Neutrino masses, Anomalous U(1) Gauge Sym. & Doublet-Triplet Splitting

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I. Introduction & Results

II. Anomalous U(1) gauge symmetry

III. D-T splitting & proton decay

IV Quark & lepton sector

V Summary

I. Introduction & Results

Grand Unified Theory (GUT)

Attractive.

- $\begin{pmatrix} \text{3 gauge forces} \\ \text{quarks \& leptons} \end{pmatrix}$ are unified in a simple group.
- Anomaly cancellation
- Charge quantization.

⋮

Difficulties.

- Doublet-triplet splitting ↔ Proton decay
- Quark & Lepton mass matrices

$$M_U = M_D = M_E \qquad y_b = y_\tau \qquad \bigcirc$$
$$(SO(10)) \quad (SU(5)) \qquad 3y_s = y_\mu. \qquad \times$$

$$\boxed{\text{We propose an attractive GUT scenario in which the above two problems are beautifully solved.}}$$

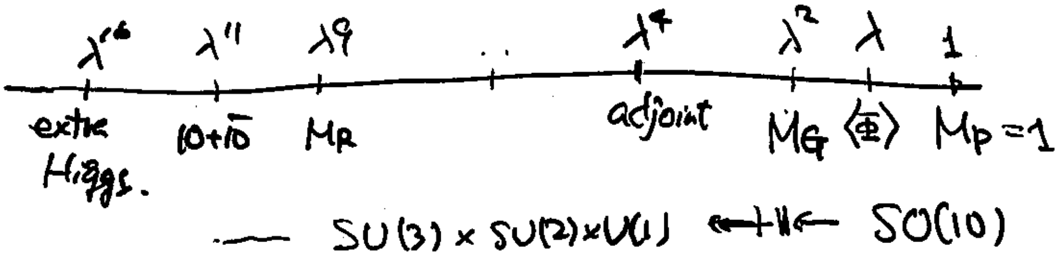
$$SO(10): \quad 16 = 10 + \bar{5} + \underset{\nu_R^c}{1}$$

No tuning parameters.

Once anomalous U(1) charges (integer) are fixed,

- various scales are determined.

$\lambda = \sin\theta_c \sim 0.22$



- doublet-triplet splitting is realised.
- proton decay is naturally suppressed.
- realistic quarks & leptons masses are obtained.

Neutrino $\longrightarrow$ Bi-maximal (LMA)

$$M_\nu = \frac{1}{\lambda^5}\begin{pmatrix} \lambda^2 & \lambda\sqrt{\lambda} & \lambda \\ \lambda\sqrt{\lambda} & \lambda & \sqrt{\lambda} \\ \lambda & \sqrt{\lambda} & 1 \end{pmatrix} \frac{\langle H_u\rangle^2}{M_P} \qquad \boxed{\frac{m_{\nu_\mu}}{m_{\nu_\tau}} \sim \lambda}$$

$\rightarrow$ LMA

$$U_{MNS} = \begin{pmatrix} 1 & \sqrt{\lambda} & \lambda \\ \sqrt{\lambda} & 1 & \sqrt{\lambda} \\ \lambda & \sqrt{\lambda} & 1 \end{pmatrix} \qquad \boxed{\sqrt{\lambda} \sim \frac{1}{2} \rightarrow \text{Bi-maximal}}$$

$U_{e3} \sim \lambda$.

Key word : Anomalous U(1) gauge symmetry.

II. Anomalous U(1) gauge symmetry.

— motivated by string theory —

Anomalous U(1) is broken by $\langle \Phi \rangle = \lambda M_P$.

Anomalous U(1) charge $\varphi = -1$. $\lambda \sim 0.2$.

◎ Yukawa hierarchy.

Q_i $i = 1, 2, 3.$ $(q_1 = 3,\ q_2 = 2,\ q_3 = 0)$

$U^c_{R\,i}$ $(u_1 = 3,\ u_2 = 2,\ u_3 = 0)$.

H_u $h_u = 0$

$$W_Y = \left(\frac{\Phi}{M_P}\right)^{q_i + u_j + h_u} Q_i U^c_{R\,j} H_u$$

$$M_u : \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \langle H_u \rangle$$

$$U_{CKM} : \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

· Wolfenstein parametrization

◎ SUSY zero

× XYZ when $x + y + z < 0$

III D-T splitting & proton decay

Standard model

$$m_H^2 = m_0^2 + \Delta m_H^2 \qquad \Delta_G \gg 100\,\mathrm{GeV}$$

$m_H^2 \sim O(100\,\mathrm{GeV})^2$, $\quad \Delta m_H^2 \sim \Delta_G^2 \xrightarrow{\boxed{\text{SUSY}}} \ln \Delta_G$

$\Rightarrow$ fine tuning.

