Neutron Majorana mass from Exotic Instantons

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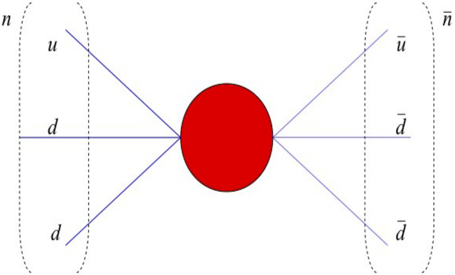
based on
A. Addazi, M. B. 1407.2897, 1502.01531, 1502.08041
A. Addazi, 1501.04660, 1504.06799, 1505.00625, 1505.02080

Why not?



?

Majorana mass for the neutron?

In 1937, Ettore Majorana proposed the neutron as a Majorana fermion $\psi_M = C\bar{\psi}_M^t$

In modern terms

$$\delta m \, n^t n \leftrightarrow \frac{1}{\mathcal{M}^5}(udd)^2$$

Baryon number violation

Neutron-Antineutron oscillations

Idea reconsidered some years later by Bruno Pontecorvo for neutrino oscillations . . . BSM

NNBar oscillations: let us vote

- $$\tau_{n\bar{n}} > 3{\cdot}10^{33}\,yr???$$
- $$\tau_{n\bar{n}} > 3{\cdot}10^{3}\,yr??$$
- $$\tau_{n\bar{n}} > 3{\cdot}yr?$$

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Experimental bound

Experimental bound [Baldo-Ceolin et al, 94]

$$\tau_{n\bar{n}} > 0.86 \cdot 10^8 s \approx 2.7 yr$$

$$\delta m < 7.7 \cdot 10^{-24} eV$$

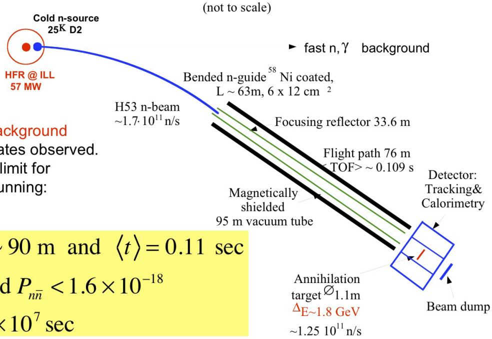
Long baseline, suppressed magnetic fields, ultra cold neutrons (UCN), velocity 1000 m/s, propagation time 0,1 s

In the near future possibility to improve the bound by two orders of magnitude

$\mathcal{M}$: PeV scale physics!

Experimental Setup

Heidelberg - ILL - Padova - Pavia $n\bar{n}$ search experiment at Grenoble 89-91



No GeV background

No candidates observed.
Measured limit for
a year of running:

with L ~ 90 m and $\langle t \rangle = 0.11$ sec

measured $P_{n\bar{n}} < 1.6 \times 10^{-18}$

$\tau > 8.6 \times 10^{7}$ sec

Baldo-Ceolin M. et al., Z. Phys. C63,409 (1994).

Nuclear stability: don't panic!

$$\mathcal{H}_{eff} = \begin{pmatrix} m_n - V_n & \delta m \\ \delta m^* & m_n - V_{\bar{n}} \end{pmatrix}$$

binding energies $V_{\bar{n}} << V_n$, $|V_{\bar{n}} - V_n| \sim V_n \sim 10 MeV$

Time for free neutron propagation $t_{free} \sim 1/E_{bind} \sim 10^{-23} s$

Oscillation probability

$$P_{n\bar{n}} = \frac{\delta m^2}{\delta m^2 + \Delta V^2} \sin^2 \sqrt{\delta m^2 + \Delta V^2}\, t \simeq \frac{\delta m^2}{(\Delta V)^2}$$

Inter-nuclear transition lifetime $\tau_A = 1/w_A > 10^{32} yr$

Resulting limits similar to direct search ones:

Oxygen $\tau > 2.4 \cdot 10^8 s$, Iron $\tau > 1.3 \cdot 10^8 s$

Further considerations

Proton decay $\tau_p \approx 10^{33} \tau_{n\bar{n}}$

Neutrino-less Double Beta decay $\tau_{0\nu\beta\beta} \approx 10^{23} \tau_{n\bar{n}}$

Note: if $p \to \pi^0 e^+$ and $\nu \leftrightarrow \bar{\nu}$, then $n \leftrightarrow \bar{n}$
yet with $\tau_{n\bar{n}} >> 2.7 yr$!!

