Probing High Scale Theories with $n - \overline{n}$ Oscillations

K.S. Babu

Oklahoma State University

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Plan

- Neutron-antineutron oscillations is governed by $d = 9$ operator

$$\frac{(udd)^2}{\Lambda^5}$$

- Near-term sensitivity on the scale of new physics is $\Lambda \sim 100$ TeV
- What true energy scale does $n - \overline{n}$ oscillation probe?
- Two examples will illustrate the true scale probed is 10^{15} GeV.
- One example based on left-right symmetry, the other based on $SO(10)$ unified theory

KB, R. Mohapatra (2001); KB, R. Mohapatra (2012)

Part I: Left-Right Symmetric Model

$n - \bar{n}$ oscillations in left-right symmetry

- Left-right symmetry well motivated as it explains origin of parity violation and introduces ν_R leading to neutrino masses
  Mohapatra, Pati (1975); Mohapatra, Senjanovic (1975)
- Gauge symmetry: $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2}$$

Marshak, Mohapatra(1980)

- Fermion content: $L = \begin{pmatrix} \nu \\ e \end{pmatrix}; \quad L^c = \begin{pmatrix} e^c \\ -\nu^c \end{pmatrix}$

$$Q = \begin{pmatrix} u \\ d \end{pmatrix}; \quad Q^c = \begin{pmatrix} d^c \\ -u^c \end{pmatrix}$$

Under Parity, $L \leftrightarrow L^c$, $Q \leftrightarrow Q^c$, $W_L \leftrightarrow W_R$

Supersymmetric left-right models

- In the SUSY version, the Higgs fields consist of:

$\Phi_a(2,2,0)$; $\{\chi(2,1,1)+\chi^c(1,2,-1)\}$, $\{\bar{\chi}(2,1,-1)+\bar{\chi}^c(1,2,1)\}$, $S(1,1,0)$

- Superpotential has a Z_4 R-parity where W and Higgs fields change sign, (Q, Q^c) are even and $(L, L^c) \sim (i, -i)$:

$$\begin{aligned} W &= h_a Q\Phi_a Q^c + h'_a L\Phi_a L^c + \lambda_a \chi\Phi_a\chi^c + \lambda'_a \bar{\chi}\Phi_a\bar{\chi}^c + \\ &\quad \kappa S(e^{i\xi}\chi^c\bar{\chi}^c + e^{-i\xi}\chi\bar{\chi} + aS^2 - M^2) + \mu_{ab}\mathrm{Tr}(\Phi_a\Phi_b)S \end{aligned}$$

- Yukawa coupling matrices h_a, h'_a are hermitian, and all parameters are real, due to Parity symmetry
- This solves the strong CP problem (without an axion), the SUSY CP problem – related to EDM of neutron, and solves μ problem

KB, Dutta, Mohapatra (2001)

Parity solution to strong CP problem

- QCD Lagrangian allows a P and CP violating term

$$\mathcal{L}_{QCD} \supset \frac{g^2}{32\pi^2}\theta G_{\mu\nu}\tilde{G}^{\mu\nu}$$

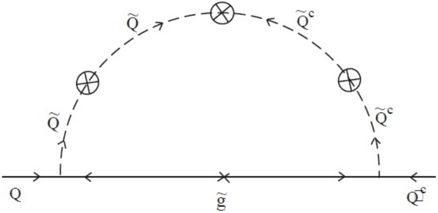
- This leads to a physical observable $\bar{\theta}$:

$$\bar{\theta} = \theta + \mathrm{ArgDet}(M_u M_d) - 3\mathrm{Arg}(M_{\tilde{g}})$$

- $\bar{\theta}$ will induce a neutron EDM, $d_n \simeq 10^{-16}\bar{\theta}$, requiring $\bar{\theta} < 10^{-10}$
- Why $\bar{\theta} \ll 1$ is the strong CP problem
- Parity can solve the problem, since $\theta = 0$ due to P, and since $M_{u,d}$ are hermitian, and gluino mass is real also due to P

Parity solution to strong CP problem

- $\bar{\theta}$ will be induced through loops, which makes $M_{u,d}$ non-hermitian:



