More about Neutron Majorana mass from Exotic Instantons: an alternative mechanism in Low-Scale String theory

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Abstract
Recently, we have proposed that Exotic instantons can generate a Majorana mass for the neutron, with emphasis to experimental researches in the next future. In this paper, we discuss an alternative model based on the same idea, in the contest of low scale string theory. In particular, with $M_S = 10 \div 10^3$ TeV, such a transition can be mediated by two color-triplets, through a quartic coupling with down-quarks, generated by exotic instantons, in a calculable and controllable way. Comparison with FCNCs imposes limits on color-triplet mass well compatible with $n \rightarrow \bar{n}$ oscillation ones. If a $n \rightarrow \bar{n}$ transition were found, this would be an indirect hint for our model. This would strongly motivate searches for direct channels in proton-proton colliders. In fact, our model can be directly tested in an experimentally challenging $100 \div 1000$ TeV proton-proton collider, searching for our desired color-triplet states and an evidence for “exotic quartic couplings”, in addition to Regge resonances, mini black holes, anomalous $Z'$-bosons. On the other hand, even if this scenario is not compatible with TeV-ish color triplets visible at LHC, it is compatible with $1 \div 10$ TeV-string scale, i.e stringy resonances at LHC.

1 Introduction
The possibility that the string scale can be at much lower energies than the Planck scale $M_P \simeq 10^{19}$ GeV, is intriguing and theoretically motivated. In fact, if the string scale was close to the TeV-scale, the hierarchy problem of the Higgs mass would be automatically solved [1,2,3,4,5]. LHC will provide a direct test for TeV-scale string theories, searching for stringy Regge resonances as well as massive gluons, massive gravitons, mini black holes. On the other hand, we can argue that also if $M_S \simeq 10^2 \div 10^3$ TeV, the hierarchy problem can be much alleviated: $m_H/M_S \sim 10^{-\left(3+4\right)}$ rather than $10^{-14}$. In this case, direct searches at LHC are not possible: stringy resonances would be found in $100 \div 1000$ TeV proton-proton colliders. However, effective operators can be generated, leading to intriguing signatures in low energy physics. Recently, we

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have shown, how in string-inspired models\textsuperscript{2} non-perturbative effects called *exotic stringy instantons* can generate new effective operators, violating Baryon and Lepton numbers\textsuperscript{7,8,9,10}. In particular, we have shown how the generation of a Majorana mass term for the neutron from exotic instantons can be possible, without proton destabilization. This leads to the possibility to test indirectly this class of models, in the next generation of experiments on neutron-antineutron oscillations. The actual best limits on \( n - \bar{n} \) transition is only \( \tau_{\bar{n}n} \simeq 3 \text{ yr} \textsuperscript{12,14} \), and the next generation of experiments will enhance this one by two orders of magnitude\textsuperscript{14}. In\textsuperscript{7,8,9,10}, we have shown how proton is not destabilized; but deviations in neutral mesons oscillations and other FCNC are generically predicted, roughly at the same scale as for \( n - \bar{n} \) oscillations. In this paper, we propose an alternative mechanism for the generation of a Neutron Majorana mass from exotic instantons, as a variant of the ones discussed in\textsuperscript{7,8,9,10}. In low scale string theory, \( M_S \simeq 10 \div 10^3 \text{ TeV} \), this mechanism can be tested indirectly in \( n - \bar{n} \) experiments and FCNC processes. In particular, we propose a general class of intersecting D-brane models, in which the SM is embedded, and extra color-triplet superfields \( C, C^c \) naturally emerge for construction. Exotic instantons generate an extra quartic superpotential for \( W_{\text{np}} = C C D^c D^c / M_0 \). As a consequence, a neutron-antineutron transition is induced by non-perturbative effects in a theory of quantum gravity!\textsuperscript{3}

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Let us consider, at effective level, a (N)MSSM plus two extra superfields \( C \) and \( C^c \).\textsuperscript{4} \( C \) is a \((\overline{3}, 1)_{Y = -2/3}\) with respect to \( SU(3)_c \times SU(2)_L \times U(1)_Y \), with a Baryon number \( B(C) = -2/3 = 2B(D^c) \). We can introduce at perturbative level the following R-parity preserving superpotential terms\textsuperscript{5}

\[
W_p = W_{(N)\text{MSSM}} + y_1 C_{ij} Q^i Q^j
\]  

\textsuperscript{2}See \textsuperscript{9} for discussions of other different aspects about string-inspired susy QFT models.

\textsuperscript{3}For other ideas about neutron-antineutron oscillations in Large Extra Dimensions, see \textsuperscript{11}.