Theoretical side?

$\Delta B = 2$ requires BSM physics

In MSSM R-breaking connects n-nbar with p-decay

Alternatively? Babu-Mohapatra (non-susy) SO(10) GUT with **126** multiplets, hard to embed in unoriented string theory, yet Pati-Salam like (susy) model possible!

Neutron Majorana mass

vs

Exotic Instantons

Open un-oriented string models

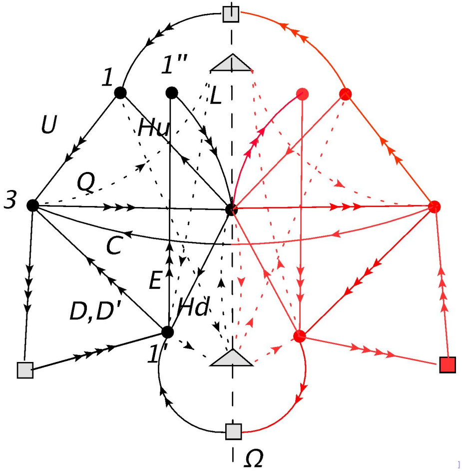
Proposal: embed MSSM + extra matter and interactions in un-oriented D-brane models

Result: indirectly generate neutron Majorana mass . . . N-Nbar transitions

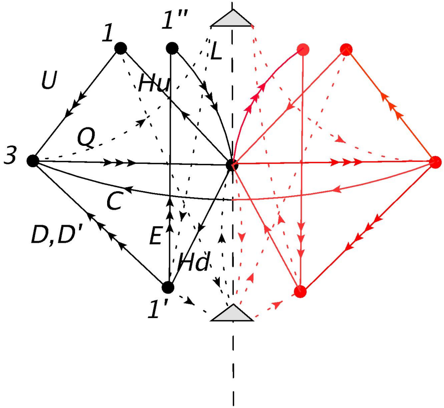
Rely on non-perturbative ‘quantum gravity’ effects in String Theory generated by Euclidean branes (E-branes) or E-strings wrapping internal cycles [Dine, Seiberg, Witten; Callan, Harvey, Strominger; Becker, Becker, Strominger; Bachas, Fabre, Kiritsis; Green, Gutperle . . .]

In particular ‘exotic’ instantons in vacuum configurations with open and un-oriented strings with no gauge theory counterpart [Billò, Lerda, Frau, Fucito, Pesando, Morales, Blumenhagen, Cvetic, Weigand, Ibanez, Uranga, MB, Kiritsis, Schellekens, Argurio, Kachru, Bertolini, . . .]

A ‘simple’ un-oriented D-brane model



. . . and its (consistent) sub-quiver



Hypercharge and Yukawa's

Sub-quiver of local tadpole free quiver: balance of in-out arrows at each node (including flavour branes and/or fluxes)

Consistent hypercharge assignement

$$Y = -\frac{1}{3}q_3 + q_1 - q_{1'} + q_{1"}$$

trace-less Chan-Paton matrix [Aldazabal, Franco, Ibanez, Rabadan, Uranga; Cvetic, Halverson, Richter].