- Induced $\bar{\theta}$ is:

$$\delta\bar{\theta} \simeq \frac{2\alpha_s}{3\pi}\left(\frac{\ln(M_U/M_W)}{16\pi^2}\right)^4 \left(k_1 \mathrm{Im}\mathrm{Tr}[Y_u^2 Y_d^4 Y_u^4 Y_d^2] + k_2 \mathrm{Im}\mathrm{Tr}[Y_d^2 Y_u^4 Y_d^4 Y_u^2]\right)$$

$$\simeq 3 \times 10^{-21}(k_1 - k_2)\left(\frac{\tan\beta}{10}\right)^6$$

Neutrino masses and $n-\bar{n}$ oscillations

- Two Planck suppressed operators allowed by all symmetries:

$$\begin{aligned} \mathcal{O}_1 &= f\left[(L^c\chi^c)^2 + (L\chi)^2\right] , \\ \mathcal{O}_2 &= f'\left[Q^cQ^cQ^c\bar{\chi}^c + QQQ\bar{\chi}\right] \end{aligned}$$

- Once $\langle\chi^c\rangle = v_R$ develops, $\mathcal{O}_1$ generates right-handed neutrino masses:

$$M_{\nu_R} = \frac{f\, v_R^2}{M_{\rm Pl}}$$

- $\mathcal{O}_2$ leads to

$$W_{\rm eff} = \left(\frac{f'\, v_R}{M_{\rm Pl}}\right) u^c d^c d^c$$

- Compare with $\lambda'' u^c d^c d^c$ operator of R-parity violating SUSY
- $\mathcal{O}_2$ leads to $n-\bar{n}$ oscillations, tied to neutrino mass generation

Neutrino masses and $n - \overline{n}$ oscillations

- Light neutrino mass given by seesaw as:

$$m_\nu = \frac{M_{\rm Pl} (m_\nu^D)^2}{f\, v_R^2}$$

- δm entering $n - \overline{n}$ oscillation is

$$\delta m_{n-\overline{n}} = \frac{C\, f'\, v_R^2}{M_{\rm Pl}^2}$$

  where C is a purely low energy parameter

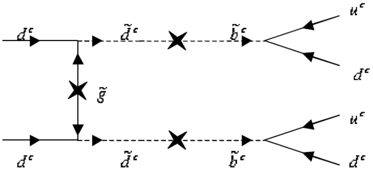
- This leads to a relation

$$m_\nu = \frac{C\, \tau_{n-\overline{n}}}{M_{\rm Pl}}$$

- $\tau_{n-\overline{n}}$ can then be computed in terms of neutrino mass, SUSY particle masses, if flavor structure of f, f' is known

Predictions for $\tau_{n-\bar{n}}$

- Dominant contribution to $\delta m_{n-\bar{n}}$:



$$G_{\Delta B=2} \simeq \frac{2g_3^2[(\delta_{RR}^{13})]^2 f'^2}{M_{\tilde{g}} m_{\tilde{q}}^4}$$

- Flavor changing coupling in squarks:

$$(\delta_{RR}^{13}) \simeq \frac{\lambda_t^2(3m_0^2 + A_0^2)}{8\pi^2(m_0^2 + 8M_{1/2}^2)}(V_{td}^* V_{tb}) \ln(M_{\rm Pl}/v_R) \simeq 2 \times 10^{-4}$$

- Estimate of $\tau_{n-\bar{n}}$ – updated with lattice matrix element (Rinaldi, Syritsyn, Wagman, Buchoff, Schroeder, 2018, 2019)

$$\tau_{n-\bar{n}} \simeq 2.2 \times 10^7 sec. \left(\frac{f}{f'^2}\right)\left(\frac{m_{\nu_\tau}}{0.06 \text{ eV}}\right)\left(\frac{m_t}{m_{\nu_\tau^D}}\right)^2\left(\frac{M_{\tilde{g}}}{3 \text{ TeV}}\right)\left(\frac{m_{\tilde{q}}}{3 \text{ TeV}}\right)^4$$