\textsuperscript{4}Even if our model is \( N = 1 \) supersymmetric, supersymmetry is not necessarily broken at TeV-scale: it can be broken close to the string-scale.

\textsuperscript{5}As commented in \textsuperscript{9,10}, extra mass parameters, such as soft susy breaking ones, can be generated by RR-RR or NS-NS three-forms fluxes in the bulk. In our case, mass term in the superpotential like \( m_{C}CC^c \) can be generated by fluxes. For recent discussions of mass deformed quivers and dimers see also \textsuperscript{13}.
Figure 1: a) Diagram inducing neutron-antineutron transitions through color-triplet scalars $\phi_C$ and an effective interaction induced by exotic instantons (black box). b) Supersymmetric diagram inducing neutron-antineutron transitions: two fermionic superpartners $\psi_C$ mediate the process, four quarks are converted into four squarks through two gaugini. (Notation: \( d,D \equiv d^c,D^c \) and \( q \equiv q_L \) so that \( \frac{1}{2} \epsilon_{\alpha\beta} q^\alpha q^\beta = u_L d_L \). c) Mixed disk amplitudes inducing the relevant effective interaction between $D^c$ and $C^c$.

At a non-perturbative level we can generate through exotic instantons the following extra term for $C^c$:

\[
W_{np} = \frac{1}{M_0} \epsilon^{ijk} \epsilon^{lmn} D_i^c D_j^c C_{jk} C_{mn} \tag{2}
\]

Superpotential term (2) violates the baryon number as $\Delta B = 2$. The superpotentials (1)-(2) generate two possible relevant diagrams for neutron-antineutron oscillations, shown in Fig.1-(a)-(b). In the first one, relevant operators in the lagrangian are $y_1 \phi_C q_L q_L$, $m_{\phi_C}^2 \phi_C \phi_C^1$, and $d^c d^c \phi_C \phi_C^* / M_0$ and their hermitian conjugates. Integrating out $\phi_C$, we obtain the effective operator $\mathcal{O}_{n\bar{n}} = Tr[y_1 y_1^\dagger] (qqd^c)^2 / \Lambda_{n\bar{n}}^5$ where $\Lambda_{n\bar{n}}^5 = m_{\phi_C}^4 M_0$. The diagram in Fig.1-(b) generates an effective operator $\mathcal{O}_{n\bar{n}}$ with a NP scale $\Lambda_{n\bar{n}}^5 = M_0 m_{\tilde{C}}^2 m_{\tilde{g}}^2$, where $m_{\tilde{g}}^2$ is the gaugino mass (gluino, zino or photino). Which one of the two diagrams dominates, depends on the particular region of the parameters considered. In Fig.1-(c) we show mixed disk amplitudes generating the effective superpotential term (2). We will return later on to the precise calculation of the relevant string amplitudes. Now let us discuss the case in which Fig.1-(a) is dominant with respect Fig.1-(b), i.e. supersymmetry is not related to the hierarchy problem of the Higgs mass in this case. Under this assumption, the relevant contributions to
FCNCs are shown in Fig.2. In particular, contributions to neutral mesons oscillations as \( K^0 - \bar{K}^0 \) are generated by box-diagrams. Among all experimental constraints, the strongest one comes from \( K^0 - \bar{K}^0 \): this process is suppressed as \( \Lambda^2_{K^0\bar{K}^0} \simeq (10^3 \text{ TeV})^2 \) [15]. Assuming \( y_1 \simeq 10^{-3} \div 1 \), we can estimate a bound for \( m_{\phi_C} \) as \( m_{\phi_C} \simeq 1 \div 1000 \text{ TeV} \).

On the other hand, a \( b \to s\gamma \) transition is also generated: the experimental suppression approximatively puts the same limits on \( m_{\phi_C} \). These bounds are higher than the direct ones coming from LHC (roughly near 1 TeV for \( y_1 \sim 1 \), as discussed in [8]). We can combine these bounds with the ones from \( n - \bar{n} \) oscillation, \( \Lambda_{n\bar{n}} > 300 \text{ TeV} \), and the LHC one on the string scale \( M_S > 1 \div 10 \text{ TeV} \) [16]. The next generation of experiments in \( n - \bar{n} \) oscillations promise to test the 1000 TeV scale. This can correspond to (assuming \( y_1 \simeq 1 \)) \( M_0 \simeq m_{\phi_C} \simeq 10^3 \text{ TeV} \). In this case, FCNC bounds are satisfied. Such a situation can be easily obtained trough exotic instantons. In case in which the diagram in Fig.1-(b) is not sub-dominant, analogous bounds on FCNCs can be obtained, with one more free parameter with than in the one in Fig.1-(a): the gaugino mass. [6]

