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Workshop on the original of P, CP and T Violation

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Solutions to the strong CP and SUSY phase problems with parity symmetry

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Solutions to the strong CP and SUSY phase problems with parity symmetry

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“Workshop on the origin of P, CP and T violation”

ICTP, Trieste, Italy

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Based on recent work

“Minimal Supersymmetric Left-Right Model”
K.S. Babu and R.N. Mohapatra

hep-ph/0807.0481

Why SUSY Left-Right Symmetry?

- Origin of parity violation better understood
- Compelling reason for neutrino mass
- Automatic R–parity in SUSY
- Natural solution to the strong CP problem
- Absence of excessive SUSY CP violation
- Pathway to $SO(10)$ unification

Minimal SUSY Left-Right Model

- Gauge group is $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
  - ◇ Enables one to define parity

- Quarks and leptons:

$$\begin{aligned} Q(3,2,1,\frac{1}{3}) &= \begin{pmatrix} u \\ d \end{pmatrix}; \quad Q^c(3^*,1,2,-\frac{1}{3}) = \begin{pmatrix} d^c \\ -u^c \end{pmatrix} \\ L(1,2,1,-1) &= \begin{pmatrix} \nu_e \\ e \end{pmatrix}; \quad L^c(1,1,2,1) = \begin{pmatrix} e^c \\ -\nu_e^c \end{pmatrix} \end{aligned}$$

- Higgs fields:

$$\begin{aligned} \Delta(1,3,1,2) &= \begin{pmatrix} \frac{\delta^+}{\sqrt{2}} & \delta^{++} \\ \delta^0 & -\frac{\delta^+}{\sqrt{2}} \end{pmatrix}; \quad \overline{\Delta}(1,3,1,-2) = \begin{pmatrix} \frac{\bar{\delta}^-}{\sqrt{2}} & \bar{\delta}^0 \\ \bar{\delta}^{--} & -\frac{\bar{\delta}^-}{\sqrt{2}} \end{pmatrix}; \\ \Delta^c(1,1,3,-2) &= \begin{pmatrix} \frac{\delta^{c^-}}{\sqrt{2}} & \delta^{c^0} \\ \delta^{c^{--}} & -\frac{\delta^{c^-}}{\sqrt{2}} \end{pmatrix}; \quad \overline{\Delta}^c(1,1,3,2) = \begin{pmatrix} \frac{\bar{\delta}^{c+}}{\sqrt{2}} & \bar{\delta}^{c^{++}} \\ \bar{\delta}^{c^0} & -\frac{\bar{\delta}^{c+}}{\sqrt{2}} \end{pmatrix}; \\ \Phi_a(1,2,2,0) &= \begin{pmatrix} \phi_1^+ & \phi_2^0 \\ \phi_1^0 & \phi_2^- \end{pmatrix}_a \quad (a = 1-2); \quad S(1,1,1,0) \end{aligned}$$

Under parity:

$$Q \rightarrow Q^{c*}, \quad L \rightarrow L^{c*}, \quad W_L \rightarrow W_R^*, \quad B \rightarrow B^*, \quad G \rightarrow G^*, \quad \theta \rightarrow \bar{\theta}$$

$$\Phi \rightarrow \Phi^\dagger, \quad \Delta \rightarrow \Delta^{c*}, \quad \overline{\Delta} \rightarrow \overline{\Delta}^{c*}, \quad S \rightarrow S^*$$

- Yukawa couplings to Φ and the A terms are hermitian
- Gluino and Bino masses real
- μ term for Φ becomes real
- If $\langle \Phi \rangle$ are also real, fermion mass matrix becomes hermitian
  - Can solve the strong CP problem
  - Can solve the SUSY CP problem

