Observable N-N-bar Oscillation with New Physics at LHC

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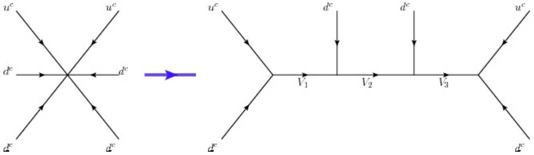
Neutron-anti-Neutron Oscillations?

- We know from experiment that neutral particles, such as kaons and neutrinos, can oscillate. Why not ask this question for neutrons.
- Neutron oscillations can help us answer questions like BAU, B-L symmetry and the path to choose towards unification.
- $\not{B}$ processes as the proton decay ($\Delta B = 1$) and $n - \overline{n}$ oscillations ($\Delta B = 2$) are interesting to probe but point to different directions towards unification.
- $n - \overline{n}$ oscillations
  - $\Delta B = 2$, $\Delta(B - L) = 2$, $\widehat{O} = u^c d^c d^c u^c d^c d^c / M^5$.
  - $\tau_{n-\overline{n}} \geq 10^8$ sec implies $M \sim$ TeV.
  - probes energy scale much lower the M_{GUT}.
- interests in $n - \overline{n}$ oscillations has revived since the neutrino mass was explained through the seesaw mechanism which also violates $B - L$ by 2.

Adding Vector like fields to mediate nnbar oscillations

- We add new TeV scale vector like particles belonging to multiplets of SU(5).



- V_1, V_2, V_3 are integrated out to get the effective $|\Delta B| = 2$ operator.
- These particles can be produced at LHC through their interactions with quarks and leptons.

B and L conservation and new Physics at TeV

- In contrast to the SM, in which B and L are conserved, MSSM can have d=4 operators (e.g. QLd^c) which violate B and L.
- R-parity forbids $d = 4$ operators, but we can still have $d = 5$ operators which violate B and L (e.g. $QQQL, u^c d^c d^c e^c$) but these are Planck suppressed.
- But the suppression is not enough if the cutoff scale is TeV and we have to somehow forbid these operators.
- One possible way to forbid these operators is to introduce a new U(1) symmetry.

New U(1) symmetry to suppress operators

- Let's consider a superpotential respecting R-parity

$$W = qu^c H_u + qd^c H_d + \ell e^c H_d + \ell \nu^c H_u + \mu H_u H_d + M_P \left(\frac{S}{M_P}\right)^m \nu^c \nu^c$$

  $q, u^c, d^c, l, e^c, \nu^c$ are quarks and lepton superfields, H_u and H_d are the Higgs superfields, S is an MSSM singlet.
- When we add a non renormalizable term as $S^n(u^c d^c d^c)^2$ the Baryon symmetry is broken in general.
- But we can have an linear combination of B and $B-L$ that remains unbroken, say $a(B-L)+bB$. Then the condition is

$$-\frac{2}{m} an - 2(a+b) = 0.$$

  Choose $a = m/2$ to make the remaining U(1) charge of S to be -1. Then, we obtain $b = -(m+n)/2$, and the remaining anomalous U(1) symmetry is $-(\mathbf{nB}+\mathbf{mL})/\mathbf{2}$.

Forbidding unwanted operators through this U(1) symmetry

- If $n \geq 0$, the $\Delta B = -2$ operator $S^n (u^c d^c d^c)^2$ is allowed. When $n \leq 0$, the $\Delta B = 2$ operator $(S^\dagger)^n (qqd^{c\dagger})^2$ is allowed.
- $\Delta B = \Delta L = \pm 1$ operators (e.g. $qqq\ell$, $u^c d^c u^c e^c$ and $qqu^{c\dagger} e^{c\dagger}$) are forbidden because there U(1) charge is $\pm(n+m)/2$, and we do not introduce a singlet field which has a half-odd-integer charge under U(1).
- $\Delta B = -1$, $\Delta L = 0$ operator $(u^c d^c d^c)$, which is an R-parity violating term, is not allowed under the U(1) symmetry when n is an odd number.
- $\Delta B = 0$, $\Delta L = 1$ $\not{R}$ operators $(qd^c \ell\ \ell \ell e^c,\ \ell h_u)$ are forbidden when m is odd.