Let us discuss the mixed disk amplitudes pictures in Fig.1-(c), where string theory enters in our model. \( C \) and \( Q \) are excitations of open strings stretched between \( D6_3 - D6\prime_3 \) branes and \( D6_3 - D6\prime_2 \)-branes respectively. In mixed disk amplitudes, the relevant \( E2 \)-brane instanton intersects two times the \( D6 \) and \( D6' \) branes. Fermionic modulini \( \tau^i, \alpha \) are excitations of open string attached to \( D6 - E2 \) and \( D6' - E2 \) respectively. As a consequence the following effective interactions are generated:

\[
\mathcal{L}_{\text{eff}} \sim D^c_i \tau^i \alpha + C_{ij} \tau^i \tau^j
\]  

(3)

As proposed recently, an auto-concealment of susy can be possible in extra dimensions, with effective Planck scale or stringy scale \( 1 - 100 \text{ TeV} \) [17]. This scenario generically implies large missing energy channels at LHC. Our proposal can be considered in this contest, in which the supersymmetric diagram is expected to be dominant or at least relevant.
Figure 3: We show a simplified scheme of a possible class of D-brane systems, generating the fields content of our model. In particular, system shown in figure reproduces $G_{\text{NMSSM}} = U(3) \times U(2) \times U(1)$. Clearly, $G_{\text{NMSSM}}$ can be extended with one (or more extra) $U(1)$. An antisymmetric $\Omega_{-}$-plane is introduced. $C, C^{c}$ are obtained as excitations of open strings attached to $U(3)_{c}$ and its mirror reflection. Notation: $3 \equiv U(3)_{c}$, $2 \equiv U(2)$, $1 \equiv U(1)$, in black ordinary D-branes, in red ”images” of physical D-branes.

We consider a number of intersections of $E2$-brane and $D6_{3} - D6'_{2}$ is equal to

$$I_{E2-D6_{3}} = -I_{E2-D6'_{2}} = 2$$

Integrating over the modulini space (as usually done for istantonic solutions), we obtain

$$W_{np} = e^{-S_{E2}} \int d^{6}\tau d^{2}\alpha e^{C_{ij}} = \frac{e^{-S_{E2}}}{M_{S}} e^{ijk} e^{kmn} D_{ij} D_{jk} C_{mn}$$

So, $\mathcal{M}_{0} = M_{S}e^{+S_{E2}}$, where $S_{E2}$ is the effective action of the $E2$-brane, depending on kahler moduli associated to 3-cycles of $E2$-brane to the Calabi-Yau $CY_{3}$. Intuitively, if 3-cycles size is small, $e^{S_{E2}} \sim 1$, on the contrary $e^{S_{E2}}$ can be much higher than one. For example, a situation in which $\mathcal{M}_{0} \simeq 10^{3}$ TeV can correspond to $M_{S} \simeq 10^{3}$ TeV ($e^{S_{E2}} \sim 1$) as well as to $M_{S} \simeq 10$ TeV ($e^{S_{E2}} \sim 10^{2}$). We note that exotic instantons have dynamically violated R-parity and the Baryon number, without generating proton or neutralino decays operators.
The effective model proposed can be embedded in several different classes of (NM)SM-like intersecting D-brane systems. See [18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34] for papers and reviews in these subjects, with particular emphasis to possible implications for LHC. A minimal choice can be to consider D-branes systems for $U(3) \times U(2) \times U(1)$. In our construction, we introduce an antisymmetric Mirror $\Omega^{-}$-plane, as shown in Fig. 3. This allows to construct $C, C^{c}$ from open strings attached between $U(3), c$ and its mirror twin. In particular, one stack of three D6-branes produces the $U(3), c$ gauge group, including $SU(3), c$ and an extra $U(1)$; one stack of two D6-branes for $U(2), L$, containing $SU(2), L$ and an extra $U(1)$, one stack of a single D6-brane for a $U(1)$ gauge group; an antisymmetric $\Omega$-plane, identifies the D-brane stacks with their images. Let us remind the, $\Omega$-planes explicitly breaks $\mathcal{N} = 4$ theory down to $\mathcal{N} = 1$ susy theory, and they are usually introduced for tadpole cancellations [35, 36, 37, 38, 40, 35, 36, 37, 41, 42]. The presence of orientifold planes $\Omega$ in intersecting D-brane system seems a key element for realistic models of particle physics. Let us note that $U(1), 3 \subset U(3), c$ and $U(1), 2 \subset U(2), L$ are anomalous in gauge theories. On the other hand, these $U(1)$s are not problematic in string theories. In fact, a generalized Green-Schwarz mechanism can cancel anomalies, through generalized Chern-Simon (GCS) terms. The new vector bosons $Z', Z''$ associated to $U(1), 2, 3$ get masses via Stückelberg mechanisms. See [44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55] for discussions about these aspects in different contests [8]. Finally, hypercharge $U(1), Y$ is a non-anomalous linear combination of $U(1), 3, U(1), 2, U(1), 1$ of Fig. 3. Our idea is so generic that can be implemented in several different D-brane models. The precise hypercharge combination depends on the particular D-brane construction considered. The construction of a precise quiver theory is not the purpose of this paper. On the other hand, our ”$\Omega$-trick” can be considered also in D-brane constructions for models like 3-3-1 as the one considered in [70, 71, 72]. Usually 3-3-1 models as the one considered in [70, 71, 72] are not easily embedded in GUT-inspired models, for its peculiar fields content, while in intersecting D-brane ones there are less difficulties to get such