Superpotential:

$$\begin{aligned} W &= Y_u Q^T \tau_2 \Phi_1 \tau_2 Q^c + Y_d Q^T \tau_2 \Phi_2 \tau_2 Q^c + Y_\nu L^T \tau_2 \Phi_1 \tau_2 L^c + Y_\ell L^T \tau_2 \Phi_2 \tau_2 L^c \\ &+ i \left(f^* L^T \tau_2 \Delta L + f L^{cT} \tau_2 \Delta^c L^c \right) \\ &+ S \left[\mathrm{Tr} \left(\lambda^* \Delta \bar{\Delta} + \lambda \Delta^c \bar{\Delta}^c \right) + \lambda'_{ab} \mathrm{Tr} \left(\Phi_a^T \tau_2 \Phi_b \tau_2 \right) - \mathcal{M}_R^2 \right] + W' \end{aligned}$$

$$W' = \left[M_\Delta \Delta \bar{\Delta} + M_\Delta^* \Delta^c \bar{\Delta}^c \right] + \mu_{ab} \mathrm{Tr} \left(\Phi_a^T \tau_2 \Phi_b \tau_2 \right) + \mathcal{M}_S S^2 + \lambda_S S^3$$

- If W' is set to zero, there is an enhanced R symmetry
  - Helps understand the μ problem
  - In the SUSY limit, $\langle S \rangle = 0$, but after SUSY breaking, $\langle S \rangle \sim m_{\mathrm{SUSY}}$
  - Bidoublet mass term of order m_{SUSY}

Problem with the minimal model

Desired vacuum:

$$\langle \Delta^c \rangle = \begin{pmatrix} 0 & v_R \\ 0 & 0 \end{pmatrix}, \quad \langle \bar{\Delta}^c \rangle = \begin{pmatrix} 0 & 0 \\ \bar{v}_R & 0 \end{pmatrix}$$

Charge breaking vacuum:

$$\langle \Delta^c \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & v_R \\ v_R & 0 \end{pmatrix}, \quad \langle \bar{\Delta}^c \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & \bar{v}_R \\ \bar{v}_R & 0 \end{pmatrix}$$

All terms in the potential are identical for the two configurations

Except for the D–term which prefers the charge breaking vacuum

Kuchimanchi, Mohapatra (1993)

Suggested solutions

1. Break R–parity. $\Rightarrow v_R \sim 1$ TeV

   (Kuchimanchi, Mohapatra, 1993)

   SUSY dark matter lost

2. Use higher dimensional operators $\Rightarrow v_R \sim 10^{11}$ GeV

   (Aulakh, Melfo, Senjanovic, 1998)

   (Chacko, Mohapatra, 1998)

   Solution to strong CP and SUSY CP problems generically lost

3. Do nothing

   (Babu, Mohapatra, 2008)

How the model heals itself

- Δ^c has Majorana Yukawa couplings with ν^c $\Rightarrow$

  The effective potential contains new type of terms which drastically modifies the tree–level result

- Tree–level potential has no term of type

  $$\mathrm{Tr}(\Delta^c\Delta^c)\mathrm{Tr}(\Delta^{c\dagger}\Delta^{c\dagger})$$

  Induced by Majorana Yukawa couplings in V_{eff}

  Higher dimensional operators generate similar couplings

- Charge and R–parity conserving vacuum can be lower than charge breaking vacuum, if coefficient is positive

