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Proton hexality and neutrino masses from an anomalous $U(1)$

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The supersymmetrized SM

renormalizable superpotential

$$W_{\text{ren.}} = \mu\, H_u\, H_d + h^u_{ij}\, H_u\, Q_i\, \bar{U}_j + h^d_{ij}\, H_d\, Q_i\, \bar{D}_j + h^e_{ij}\, H_d\, L_i\, \bar{E}_j$$
$$+ \kappa_i\, H_u\, L_i + \lambda_{ijk}\, L_i\, L_j\, \bar{E}_k + \lambda'_{ijk}\, L_i\, Q_j\, \bar{D}_k + \lambda''_{ijk}\, \bar{U}_i\, \bar{D}_j\, \bar{D}_k$$

non-renormalizable terms:

$$W_{\text{non-ren.}} = \frac{c_{ijkl}}{M_{\text{grav}}}\, Q_i\, Q_j\, Q_k\, L_l + \frac{c'_{ijkl}}{M_{\text{grav}}}\, \bar{U}_i\, \bar{U}_j\, \bar{D}_k\, \bar{E}_l + \cdots$$

Overview

extended gauge group: SM $\times\ U(1)_X$

anomalous $U(1)_X \longrightarrow$ broken spontaneously slightly below M_{grav}
(Dine-Seiberg-Wen-Witten mechanism)

proton-decay	family structure	μ-term	anomalies
$U(1) \supset \mathcal{Z}_N$	Froggatt-Nielsen mechanism	Giudice-Masiero mechanism	Green-Schwarz mechanism
proton hexality	(also for neutrinos)		
1.	**2.**		

1. Proton hexality

Proton-decay and discrete symmetries

- $LQ\bar{D}$ and $\bar{U}\bar{D}\bar{D} \longrightarrow$ rapid p-decay
- introduction of matter parity (M_p)
- "dirty little secret": $\frac{1}{M}QQQL \longrightarrow M \gtrsim 10^8 \cdot M_{\text{grav}}$
- use proton hexality (P_6) instead

	Q	$\bar{U}$	$\bar{D}$	L	$\bar{E}$	H_u	H_d
matter parity (M_p)	0	1	1	0	1	1	1
proton hexality (P_6)	0	1	5	4	1	5	1

$$M_p[QQQL] = 0 \qquad M_p[\bar{U}\bar{U}\bar{D}\bar{E}] = 4 = 0 \text{ mod } 2$$

$$P_6[QQQL] = 4 \qquad P_6[\bar{U}\bar{U}\bar{D}\bar{E}] = 8 = 2 \text{ mod } 6$$

Proton hexality

$$P_6 \;\cong\; M_p \times B_3$$

- $M_p \quad \longrightarrow \quad$ stable LSP
- $B_3 \quad \longrightarrow \quad$ stable proton

Proton hexality combines the attractive features of M_p and B_3

(M_p-MSSM $\quad\rightarrow\quad$ P_6-MSSM)

Origin of the discrete symmetry P_6

$U(1)_X$ breaking (flavon) field A: $\langle A \rangle \neq 0\ ,\ \ X_A = -1$

$U(1)_X \rightarrow P_6$ $\quad$ $\boxed{X_\phi = \frac{q_\phi}{6} + s_\phi}$ $\quad$ $q_\phi, s_\phi \in \mathbb{Z}$

q_ϕ = discrete charge for P_6

all P_6 conserving operators $\longrightarrow$ integer overall X-charge

all P_6 violating operators $\longrightarrow$ fractional overall X-charge

necessary and sufficient condition:

$$\boxed{X_{H_d} - X_{L_1} = \tfrac{1}{2} + \mathbb{Z} \quad \wedge \quad 3X_{Q_1} + X_{L_1} = \tfrac{1 \text{ or } 2}{3} + \mathbb{Z}}$$

tacit assumption: $\exists\ H_u H_d,\ H_u Q\bar{U},\ H_d Q\bar{D},\ H_d L\bar{E}$ effectively

2. Family structure

Family structure

Froggatt-Nielsen:
- hierarchy of masses and CKM structure due to family dependent X-charges
- $\mathcal{O}(1)$ coefficients and phases remain undetermined

q_ϕ family independent $\rightsquigarrow$ discrete symmetry

$\uparrow$

$$\boxed{X_\phi = \frac{q_\phi}{N} + s_\phi} \longrightarrow \quad s_\phi \text{ family dependent} \rightsquigarrow \text{family structure}$$

$$\left.\begin{array}{c} H_u\, Q_i\, \bar{U}_j \left(\frac{A}{M_{\text{grav}}}\right)^{X_{H_u}+X_{Q_i}+X_{\bar{U}_j}} \\ \text{with } \frac{\langle A \rangle}{M_{\text{grav}}} = \epsilon \approx \lambda_c \end{array}\right\} \qquad m_{ij}^{(u)} \sim \langle H_u \rangle \cdot \begin{pmatrix} \lambda_c^8 & \lambda_c^5 & \lambda_c^3 \\ \lambda_c^7 & \lambda_c^4 & \lambda_c^2 \\ \lambda_c^5 & \lambda_c^2 & 1 \end{pmatrix}_{ij}$$

$\uparrow$

λ_c = Wolfenstein parameter

Dine-Seiberg-Wen-Witten

$$m_u : m_c : m_t \sim \lambda_c^8 : \lambda_c^4 : 1$$

Origin of neutrino masses

without right-handed neutrinos

- LH_u, $LQ\bar{D}$, $LL\bar{E}$ - forbidden by P_6 ☹
- $\frac{1}{M_{\text{grav}}} L\,H_u\,L\,H_u$ - too small ☹

with right-handed neutrinos

- choose $q_{\bar{N}}$ so that $\bar{N}$ couples to LH_u: $\longrightarrow$ $LH_u\bar{N}$ and $\bar{N}\bar{N}$
- see-saw: $$\begin{pmatrix} 0 & M_{\text{D}} \\ M_{\text{D}}^T & M_{\text{M}} \end{pmatrix} \rightarrow \quad M_\nu = M_{\text{D}} \cdot M_{\text{M}}^{-1} \cdot M_{\text{D}}^T$$

$$X_{L_i} + X_{H_u} + X_{\bar{N}_j} \geq 0 \qquad {M_{\text{D}}}^{ij} \sim \langle H_u \rangle \cdot \epsilon^{X_{L_i}+X_{H_u}+X_{\bar{N}_j}}$$

$$X_{\bar{N}_i} + X_{\bar{N}_j} \geq 0 \qquad {M_{\text{M}}}^{ij} \sim M_{\text{grav}} \cdot \epsilon^{X_{\bar{N}_i}+X_{\bar{N}_j}} \qquad \rightarrow \quad \text{Case I}$$

$$X_{\bar{N}_i} + X_{\bar{N}_j} < 0 \qquad {M_{\text{M}}}^{ij} \sim m_{\text{soft}} \cdot \epsilon^{-X_{\bar{N}_i}-X_{\bar{N}_j}} \qquad \rightarrow \quad \text{Case II}$$

RESULTS

$U(1)_X$ charges of MSSM particles constrained by:

proton-hexality family structure Giudice-Masiero for μ-term Green-Schwarz anomaly cancellation	$\Bigg\}$ 48+504 X-charge assignments for Case I + II

in addition:

- no X-charged hidden sector fields $\longrightarrow$ 48+24 models survive
- anomaly condition determine Kač-Moody level k_C of $SU(3)_C$, thus g_{string}

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