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7 Another important element for intersecting D-brane models can be flavor branes [66, 67, 68, 69], but we do not discuss possible explicit model with these ones.

8 Let us mention that another implementation of the Stückelberg mechanism is in the realization of a Lorentz Violating Massive gravity [50, 57, 58]. Recently, geodetic instabilities of Stückelberg Lorentz Violating Massive gravity were discussed in [59].

9 Another intriguing application of exotic instantons regards the generation of RH neutrini masses and $\mu$-terms [60, 61, 62, 65]. This idea is compatible with our one.
Finally, an $E2$-brane is introduced, intersecting stacks in Fig. 3 as indicated in Fig. 1-(c), and generating our desiderata superpotential \cite{2}.

3 Conclusions and discussions

In this paper, we have seen a model for the generation of a Majorana mass from Exotic stringy instantons, as a variant of models proposed in \cite{7,8,9,10}. We have discussed a scenario in which new color-triplet states interact with ordinary quarks, mediating a neutron-antineutron transition. The key of the mechanism is the generation of a non-perturbative quartic interaction among color-triplets and quarks from Exotic Instantons. Proton is not destabilized in this model as well as neutralino or other possible LSP. As a consequence, neutron-antineutron transition can be fast as $\tau_{n\bar{n}} \simeq 300 \text{ yr} (1000 \text{ TeV})$, in a low scale string theory scenario $M_S = 10 \div 10^3 \text{ TeV}$. This scenario can be well compatible with FCNC limits, in particular with $K_0 - \bar{K}_0$ and $b \rightarrow s\gamma$. In the Early Universe, new decays $\phi_C \rightarrow q\bar{q}, qq$, also counting one-loop contributions, could generate a Baryon asymmetry (BAU). However, such a processes could be not enough efficient because of washing-out collisions, generated by exotic instantons, like $d^c d^c \rightarrow \phi_C \phi_C$, and by sphalerons successively. On the other hand, string theory suggests that all couplings are dynamical degrees of freedom, stabilized by fluxes and instantons. The scale generated by exotic instantons depends on geometric moduli, associated to the shape of $E2$-brane cycles wrapping the Calabi-Yau. As a consequence, $E2$-branes’ kahler moduli can evolve as dynamical degrees of freedom, so that $e^{-S_{E2}}(\text{moduli})[t_{\text{Early-Universe}}] << e^{-S_{E2}}(\text{moduli})[t_{\text{Present-Epoch}}]$. This corresponds to a dynamical enlargement of 3-cycles radii, wrapped in the Calabi-Yau, during the cosmological evolution. For example, geometric moduli can be stabilized to a ”solitonic solution” of the Cosmological time $t$, $\mathcal{F}(t) = e^{-S_{E2}}(t)$, connecting two asymptotic branches $\mathcal{F}_1 = \mathcal{F}(t_{\text{Early-Universe}})$ and $\mathcal{F}_2 = \mathcal{F}(t_{\text{Present-Epoch}}) \gg \mathcal{F}_1$. This is plausible, also considering that usually the dependence on moduli is exponential-like, while a soliton solution is usually a combination of hyperbolic functions, i.e a combination of exponentials. In this way, exotic instantons’ effects are strongly suppressed during the Early Universe, not washing-out baryon asymmetries, generated after inflation. On the other hand, neutron-antineutron oscillations remain reachable.

\footnote{I would like to thank José Valle for useful comments on these subjects.}
for the next generation of experiments. Such a hypothesis deserves future theoretical and numerical investigations in string phenomenology and baryogenesis calculations.

We conclude that exotic instantons continue to surprise with their intriguing implications in phenomenology. This strongly motivates researches on neutron physics from the experimental side, and the researches of consistent quivers and Calabi-Yau singularities for the class of D-brane models proposed, as already done in similar cases [73, 74, 75, 76].

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