{\pm}$ exchanges) lead to dominant contributions as (4.7) cited above. From this, we can estimate $\epsilon \simeq 10^{-8} \div 10^{-9}$, for $k \sim 1$ (natural couplings), ulteriorly suppressed by by dilution factor for 10^{-1}, as discussed in the previous subsection. We conclude that also mechanism seems a viable way to generate the observed Baryon asymmetry.

5 Beyond the toy-model: string-inspired standard model and exotic instantons

In this section, we would like to discuss a possible explanation of the toy-model,[8] as a String-Inspired class of model, embedding the Standard Model, generating an exotic mass term for the vector-like pairs We suggest a little different variant with respect to the one suggested in [28]: a IIA (un)-oriented string theory, with stacks of D6 ordinary branes, and Euclidean and D2-branes, wrapping 3-cycles on CY_3, and an antisymmetric Mirror Plane Ω_-, recovering at low energy limit $\mathrm{U}(3)\times\mathrm{U}(2)\times\mathrm{U}(1)\times U'(1)$ or $\mathrm{U}(3)\times\mathrm{Sp}(2)\times\mathrm{U}(1)\times U'(1)$, $\mathcal{N} = 1$ susy, R-parity preserving. A possible simplified scheme of D-brane stacks (sub)-system is shown in figure 7-(a): $\mathcal{X}, \mathcal{Y}$ are scalar parts of superfields $\mathbf{X}, \mathbf{Y}$, attached between a U(3) stack and a U(1) stack, and a U(3) stack and its mirror twin, with respect the mirror plane Ω, respectively. On the other hand, ψ is the fermionic part of a superfield $\boldsymbol{\Psi}$ living between two U(1) stacks. Finally, also ϕ can be constructed, similarly to ψ. We can introduce an Exotic $E2$-brane intersecting with ordinary ones. In this way, we generate interactions between Grassmann moduli (or modulini), living between $E2 - D6$

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[8] We mention that, recently, a toy model for a supersymmetric non-local QFT was discussed in [57].

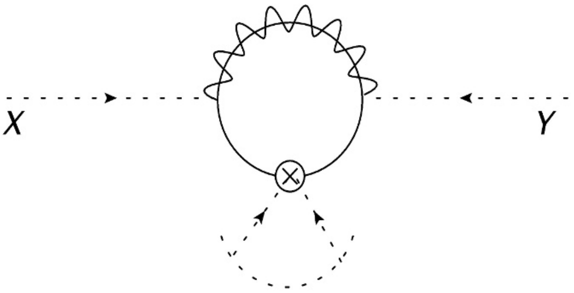

Figure 8. Exotic mass for $\mathcal{X},\mathcal{Y}$, generated by one-loop corrections, containing one gaugino, and a $\psi_{\mathcal{X},\mathcal{Y}}$ mixing induced by Exotic Instantons (white blob with dashed lines).

intersections, and ordinary superfields. Let us discuss the consistency of the hypercharges in a construction like the one suggested in figure 7. For intersecting D-brane model considered in figure 7, $\mathrm{U}(1)_Y$ is defined as a linear of U(1) stacks:

$$\mathrm{U}(1)_Y = c_1\mathrm{U}(1)_1 + c_1' U'(1) + c_3\mathrm{U}(1)_3 \tag{5.1}$$

where $\mathrm{U}(1)_2 \subset \mathrm{U}(2)$, $\mathrm{U}(1)_2 \subset \mathrm{U}(2)$. So the hypercharge is a combination of four abelian charges. From (5.1), a consistent assignation of hypercharges, $Y(\mathcal{X}) = -Y(\mathcal{Y}) = -2/3$, $Y(\Psi) = 0$, and the ones of SM particles, can be found. In particular, we find $c_3 = 1/3$, $c_1 = c_1' = -1$.