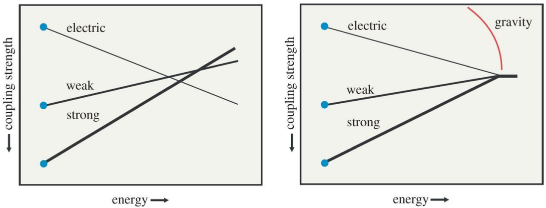
Predictions for $\tau_{n-\overline{n}}$

- The Dirac neutrino mass of ν_τ is $m^D_{\nu_\tau} \simeq m_t(m_\tau/m_b) \simeq m_t$ in the model
- Uncertainty arises from flavor structure of f, f'. Since these arise from Planck scale physics, they could be flavor universal
- SUSY particle masses are the other unknowns
- If SUSY is discovered at the LHC, this model would suggest observable $n - \overline{n}$ oscillation rate
- General SUSY models with R parity violation via $\lambda'' u^c d^c d^c$ couplings would lead to $n - \overline{n}$, but less predictive

Part II: $SO(10)$ Unified Model

$n - \overline{n}$ oscillation in $SO(10)$

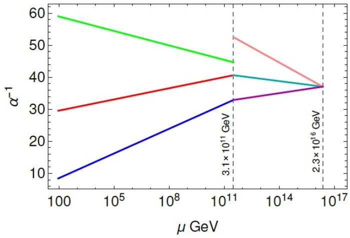
- Unification of couplings and matter fields is very attractive – GUTs
- Baryon number violation necessarily exist in such unified models
- Gauge couplings do not quite unify within Standard Model



- With SUSY unification works well. In non-SUSY $SO(10)$ typically intermediate scale assumed

Unification of couplings in $SO(10)$

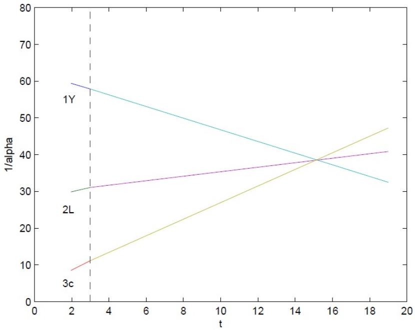
- Unification in non-SUSY $SO(10)$ with an intermediate scale Pati-Salam symmetry



- It is possible for $SO(10)$ to directly break to Standard Model. Some new particle should survive to TeV scale
- Among colored scalars, only sextets and octets are allowed due to proton decay limits

Unification of couplings in $SO(10)$

- Scenario: Color sextet $\Delta_{u^c d^c}$ and a weak triplet $(1,3,0)$ survive to TeV:



- Unification occurs around 5×10^{15} GeV, consistent with $p \to e^+ \pi^0$ limit
- For color sextet mass heavier than few TeV, a GUT triangle develops

$n - \overline{n}$ oscillation in $SO(10)$

- $\Delta_{u^c d^c}$ color sextet is part of 126_H Higgs needed for symmetry breaking
- It is accompanied by $\Delta_{u^c u^c}$ and $\Delta_{d^c d^c}$ color sextets with GUT scale masses
- Baryon number violating interactions relevant for $n - \overline{n}$:

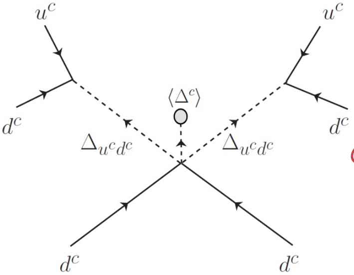
$$\begin{aligned} \mathcal{L}_{\Delta B \neq 0} &= f_{dd}\, d^c d^c \Delta_{d^c d^c} + \frac{f_{ud}}{\sqrt{2}} (u^c d^c + d^c u^c) \Delta_{u^c d^c} + f_{uu}\, u^c u^c \Delta_{u^c u^c} \\ &+ \lambda v_{BL} \left(\Delta_{u^c d^c} \Delta_{u^c d^c} \Delta_{d^c d^c} + \Delta_{d^c d^c} \Delta_{d^c d^c} \Delta_{u^c u^c} \right) + h.c. \end{aligned}$$

- Effective Lagrangian after heavy states are integrated out:

$$\mathcal{L}^{\mathrm{eff}}_{\Delta B \neq 0} = \frac{f_{ud}}{\sqrt{2}} (u^c d^c + d^c u^c) \Delta_{u^c d^c} + \frac{\lambda v_{BL} f_{dd}}{M^2_{\Delta_{d^c d^c}}} d^c d^c\, \Delta^*_{u^c d^c} \Delta^*_{u^c d^c} + h.c.$$