All perturbative Yukawa's are encoded, while exotic instantons induce extra mass terms

Interesting challenge for the future: global consistency and CY-singularities

Super-field content and interactions

To minimal superfield content of MSSM

$$Q^{i,\alpha,f}_{+1/3},\ L^{\alpha,f}_{-1},\ U^{c,f}_{i,-4/3},\ E^{c,f}_{+2},\ D^{c,f}_{i,+2/3},\ H^{\alpha}_{u,+1},\ H^{\alpha}_{d,-1}$$

add ‘vector-like’ pair

$$D^{c'}_{i,+2/3}(B=-1/3), \quad C_{[jk],-2/3}(B=-2/3)=\epsilon_{ijk}\tilde{C}^{i}$$

B and *L* preserving renormalisable superpotential

$$\mathcal{W}_{pert}=\mathcal{W}_{MSSM}+\mathcal{W}_{new}$$

with

$$\mathcal{W}_{MSSM}=h_D H^{\alpha}_{d} Q^{i}_{\alpha} D^{c}_{i}+h_E H^{\alpha}_{d} L_{\alpha} E^{c}+h_U H^{\alpha}_{u} Q^{i}_{\alpha} U^{c}_{i}+\mu H^{\alpha}_{u} H_{\alpha d}$$

and

$$\mathcal{W}_{new}=h_{D'} Q^{\alpha i} H_{d\alpha} D'^{c}_{i}+h_C Q^{i} Q^{j} C_{ij}$$

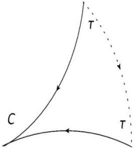
Including ‘exotic’ instantons

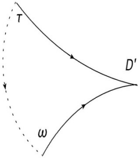
Minimal $O(1)$ E2-instanton: $S_{E2} \sim V(\Sigma_3)/g_s + i\int_{\Sigma_3} C_3$

E2-D6-D6’ interactions $\mathcal{L}_{E2-D6-D6'} \sim \omega D'_i \tau^i + C_{jk}\tau^j\tau^k$

Integrating out the fermionic modulini ω, τ^i produces R- and B- violating non-perturbative super-potential

$$\mathcal{W}_{E2} = M_S e^{-S_{E2}} \int d^3\tau d\omega e^{\omega D'_i \tau^i + C_{jk}\tau^j\tau^k} = M_S e^{-S_{E2}} \epsilon^{ijk} D'_i C_{jk}$$





Effective Superpotential for $E << \mathcal{M}_0$

Integrating out $D'_i, \tilde{C}^i$ pair ($\mathcal{M}_0 = M_S e^{-S_{E2}}$)

$$\mathcal{W}_{eff} = h_C h_{D'} \frac{1}{\mathcal{M}_0} Q^{\alpha i} H_{d\alpha} Q^j_\beta Q^{k\beta} \epsilon_{ijk}$$

R-symmetry and Baryon number violation

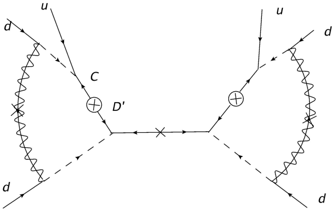
Integrating out Higgs super-fields

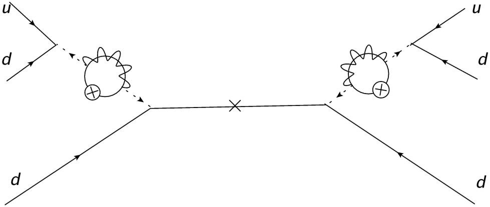
$$\frac{\tilde{q}\tilde{q}q}{\mathcal{M}_0} \frac{1}{M_{\tilde{H}}} \frac{\tilde{q}\tilde{q}q}{\mathcal{M}_0}$$

Conversion from s-quarks to quarks, further suppression

$$\delta m\, n^t n \sim \frac{qqq}{m_{\tilde{g}} \mathcal{M}_0} \frac{1}{M_{\tilde{H}}} \frac{qqq}{\mathcal{M}_0 m_{\tilde{g}}}$$

Effective Majorana mass for the Neutron





Mass scales

Including strong IR dynamics (MIT bag model, lattice, ... holography?) $\delta m = \langle \bar{n} | \mathcal{H}_{eff} | n \rangle \approx \Lambda^6_{QCD} / \mathcal{M}^5 < 10^{-23}\, eV$