Constrainst on GUT representations

- The new matter fields are constrained perturbativity condition which requires that the three MSSM gauge coupling remain perturbative upto M_G.
- It was shown in a recent paper[1] that we can have
  - Upto 4 pairs of $5+\overline{5}$
  - One pair of $10+\overline{10}$
  - or one pair of $5+\overline{5+}10+\overline{10}$

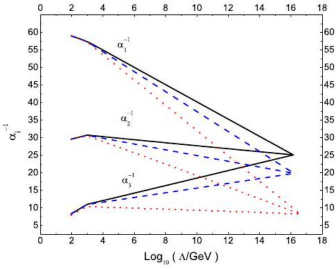


Fig.: Dashed line is MSSM $+5+\overline{5}$ and dotted line is MSSM $+\ 10+\overline{10}$

[1] K.S. Babu, I. Gogoladze, M.U. Rehman, Q. Shafi, Phys. Rev. D 78, 055017 (2008)

$n-\overline{n}$ Oscillation Operators

- The six-quark operators which contribute to $n-\overline{n}$ oscillations are $u^c d^c d^c u^c d^c d^c$, $qqd^{c\dagger}qqd^{c\dagger}$ and $qqd^{c\dagger}u^{c\dagger}d^{c\dagger}d^{c\dagger}$.
- Among them, only $u^c d^c d^c u^c d^c d^c$ is holomorphic, and in SUSY theories, it will provide the dominant contribution to $n-\overline{n}$ oscillations when $m_{\rm SUSY} \ll M_V$.
- The contributions from holomorphic and non-holomorphic operators at tree level is

$$
\begin{aligned}
G_{n-\overline{n}} &\sim (\alpha_s/4\pi)^2 1/(m_{SUSY}^2 M_V^3) \quad \text{Holomorphic} \\
G_{n-\overline{n}} &\sim 1/M_V^5 \quad \text{Non-holomorphic}
\end{aligned}
$$

- But with $m_{\rm SUSY} \sim M_V$, the contributions of both types of operators to $n-\overline{n}$ oscillations can be comparable.

MSSM+5+$\overline{5}$ and $n-\overline{n}$ Oscillations

- The representation $5+\overline{5}$ of SU(5) decomposes under the MSSM gauge symmetry as follows:

$$5+\overline{5} = L_5\left(1,2,-\frac{1}{2}\right)+\overline{L}_5\left(1,2,\frac{1}{2}\right)+ \overline{D}_5\left(\overline{3},1,\frac{1}{3}\right)+D_5\left(3,1,-\frac{1}{3}\right)$$

- In order for $5+\overline{5}$ to induce $n-\overline{n}$ oscillations we need an additional MSSM singlet field (N, $\overline{N}$).The additional contribution to the MSSM superpotential relevant for $n-\overline{n}$ oscillation is given by

$$W=\kappa_1 qqD_5+\kappa_2 u^c d^c \overline{D}_5+\kappa_3 D_5 d^c N+\kappa_4 D_5 d^c \overline{N}+\frac{1}{2}M_N NN+M_V\left(\overline{D}_5 D_5+\overline{L}_5 L_5+N\overline{N}\right)$$

Diagrams generating relevant operators

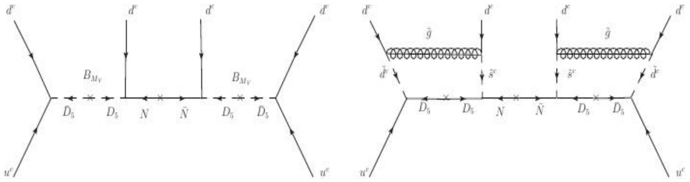


Fig.: Diagrams generating the operator $(u^c d^c d^c)^2$ via $5 + \overline{5}$. When $M_V \sim m_{SUSY}$, the tree-level diagram (right) dominates instead of the gaugino dressed diagram (left).