$\tau_{n-\bar{n}}$ in $SO(10)$

- $n - \bar{n}$ transition is mediate by the diagram:



$$G_{N-\bar{N}} \simeq \frac{\eta f_{ud}^2 f_{dd} \lambda v_{BL}}{M^4_{\Delta_{u^c d^c}} M^2_{\Delta_{d^c d^c}}}$$

- $\eta \simeq 50$ is a renormalization factor in going from GUT to TeV

- For $f_{dd} = f_{ud} = 5 \times 10^{-3}$, $\lambda v_{BL} = 6 \times 10^{15}$ GeV, $M_{\Delta_{u^c d^c}} = 5$ TeV, and $M_{\Delta_{d^c d^c}} = 10^{14}$ GeV

$$\tau_{n-\bar{n}} \approx 4 \times 10^9 \text{ sec.}$$

GUT scale baryogenesis

- Baryogensis in this model is tied to $n - \overline{n}$ oscillations
- Arises from decay of GUT scale sextet $\Delta_{d^c d^c}$. It has two decays:

$$\Delta_{d^c d^c} \to \overline{d^c d^c}, \quad \Delta_{d^c d^c} \to \Delta^*_{ud} \Delta^*_{ud}$$

- Since $\Delta_{u^c d^c} \to \overline{u^c}\,\overline{d^c}$, both $\Delta_{u^c d^c}$ and $\Delta_{d^c d^c}$ can be assigned $B = 2/3$. Then the second decay violated B by two units
- B asymmetry is generated in the decay of $\Delta_{d^c d^c} \to \Delta^*_{u^c d^c} \Delta^*_{u^c d^c}$
- Adequate asymmetry that is not washed out by sphalerons is induced
- There is a second $\Delta'_{d^c d^c}$ from 54_H needed to break symmetry. These two states mix

GUT scale baryogenesis

- Mixing of the color sextets:

$$\begin{aligned} \Delta_{d^c d^c} &= a\,\Delta_{d^c d^c}(126) + b\,\Delta_{d^c d^c}(54) \\ \Delta'_{d^c d^c} &= -b^*\,\Delta_{d^c d^c}(126) + a^*\,\Delta_{d^c d^c}(54) \end{aligned}$$

- Cubic scalar coupling with B violation:

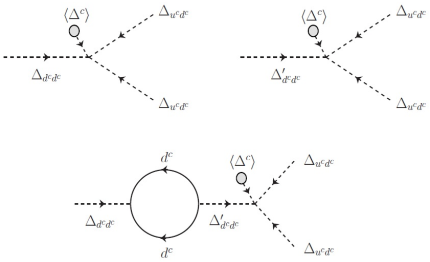
$$V^{(3)} = \Delta_{u^c d^c}\Delta_{u^c d^c}\left\{\Delta_{d^c d^c}(\lambda v_{BL} a^* + \mu b^*) + \Delta'_{d^c d^c}(-\lambda v_{BL} b + \mu a)\right\} + h.c.$$

- Fermion Yukawa couplings in mass basis:

$$\mathcal{L}_{\rm Yuk} = f_{dd}\, d^c d^c\, \left(a^*\,\Delta_{d^c d^c} - b\,\Delta'_{d^c d^c}\right) + h.c.$$

From here B asymmetry can be computed

GUT scale baryogenesis



- Baryon asymmetry:

$$\epsilon_{B-L} = \frac{2}{\pi}\,\mathrm{Tr}(f_{dd}^{\dagger} f_{dd})\,\mathrm{Im}\left\{\frac{-\lambda v_{BL} b + \mu a}{\lambda v_{BL} a^* + \mu b^*}\right\}\left(\frac{x}{1-x}\right)\mathrm{Br}, \quad x = M^2_{\Delta_{d^c d^c}}/M^2_{\Delta'_{d^c d^c}}$$

- $\eta \simeq 10^{-10}$ can be easily generated
- Note that the asymmetry is related to $-\overline{n}$ oscillation parameters

Conclusions

- Although the $n - \overline{n}$ oscillation operator is $d = 9$,

$$\frac{(udd)^2}{\Lambda^5}$$

  it can probe GUT scale physics
- Two examples, one based on left-right symmetry, and one with $SO(10)$ were presented
- $n - \overline{n}$ oscillations and neutrino masses are connected in left-right model
- Baryon asymmetry and $n - \overline{n}$ oscillations are connected in the $SO(10)$ model