$\rightarrow$ new physics mass scale at PeV

$\mathcal{M} = (m^2_{\tilde{g}} \mathcal{M}^2_0 M_{\tilde{H}})^{1/5} > 300\, TeV$

- Trivial 'democratic' choice $m_{\tilde{g}} \approx \mathcal{M}_0 \approx M_{\tilde{H}} \approx 300\, TeV$
- Heavy Higgsino, gaugino with $m_{\tilde{g}} \approx M_{\tilde{H}} \approx M_{SUSY} \approx 10^4\, TeV$, vector-like pair at $\mathcal{M}_0 = 1\, TeV$ or less ... LHC!!
- TeV SUSY with $m_{\tilde{g}} \approx M_{\tilde{H}} \approx M_{SUSY} \approx 1\, TeV$, vector-like pair at $\mathcal{M}_0 = 10^{15}\, TeV$

String scale could be very high

Suppressed proton decay

With desired intersections of D6-branes with each other and with E2-instanton(s) R-parity and B-number violated only non-perturbatively by $\mathcal{W}_{E2}$

$QQQQU^c/\mu\mathcal{M}_0$ terms irrelevant for proton decay: at least one super-partner, not energetically allowed, in final state

Yet, adding RH neutrini with

$$\mathcal{W}_N = \frac{1}{2} m_N N^2 + y_N H_u L N$$

Majorana mass induces dangerous super-potential terms $L^2(QD^c + LE^c)^2/m_N\mu^2, L^2Q^3(QD^c + LE^c)^2/m_N\mu^2\mathcal{M}_0$

Dirac masses still OK

FCNC's and scalar sector

Most stringent bound from K-Kbar: $\mathcal{M} > 100\,TeV$

Possible deviations in b-sγ transitions indirect hint for $\phi_{D'}$

Two possibilities

- F$>$B hierarchy: natural for C (Higgs-like), inverted for D' (quark-like)
- B$>$F hierarchy: inverted for C (Higgs-like), natural for D' (quark-like)

Interesting phenomenology at LHC from jj+missing (similar to other $\tilde{q}$), 4j or ttjj $\mathcal{M}_{light} > 1\,TeV$ [. . . Addazi's talk]

Neutralino-Neutron Mixings

Combining B-ino, W$_3$-ino, higgs-ini with neutron and anti-neutron $\mathcal{W}_{mix} = y_C y_{D'} QQQH_d/\mathcal{M}_0$

$$\begin{pmatrix} M_1 & 0 & M_Z \cos\beta \sin\theta_W & -M_Z \sin\beta \sin\theta_W & 0 & 0 \\ 0 & M_2 & -M_Z \cos\beta \cos\theta_W & M_Z \sin\beta \cos\theta_W & 0 & 0 \\ M_Z \cos\beta \sin\theta_W & -M_Z \cos\beta \cos\theta_W & 0 & -\mu & 0 & 0 \\ -M_Z \sin\beta \sin\theta_W & M_Z \sin\beta \cos\theta_W & -\mu & 0 & \delta\mu_{dn} & \delta\mu_{d\bar{n}} \\ 0 & 0 & 0 & \delta\mu^*_{dn} & m_n & \delta m \\ 0 & 0 & 0 & \delta\mu^*_{d\bar{n}} & \delta m^* & m_n \end{pmatrix}$$

Also neutralini-axini mixings could be considered, further enlarging the above mass matrix [Coriano, Irges, Kititsis; Anastasopoulos, Fucito, Lionetto, Pradisi, Racioppi, Stanev; . . .]

A crazy idea (... maybe so crazy to be true)

Very Fast Transitions? Very low limits in Ultra Cold Neutron Chambers. In absence of magnetic field

$$\tau_{n-invis} > 414s$$

[Serebrov et al (2008), Altarev et al (2009), Bodek et al. (2009), Nakamura et al (2010); PDG]

Shift of GZK cutoff: $P(p\gamma \to \pi^0 p) \approx P(p\gamma \to \pi^+ n)$ then neutron conversion . . .