Diagrams generating relevant operators

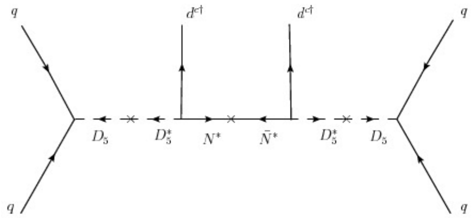


Fig.: Diagram which generates the operator $\left(qqd^{c\dagger}\right)^2$ via exchange of $5 + \overline{5}$

- the strength of $n-\overline{n}$ oscillations can be written as follows,

$$G_{n-\overline{n}} \simeq (\kappa_1^2 + \kappa_2^2)\left[-\frac{1}{2}\kappa_4^2\frac{M_V}{M_N} + \kappa_3\kappa_4\right]\frac{1}{M_V^5}.$$

- The current experimental bound on $n{-}\overline{n}$ oscillation, $\tau_{n-\bar{n}} \geqslant 0.86 \times 10^{8}$ s, implies an upper limit

$$G_{n-\overline{n}} \leqslant 3 \times 10^{-28}\ \mathrm{GeV}^{-5}.$$

- The bound on the dimensionless coupling can be expressed as follows:

$$M_V^5 G_{n-\overline{n}} \leqslant \left(\frac{M_V}{1\ \mathrm{TeV}}\right)^5 \times 3 \times 10^{-13}.$$

we find that the couplings $\kappa_i \sim 10^{-3} - 10^{-4}$ to satisfy experimental bound.

Superposing the Flavor symmetry on the $-(nB + mL)/2$ symmetry

- We know the Yukawa couplings related to the first and second generations are suppressed and the inter-generation mixing in the quark sector is small.
- We can explain the flavor structure by superposing $U(1)_A$ flavor symmetry on the $-(nB + mL)/2$ symmetry.
- We assign the integers $(n_i^q n_i^u$, etc.) such that the observed fermion mass and mixing hierarchies are realized

- Employing the following texture gives

$$M_u \sim \langle H_u \rangle \begin{pmatrix} \epsilon^{8-2\alpha} & \epsilon^{6-\alpha} & \epsilon^{4-\alpha} \\ \epsilon^{6-\alpha} & \epsilon^{4} & \epsilon^{2} \\ \epsilon^{4-\alpha} & \epsilon^{2} & 1 \end{pmatrix},$$

$$M_d \sim \langle H_d \rangle \epsilon \begin{pmatrix} \epsilon^{5-\alpha} & \epsilon^{4-\alpha} & \epsilon^{4-\alpha} \\ \epsilon^{3} & \epsilon^{2} & \epsilon^{2} \\ \epsilon & 1 & 1 \end{pmatrix},$$

$$M_e \sim \langle H_d \rangle \epsilon \begin{pmatrix} \epsilon^{5-\alpha} & \epsilon^{3} & \epsilon \\ \epsilon^{4-\alpha} & \epsilon^{2} & 1 \\ \epsilon^{4-\alpha} & \epsilon^{2} & 1 \end{pmatrix}$$

$$M_{\nu^c} \sim M_{st} \epsilon^{m+2\gamma} \begin{pmatrix} \epsilon^{2} & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix}$$

$$\Rightarrow M_\nu^{\text{light}} \sim \frac{\langle H_u \rangle^2}{\epsilon^{m-2} M_{st}} \begin{pmatrix} \epsilon^{2} & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix}$$

where $\epsilon = < S > / M_{st}$

- The above mass matrix texture nicely fits the observed fermion masses and mixings.

Observing new vector like matter fields at LHC

- As previously mentioned, vector-like matter fields at the TeV scale can be found at the LHC as they decay into MSSM matter fields as well as gauginos.
- All unwanted couplings can be excluded by choosing the integers X_Q, X_U, etc. to be even or odd.
- For example for the term

$$W = \left(\frac{S}{M_{st}}\right)^{n_i^q + n_j^q + \frac{X_D}{2}} D_5 q_i q_j + \ldots$$

If say $X_D = 0$, thanfor $i = j = 3$, we have
$\left(\frac{S}{M_{st}}\right)^{n_3^q + n_3^q + \frac{X_D}{2}} D_5 q_3 q_3 = D_5 q_3 q_3$