Effective Potential

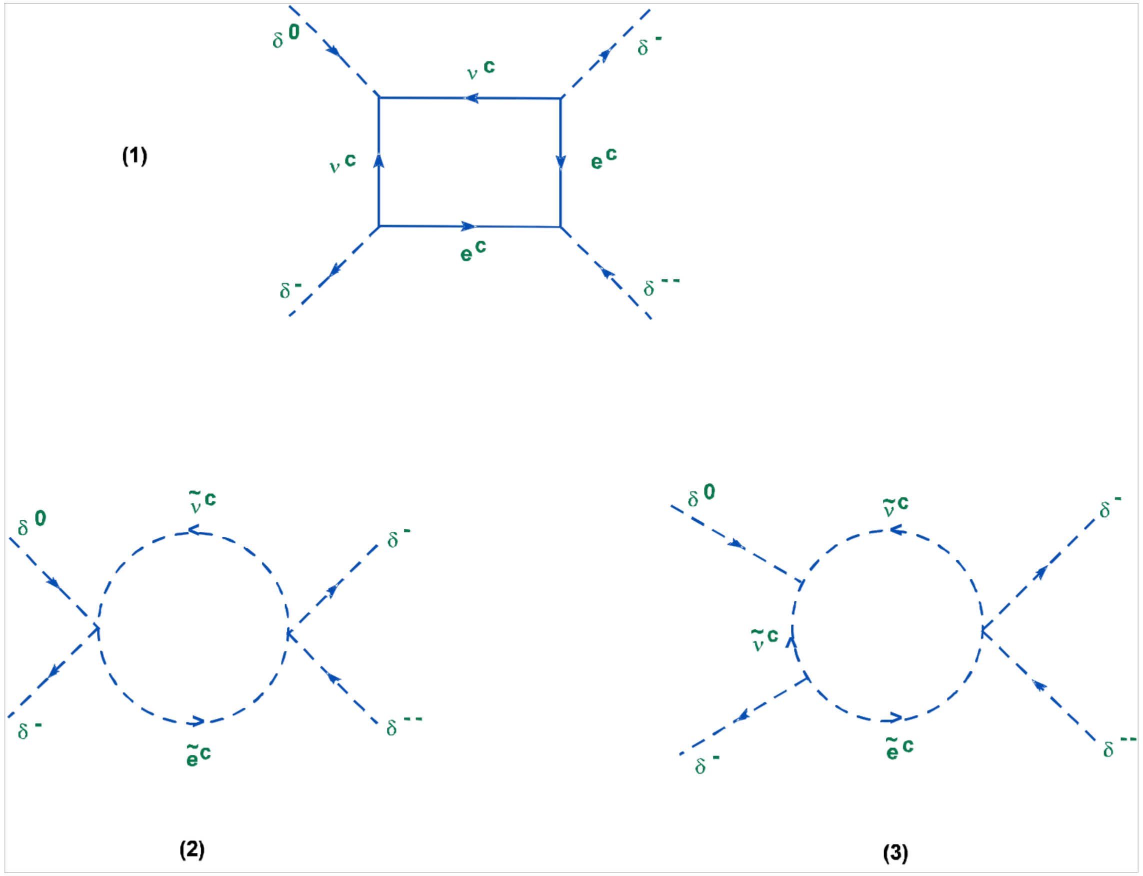
Field–dependent masses of (ν^c, e^c):

$$D^2_{1,2} = \frac{1}{2}\left[\mathrm{Tr}(\Delta^{c\dagger}\Delta^c) \pm \sqrt{\mathrm{Tr}(\Delta^{c\dagger}\Delta^c)^2 - \mathrm{Tr}(\Delta^c\Delta^c)\mathrm{Tr}(\Delta^{c\dagger}\Delta^{c\dagger})}\right]$$

$$\begin{aligned}
m^2_{1,2} &= |f|^2 D_1^2 + m^2_{L^c} + \frac{g_R^2}{2}[(D_2^2 - \overline{D}_2^2) - (D_1^2 - \overline{D}_1^2)] - \frac{g'^2}{2}[(D_1^2 - \overline{D}_1^2) + (D_2^2 - \overline{D}_2^2)], \\
&\pm \left|A_f f D_1 + \lambda^* S^* f \overline{D}_1\right|^2 \\
m^2_{3,4} &= |f|^2 D_2^2 + m^2_{L^c} + \frac{g_R^2}{2}[(D_1^2 - \overline{D}_1^2) - (D_2^2 - \overline{D}_2^2)] - \frac{g'^2}{2}[(D_1^2 - \overline{D}_1^2) + (D_2^2 - \overline{D}_2^2)], \\
&\pm \left|A_f f D_2 + \lambda^* S^* f \overline{D}_2\right|^2 \\
m^2_{F_1} &= |f D_1|^2 \\
m^2_{F_2} &= |f D_2|^2
\end{aligned}$$

$$V_{\mathrm{eff}}^{1-\mathrm{loop}} = \frac{1}{64\pi^2}\sum_i (-1)^{2s}(2s+1) M_i^4 \left[\mathrm{Log}(\frac{M_i^2}{\mu^2}) - \frac{3}{2}\right]$$