In principle, transitions as fast as $\tau_{n-invis} \sim$ 500 s possible, if

- a neutralino of the mass of the neutron.
- one or more axini extending the mass matrix,
- tuning of CP violating parameters to fast neutron-neutralino but slow neutralino-antineutron

The Neutron-νeutrino connection

Pati-Salam and related models

L-R symmetry $SU(2)_L \times SU(2)_R \times SU_c(3) \times U(1)_{B-L}$, Pati-Salam (P-S) $SU(2)_L \times SU(2)_R \times SU(4)_d \subset SO(10)$ …GUT*

Connection between B- and L- number violations [Pati-Salam; Babu, Mohapatra, Senyanovic]

Higgses $\Delta_R = (\mathbf{1}, \mathbf{3}, \mathbf{10})$ and $\Delta_L = (\mathbf{3}, \mathbf{1}, \mathbf{10}^*)$ break L-R symmetry and $U(1)_{B-L}$ if $\langle \Delta_R \rangle = v_R \neq 0$, $\langle \Delta_L \rangle = 0$.

After $SU(4)_d \to SU(3)_c \times U(1)_{B-L}$

$$(\mathbf{1}, \mathbf{3}, \mathbf{10}) = (\mathbf{1}, \mathbf{3}, \mathbf{1})_{-2} + (\mathbf{1}, \mathbf{3}, \mathbf{3})_{-2/3}, +(\mathbf{1}, \mathbf{3}, \mathbf{6})_{2/3}$$

Color singlet di-leptons → RH neutrini mass $\langle \Delta^c_{\nu^c \nu^c} \rangle \nu^c \nu^c$

Color sextet di-quarks → Baryon number violation

Neutron-neutrino connection

In susy extensions, quartic superpotential

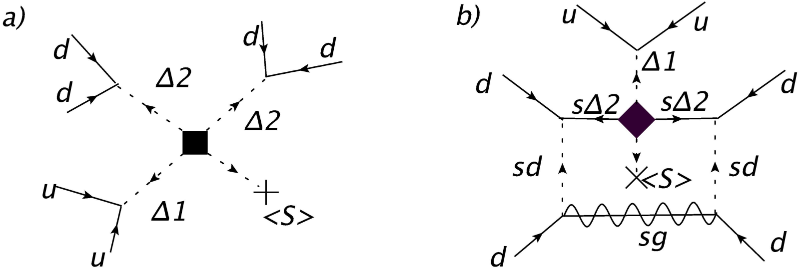
$$\mathcal{W}_4 = \frac{1}{\mathcal{M}_0} \Delta^c \Delta^c \Delta^c \Delta^c \to \frac{1}{\mathcal{M}_0} \Delta^c_{u^c u^c} \Delta^c_{d^c d^c} \Delta^c_{d^c d^c} \Delta^c_{\nu^c \nu^c} + \dots$$

When $\langle \Delta^c_{\nu^c \nu^c} \rangle \neq 0$ $U(1)_{B-L}$ breaking, RH neutrini masses

Moreover Majorana mass for neutron as in Figures

FCNC's constraints: mass of color sextets above TeV-scale

NNbar transition in PS-like model



PS-like models with open unoriented strings

OK PS-like $U(4) \times Sp(2) \times Sp(2)$ or $U(4) \times U(2) \times U(2)$

But NO $(\mathbf{1}, \mathbf{3}, \mathbf{10})$ two ends on $U(4)$, two on $Sp(2)_R$
…multi-pronged strings (?)

Rather $\phi_{RR}(\mathbf{1}, \mathbf{3_R}, \mathbf{1})$, $\phi_{LL}(\mathbf{3_L}, \mathbf{1}, \mathbf{1})$, $\Delta(\mathbf{1}, \mathbf{1}, \mathbf{10})$, $\Delta^c(\mathbf{1}, \mathbf{1}, \mathbf{10}^*)$

$\langle \phi_{RR} \rangle = v_R$ and $\langle \phi_{LL} \rangle = 0$ break L-R symmetry

$\langle S \rangle = v_{B-L}$ color singlet in Δ breaks $U(1)_{B-L}$:
$SU(4) \to SU(3)^*$