As in [28], a non-perturbative mass term between $\mathbf{X},\mathbf{Y}$ can be generated by two mixed-disk amplitudes, shown in figure 7-(b). In fact, from these,

$$\mathcal{L}_{E2-D6-D6''} \sim \nu\tau^i\mathbf{X}_i + \mathbf{Y}_{ij}\tau^i\tau^j \tag{5.2}$$

where i,j are the color indices of the U(3)-stack. A new superpotential term, not allowed at perturbative level, is obtained, integrating out modulini:

$$\mathcal{W}_{E2} = M_S e^{-S_{E2}} \int d^3\tau d\omega e^{\nu\tau^i\mathbf{X}_i + \mathbf{Y}_{ij}\tau^i\tau^j} = M_S e^{-S_{E2}}\epsilon_{ijk}\mathbf{X}^i\mathbf{Y}^{jk} \tag{5.3}$$

where M_S is the String scale and $e^{-S_{E2}}$ is the parameterize by geometric moduli of the 3-cycles wrapped by the Euclidean D2-brane in the Calabi-Yau CY_3. As shown figure 8, an exotic mass term can be generated, in a supersymmetric model, as a loop of susy partners $\psi_{\mathcal{X}},\psi_{\mathcal{Y}}$ and a gaugino (gluino, zino or photino), with $\mathcal{M}_0^2 \sim m_{\tilde{g}} M_S e^{-S_{E2}}$, $m_{\tilde{g}}$ gaugino mass.

We would like to note that all contributions on irreducible gauge anomalies, cancel each other, in this D-brane construction. In fact, $\mathcal{X},\mathcal{Y}$ do not introduce extra anomalous contributions with respect to SM fields content. For instance, $\mathrm{SU}(3)^3$ anomalies give equal and opposite contributions because of $Tr[\mathcal{X}] = 1$ and $Tr[\mathcal{Y}] = N_c - 4 = -1$. On the other hand, anomalous extra U(1) are introduced with respect to SM gauge group: new Z' are introduced as in any string-inspired model, with masses generated by a Stückelberg mechanism [58, 59]. Anomalies that could appear as a serious problem in gauge models, are cancelled by Generalized Chern-Simons (GCS) terms as a generalized Green-Schwarz mechanism [60, 61].[9]

Finally, we would like to remark that, an exotic mass term (5.3) cannot be introduced by-hand, at perturbative level, because of R-parity, i.e R-parity is dynamically broken, without the generation of other dangerous R-parity violating operators, as explained in [28, 29, 66].

6 Conclusions

In this paper, we have discussed a simple alternative model generating a Majorana mass for the neutron, connecting Majorana's proposal to deep issues regarding Baryogenesis and Dark Matter. In particular, we have introduced just one exotic vector-like pair of color-triplet scalars, a sterile Majorana fermion ψ, and a scalar giving mass to ψ. An exotic vector-like pair is characterized by an extra peculiar mass term, violating baryon number by $\Delta B = 1$. In particular, we got limits on exotic mixing mass parameter from LHC physics. We have seen how Baryogenesis can be realized, also during the post-sphaleron epoch, and we predict a neutron-antineutron transition with a time interesting for the next generation of experiments: $\tau_{n\bar{n}} \sim 300\,\mathrm{yr}$. We have also considered, an alternative scenario, in which the sterile fermion is a metastable WIMP-like particle. In this case, a neutron-antineutron transition can be generated by two $\Delta B = 1$ oscillations, $n - \psi$ and $\psi - \bar{n}$. Finally, we have also shown a possible completion and explanation of such a toy-model, in which the exotic mass term is generated by non-perturbative exotic stringy istantons.

We conclude that this model, postulating an exotic vector-like pair of color-triplet scalars, deserves attention for its peculiarity and simplicity, especially considering its possible connections with fundamental issues and its implications in B-violations phenomenology such as neutron-antineutron physics and LHC.

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[9] The Stückelberg mechanism has a lot of different intriguing applications. Let us mention that a Lorentz Violating Massive gravity can be realized through a Stückelberg mechanism [62–64]. Recently, geodetic instabilities of Stückelberg Lorentz Violating Massive gravity were discussed in [65].

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