Diagrams inducing effective potential



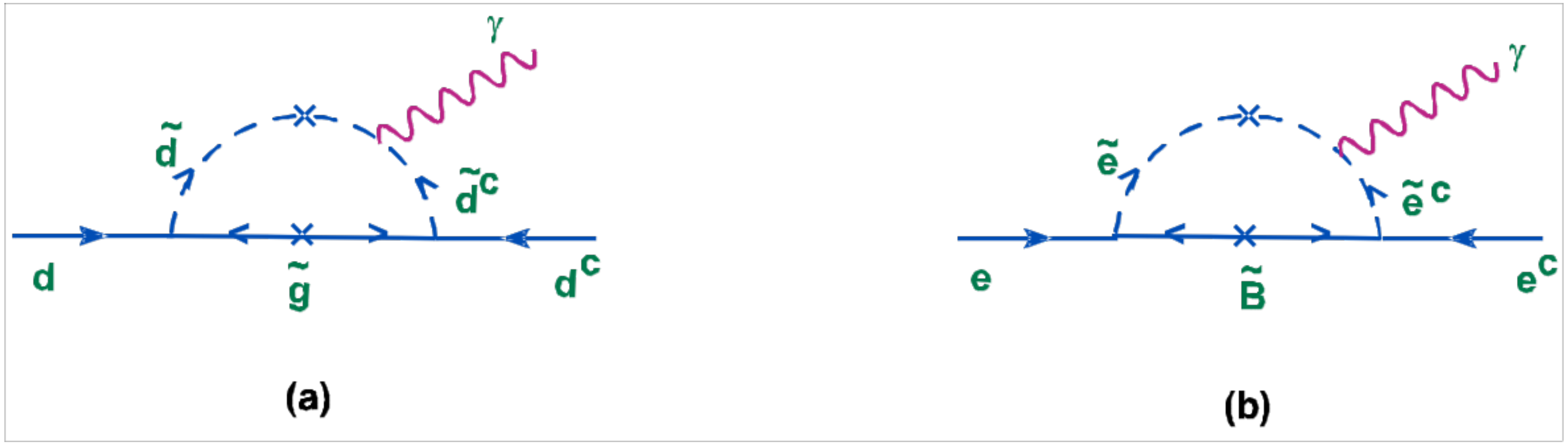
$$x = \frac{\mathrm{Tr}(\Delta^c \Delta^c)\mathrm{Tr}(\Delta^{c\dagger}\Delta^{c\dagger})}{[\mathrm{Tr}(\Delta^{c\dagger}\Delta^c)]^2}$$

$$\begin{aligned}
V_{\text{eff}}^{1-\text{loop}} &= -\frac{|f|^2 m_{L^c}^2 \mathrm{Tr}(\Delta^c \Delta^{c\dagger})}{64\pi^2}\Big[(4+2\ \ln 2) + 2(a_1 - a_2) g_R^2 \sqrt{1-x} + 2(a_1+a_2) g'^2 + \\
&- \left\{2 + (a_2 - a_1) g_R^2 + (a_2 + a_1) g'^2\right\}\left(1-\sqrt{1-x}\right) \ln\left(\frac{|f|^2 \mathrm{Tr}(\Delta^c \Delta^{c\dagger})}{2\mu^2}\left(1-\sqrt{1-x}\right)\right) \\
&+ \left\{\left((a_2 - a_1) g_R^2 - (a_2 + a_1) g'^2\right)\left(1+\sqrt{1-x}\right) + 2\sqrt{1-x}\right\} \ln\left(\frac{|f|^2 \mathrm{Tr}(\Delta^c \Delta^{c\dagger})}{2\mu^2}\left(1+\sqrt{1-x}\right)\right) \\
&- 2\ \ln\left(\frac{|f|^2 \mathrm{Tr}(\Delta^c \Delta^{c\dagger})}{\mu^2}\left(1+\sqrt{1-x}\right)\right)\Big]
\end{aligned}$$