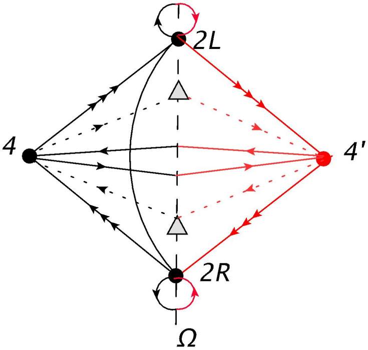
$$\mathcal{W}_4 = \Delta^c \Delta^c \Delta^c \Delta^c / \mathcal{M}_0 \to S^c \Delta^c_6 \Delta^c_6 \Delta^c_6 / \mathcal{M}_0 + \dots$$

generated by exotic instantons

$U(1)_4$ anomalous, Stückelberg mechanism

*For different Higgsing [Anastasopoulos, Leontaris, Vlachos]

Un-oriented PS-like quiver



Non-perturbative Superpotential

$E2$-brane $O(1)$ instanton intersecting **twice** $U(4)$ stack

8 fermionic modulini τ^i_r, $i = 1, ..., 4$, $r, s = 1, 2$

$$\mathcal{L}_{E2-D6-D6} \sim \tau^i_r \Delta^c_{(ij)} \tau^j_s \epsilon^{rs}$$

Integrating fermionic modulini

$$\mathcal{W}_{E2} = \frac{1}{\mathcal{M}_0} \epsilon^{ijkl} \epsilon^{i'j'k'l'} \Delta^c_{ii'} \Delta^c_{jj'} \Delta^c_{kk'} \Delta^c_{ll'}$$

After $SU(4) \to SU(3) \times U(1)_{B-L}$, $\mathbf{10} \to (\mathbf{6}_{+2/3}, \mathbf{3}_{-2/3}, \mathbf{1}_{-2})$,

$\Delta^c_{\mathbf{10}} \to \Delta_{\mathbf{6}}$ (di-quark), $T_{\mathbf{3}}$ (triplet), S (singlet di-lepton)

Complete super-potential after $SU(4) \to SU(3) \times U(1)_{B-L}$ breaking

Schematically

$$
\begin{gathered}
\mathcal{W} \sim y_1 h_{\alpha\dot{\alpha}} Q^{i\alpha} Q^{c^{i\dot{\alpha}}} + y_1 h_{\alpha\dot{\alpha}} L^{\alpha} L^{c^{\dot{\alpha}}} + \mu h_{\alpha\dot{\alpha}} h^{\dot{\alpha}\alpha} \\
+ m_L \phi_{LL}^2 + m_R \phi_{RR}^2 + a_L \phi_{LL}^3 + a_R \phi_{RR}^3 \\
+ \frac{1}{M_1} \phi_{LL}^{\alpha\beta} (Q_\alpha^i Q_\beta^j \Delta_{ij} + Q_\alpha^i L_\beta T_{3i} + L_\alpha L_\beta S) \\
+ \frac{1}{M_2} \phi_{RR}^{\dot{\alpha}\dot{\beta}} (Q_{\dot{\alpha}}^{c,i} Q_{\dot{\beta}}^{c,j} \Delta_{ij}^c + Q_{\dot{\alpha}}^{c,i} L_{\dot{\beta}}^c T_{3i}^c + L_{\dot{\alpha}}^c L_{\dot{\beta}}^c S^c) \\
+ \frac{1}{M_3} h^t \phi_{LL} h \phi_{RR} + m_\Delta (\Delta_6 \Delta_6^c + T_3 T_3^c + S S^c) + \frac{1}{M_4} (\Delta_6 \Delta_6^c + T_3 T_3^c + S S^c)^2 \\
+ \frac{1}{\mathcal{M}_0} \left[\epsilon_{ijk}^{SU(3)} \epsilon_{i'j'k'}^{SU(3)} \Delta_6^{c^{ii'}} \Delta_6^{c^{jj'}} \Delta_6^{c^{kk'}} S + \epsilon_{ijk}^{SU(3)} \epsilon_{i'j'k'}^{SU(3)} \Delta_6^{c^{ii'}} \Delta_6^{c^{jj'}} T_3^{c^k} T_3^{c^{k'}} + c.c \right]
\end{gathered}
$$