- The coupling of $D_5 q_3 q_3$ is O(1) and $\overline{D}_5 t_c b_c$ is O(ϵ). If D_5 is produced at LHC its main decay mode will then be

$$D_5 \to \bar{t}\,\bar{b}$$

and if the diquarks are pair created in the collider the associated mode is $tb\bar{t}\bar{b}$

Various decay modes

- If we take $X_D + n + m = 0$, then both $D_5 u^c e^c$ and $\overline{D}_5 q \ell$ couplings are possible.The field D_5 for this case can be considered a 'leptoquark', and the main decay mode will be

$$D_5 \to t\,\tau$$

- In addition to $\Delta B = 2$, $\Delta L = 0$ operators, $\Delta B = \Delta L = 2$ operators can be allowed under the $-(nB + mL)/2$ symmetry.
- The $\Delta B = \Delta L = 2$ operators (typically $(qqq\ell)^2$) are responsible for $H - \overline{H}$ (hydrogen-anti hydrogen) oscillation, and double nucleon decays (e.g. $pp \to e^+ e^+$, $pp \to \mu^+ \mu^+$)
- In a recent work [hep-ph 1001.5260] it was shown that the scalar diquark can be detected at the LHC through its decay into a top quark and a hadronic jet.

Conclusions

- $n - \overline{n}$ oscillations can help us answer questions about unification , BAU and B-L symmetry.
- $n - \overline{n}$ oscillations might be observable at the LHC with possible vector-like particles.
- These colored vector like particles can be detected at LHC through various decay modes arising from their couplings to quarks.
- A $U(1)_{\frac{-(nB+mL)}{2}}$ symmetry in our case plays an important role in forbidding various unwanted interactions.

	q_i	u_i^c	d_i^c	ℓ_i	S
$\mathrm{U}(1)_A$	$-\frac{n}{6}+n_i^q$	$\frac{n}{6}+n_i^u$	$\frac{n}{6}+n_i^d$	$-\frac{m}{2}+n_i^\ell$	-1
	e_i^c	ν_i^c	h_u	h_d	
	$\frac{m}{2}+n_i^e$	$\frac{m}{2}+n_i^\nu$	0	0	

Table: The $\mathrm{U}(1)_A$ charge assignment. n^q, n^u are integers to generate the mass hierarchy for quarks and leptons.

	q	u^c	d^c	ℓ	e^c	ν^c	h_u	h_d	S
$-(nB+mL)/2$	$-\frac{n}{6}$	$\frac{n}{6}$	$\frac{n}{6}$	$-\frac{m}{2}$	$\frac{m}{2}$	$\frac{m}{2}$	0	0	-1

Table: U(1) charge assignments to forbid rapid nucleon decay. When n odd and m even, all $\Delta B=\pm 1$ operators are forbidden.

$n_i^q = (4-\alpha, 2, 0)$, $n_i^u = (4-\alpha, 2, 0)$, $n_i^d = (2,1,1)$, $n_i^\ell = (2,1,1)$, $n_i^e = (4-\alpha, 2, 0)$, $n_i^\nu = (\gamma+1, \gamma, \gamma)$

	Q_{10}	$\overline{U}_{10}$	$\overline{D}_5$	L_5	$\overline{E}_{10}$
$\mathrm{U}(1)_A$	$\frac{n}{3}+\frac{X_Q}{2}$	$-\frac{n}{3}-\frac{X_U}{2}$	$-\frac{n}{3}-\frac{X_D}{2}$	$\frac{n}{2}+\frac{X_L}{2}$	$-\frac{n}{2}-\frac{X_E}{2}$
	$\overline{N}$				
	$-\frac{n}{2}-\frac{X_N}{2}$				

Table: $\mathrm{U}(1)_A$ charge assignments for the vector-like fields. The parameters X_Q, X_U etc. are all integers.

	Q	u^c	d^c	L	e^c	ν^c	H_u	H_d	S
Y	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	1	0	$\frac{1}{2}$	$-\frac{1}{2}$	0
$B-L$	$\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	-1	1	1	0	0	$-\frac{2}{m}$
B	$\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	0	0	0	0	0