$$\begin{aligned}
V^{\text{quartic}} &= -\frac{|f|^2 m_{L^c}^2 \mathrm{Tr}(\Delta^c \Delta^c)\mathrm{Tr}(\Delta^{c\dagger}\Delta^{c\dagger})}{128\pi^2 |v_R|^2}\Big[\{2 - \{a_1 - a_2) g_R^2 - (a_1 + a_2) g'^2\}(1 + 2\ \ln 2) \\
&+ (a_1 - a_2) g_R^2\ \ln\frac{|f v_R|^2}{\mu^2} - \{2 - (a_1 - a_2) g_R^2 + (a_1 + a_2) g'^2\}\ \ln x\Big] + \ldots
\end{aligned}$$

Global minimum problem is solved

Solving the SUSY CP problem



SUSY models generically lead to large EDM for neutron and electron

$$d_n^e \approx 10^{-23} \sin\phi \text{ e} - \text{cm}$$

Hermitian Yukawa couplings and A–terms $\Rightarrow$

$$\sin\phi = 0 \text{ at } v_R$$

RGE induced EDM $d_n^e \simeq 10^{-29}$ e-cm

Solving the strong CP problem

$$\bar{\theta} = \theta_{QCD} + \text{Arg}\{\text{Det}(M_u M_d)\} - 3\text{Arg}(M_{\tilde{g}}) \ .$$

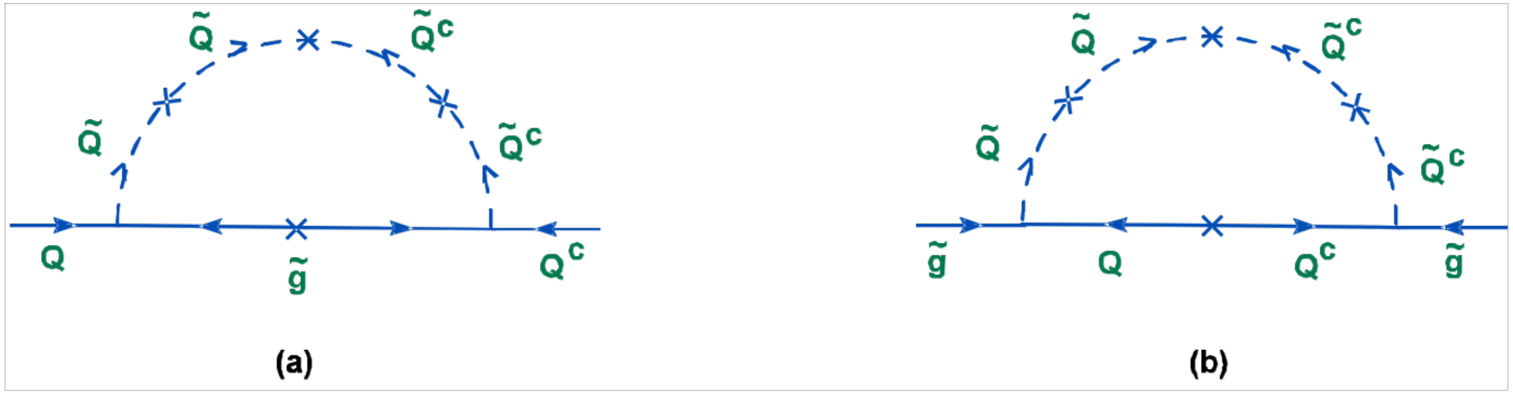
Leads to $d_n^e \simeq 10^{-16}\ \overline{\theta}$

$$\Rightarrow \overline{\theta} \leq 10^{-9}$$

- Parity makes $\theta_{QCD} = 0$
- Quark Yukawa matrices hermitian
- gluino mass is real
  $\Rightarrow \overline{\theta} = 0$ at tree level