Connection neutron/neutrino mass

Majorana mass for neutrini $m_N \sim v_R v_{B-L}/M_2$.
For example, $m_N \simeq 10^{12} GeV$
if $v_R = \langle \phi_{RR} \rangle \simeq M_2$ and $v_{B-L} = \langle S \rangle \simeq 10^{12} GeV$.
Dirac masses via Yukawa couplings to $h_{LR} = h_{\alpha\dot{\alpha}}$
At the same time

$$\mathcal{W}_{\Delta B=2} = \frac{1}{\mathcal{M}_0} \epsilon^{u^c d^c d^c \nu^c} \epsilon^{u'^c d'^c d'^c \nu'^c} \Delta^c_{u^c u'^c} \Delta^c_{d^c d'^c} \Delta^c_{d^c d'^c} S^c_{\nu^c \nu'^c}$$

$$\rightarrow (v_{B-L}/\mathcal{M}_0) \epsilon^{SU(3)}_{ijk} \epsilon^{SU(3)}_{i'j'k'} \Delta_6^{c^{ii'}} \Delta_6^{c^{jj'}} \Delta_6^{c^{kk'}}$$

induces NNbar transitions (shown in Figure)

NNbar transitions, parameters

Relevant Yukawa coupling

$$y v_R Q^c Q^c \Delta^c / M_2 \to \tilde{y} [\Delta^c_{u^c u^c} u^c u^c + \Delta^c_{d^c d^c} d^c d^c]$$

with $\tilde{y} = y v_R / M_2$

Effective operator $G_{n-\bar{n}} (udd)^2$ with

$$G_{n-\bar{n}} \simeq \frac{g_3^2}{16\pi} \frac{\tilde{y}^2 v_{BL}}{M^2_{\Delta^c_{u^c u^c}} M^2_{\Delta^c_{d^c d^c}} M_{SUSY} \mathcal{M}_0}$$

Further insights

No proton decay $\Delta B = 2$

S similar to Majoron (di-lepton, emitted in $0\nu\beta\beta$), rather *exoticon*

If exoticon coupling to three color sextets with μ_S, then replace v_{B-L} with μ_S in $G_{n-\bar{n}}$

Nuclear transitions

$$(Z, A) \to (Z, A{-}2) + \textit{missing energy}$$

Estimated rate $\Gamma \sim \kappa_h (\mathcal{M}_{n\bar{n}})^{-3} m_N^{14} G^2_{n-\bar{n}} GeV$, where $\kappa_h \sim 10^{-6}$ for hadronic corrections (strong IR dynamics)

Very suppressed process $\tau_{A\to A-2} > 10^{40}\, yr > \tau_p$

Conclusions

- Exotic instantons can indirectly generate neutron Majorana mass, avoiding fast proton decay, FCNC's
- Neutron-Antineutron oscillations compatible with present experimental bound $\tau_{n\bar{n}} \approx 2.7 yr$ can be tested in near future experiments to set $\tau_{n\bar{n}} > 10^2 yr$
- Interesting signatures for LHC (D'-C pair), future colliders, UCN ($n \to inv$), UHECR (shift of GZK cutoff) and even DA-MA (neutron-neutralino mixing)
- No (compelling) need for TeV-scale SUSY breaking nor for TeV-scale gravity/strings.
- Neutron physics as a portal on non-perturbative String Theory / Quantum Gravity with a new scale $\mathcal{M} \approx PeV$

Outlook

- How generally extra matter and/or extra (non-)perturbative couplings can generate neutron Majorana masses and trigger $n - \bar{n}$ oscillations?
- Consistency of local (easy?) and global (hard!) embedding, including effects of fluxes
- Phenomenology vs experimental constraints
- Baryogenesis vs Lepto-genesis