(if $\langle \Phi \rangle \sim$ real)

Loop corrections to theta-bar



$$\delta\bar{\theta} \simeq \left(\frac{\ln(M_R/M_W)}{16\pi^2}\right)^4 \left[c_1 \mathrm{Im Tr}\left(Y_u^2 Y_d^4 Y_u^4 Y_d^2\right) + c_2 \mathrm{Im Tr}\left(Y_d^2 Y_u^4 Y_d^4 Y_u^2\right)\right]$$

$$\delta\bar{\theta} \sim 3 \times 10^{-27} (\tan\beta)^6 (c_1 - c_2)$$

Loop corrections preserve solution to strong CP problem

KB, Dutta, Mohapatra (2000)

Predictions of the minimal model

1. A pair of light doubly charged Higgs and Higgsino below TeV

   Pseudo–Goldstone of $SU(2)_R$ symmetry breaking

Doubly charged Higgs boson mass matrix:

$$\mathcal{M}^2_{\delta^{++}} = \begin{pmatrix} -2g_R^2(|v_R|^2 - |\overline{v}_R|^2 + \frac{X}{2}) - \frac{\overline{v}_R}{v_R^*}Y & Y^* \\ Y & 2g_R^2(|v_R|^2 - |\overline{v}_R|^2 + \frac{X}{2}) - \frac{v_R}{\overline{v}_R^*}Y \end{pmatrix}$$

$$Y = \lambda A_\lambda S + |\lambda|^2 (v_R \overline{v}_R - \frac{\mathcal{M}_R^2}{\lambda})^*$$

One doubly charged Higgs is massless at v_R

Acquires mass only via RGE

Mass $\leq (2-3)M_1$

Predictions of the minimal model (cont.)

2. Two pairs of Higgs doublets must remain light below v_R

   Otherwise CKM mixing vanish, even with two Yukawa coupling matrices for quarks

   Calculable SUSY flavor violation

   Proportional to $Y_u^\dagger Y_u$ in down sector

   Flavor structure identical to CKM structure

   Neutral Higgs mediated FCNC

   Similar to CKM structure

   Requires one pair of Higgs to be heavier than 10 TeV

Predictions of the minimal model (cont.)

3. CKM mixings arise only after radiative corrections

   Bidoublet Higgsino mass matrix:

$$m_\Phi = \begin{pmatrix} \mu_{11} & \mu_{12} \\ \mu_{21} & \mu_{22} \end{pmatrix}$$

   At v_R, $\mu_{12} = \mu_{21}$ due to parity

   Quark Yukawa couplings do not create asymmetry in μ_{ij}

   However, leptonic Yukawa couplings cause asymmetry $\mu_{12} \neq \mu_{21}$ since ν^c decouple at v_R

$$\frac{d}{dt}(\mu_{12} - \mu_{21}) = \frac{\mu_{12} + \mu_{21}}{32\pi^2} \mathrm{Tr}(Y_\nu^\dagger Y_\nu - Y_\ell^\dagger Y_\ell),$$

   Parametrically quark mixings are small,
   while leptonic mixings are not small

Predictions of the minimal model (cont.)

4. In the simplest version, $(\Delta, \overline{\Delta})$ remain light below TeV

$(\Delta, \overline{\Delta})$ Higgsino degenerate at v_R

Coupings of these particles probe right–handed neutrino mass structure

Rich collider phenomenology

Summary and conclusions

- Minimal SUSY left–right model works!
- Global minimum problem cured by efective potential
- Simple solution to SUSY CP and strong CP problems
- Predicts two sub–TeV doubly charged Higgs
- Left–handed triplet fields naturally light
- Rich collider phenomenology
- Much more works remains to be done

Thank you!