GUT (SU(5)) $\rightarrow G_{SM}$

$$24 : \langle \Sigma \rangle = \left(\begin{array}{ccc|cc} \frac{1}{3}v & & & & \\ & \frac{1}{3}v & & & \\ & & \frac{1}{3}v & & \\ \hline & & & -\frac{1}{2}v & \\ & & & & -\frac{1}{2}v \end{array}\right) \begin{array}{l} \} \; SU(3) \\ \\ \} \; SU(2) \end{array}$$

$$5_H : \begin{pmatrix} H_T \\ \hdashline H_D \end{pmatrix} \qquad \bar{5}_{\bar{H}} : \begin{pmatrix} H_T \\ \hdashline H_D \end{pmatrix} \begin{array}{l} \} \; SU(3) \\ \} \; SU(2) \end{array}$$

$$W = m\, \bar{5}_{\bar{H}} 5_H + y\, \bar{5}_{\bar{H}} \Sigma 5_H$$

$$m_T = m + \frac{1}{3} y v \gtrsim \Delta_G \quad \leftrightarrow \quad \frac{1}{m_T} QQQL$$

$\rightarrow$ proton decay.

$$m_D = m - \frac{1}{2} y v \lesssim O(m_W)$$

$m \sim 10^{16}$, $\quad \frac{1}{2}yv \sim 10^{16}$, $\quad O(m_W) \sim 10^2$

$$\boxed{\text{How does } m_T \gg m_D \text{ realize naturally?}}$$

D-T splitting problem.

Various solutions for DT splitting problem.

① Introducing other gauge groups.

$$\underline{SU(5)_G} \times \underline{SU(3)_H} \to SU(3)_C \times SU(2)_L \times U(1)_Y$$

Yanagida, Izawa, Watari, Imamura ...

Ishimura. Hirayama & N.M.

"To save GUT, give up GUT."

② No GUT (in 4 dim.)

"The standard model is derived from string theory"

extra dim. Kawamura, Hall-Nomura

③ Group theoretical arguments.

- Sliding singlet Witten.
- Missing partner Yanagida et al.
- Dimopoulos-Wilczek mechanism.

∘ complex.

∘ artificial.

— Terms allowed by the sym. are omitted by hand. ←

Dimopoulos - Wilczek mechanism

SO(10) A : adjoint 45 , $H, \bar{H}$: 10

$$\langle A \rangle \propto \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \otimes \underbrace{\begin{pmatrix} v & & & & \\ & v & & & \\ & & v & & \\ & & & 0 & \\ & & & & 0 \end{pmatrix}}_{\sim \Sigma(24)+1}$$

$$W = \bar{H} A H \longrightarrow \text{DT splitting.}$$

One of various problems.

⊙ <u>How to realize such a VEV ?</u>

$\boxed{\text{In our scenario}}$, $A'(a'=6)$, $A(a=-2)$

$$W = \lambda^{a'+a} A'A + \lambda^{a'+3a} A'A^3 + \cancel{A'A^5} \cdots$$

SUSY zero

$$\langle A \rangle = \begin{pmatrix} & 1 \\ -1 & \end{pmatrix} \otimes \begin{pmatrix} x_1 & & & & \\ & x_2 & & & \\ & & x_3 & & \\ & & & x_4 & \\ & & & & x_5 \end{pmatrix}$$

$$\frac{\partial W}{\partial A'} = 0 \Rightarrow x_i (1 + x_i^2 \lambda^{2a}) = 0$$

$x_i = 0$ or λ^{-a} only two solutions

SUSY zero

$\cancel{A'A^{2L+1}}$ $L \geq 2$ $\longrightarrow \frac{\partial W}{\partial A'} = 0$ have more solutions

$\longrightarrow$ less natural to obtain DW VEV.

<u>"Usual sym. cannot forbid them".</u>

$v \sim \lambda^{-a}$: $\boxed{\text{GUT scale is determined by the charge.}}$

IV Quark & Lepton sector

SO(10)

16 $\quad \Psi_i = 10_i + \bar{5}_i + 1_i$

10 $\quad T = 5_T + \bar{5}_T$.

Yukawa. $\quad \lambda^{\varphi_i+\varphi_j+h}\left[\Psi_i \Psi_j H \to \underset{M_u}{10_i 10_j 5_H} + \underset{M_d,\, M_e}{10_i \bar{5}_j \bar{5}_H}\right]$

$M_u = M_d = M_e$ unrealistic

$T \to$

$\bar{5}$ massless mode $\quad (\bar{5}_1,\ \bar{5}_T + \lambda^{\frac{5}{2}} \bar{5}_3,\ \bar{5}_2)$

$$M_u = \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \langle H_u \rangle$$

almost good for small $\tan\beta$.

$$\boxed{\begin{array}{l} y_t \sim 1,\ y_c \sim \lambda^4\ \ y_u \sim \lambda^6 \\ y_b \sim \lambda^2,\ y_s \sim \lambda^{4.5},\ y_d \sim \lambda^6 \end{array}}$$

$\Rightarrow$

$$M_d = \lambda^2 \begin{pmatrix} \lambda^4 & \lambda^3\sqrt{\lambda} & \lambda^3 \\ \lambda^3 & \lambda^2\sqrt{\lambda} & \lambda^2 \\ \lambda & \sqrt{\lambda} & 1 \end{pmatrix} \langle H_d \rangle \qquad U_{CKM} = \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \text{ good}$$

$= M_e$ unrealistic. ○ $y_b = y_\tau$

$\times 3\, y_s = y_\mu$

$\langle A \rangle \propto Q_{B-L}$

$a = -2$

$$\Delta M_e \sim \lambda^2 \begin{pmatrix} \lambda^4 & 0 & \lambda^3 \\ \lambda^3 & 0 & \lambda^2 \\ 0 & 0 & 0 \end{pmatrix} \langle H_d \rangle$$

$v^2 \sim \lambda^4$

$\Psi_i A^2 \Psi_j H$

This correction is $\overset{\text{SUSY zero}}{\text{just for}}$ 1st & 2nd generation.

$\Updownarrow$

good!

$\Lambda_G \sim \lambda^{-a} < M_P$

· Neutrino $\qquad\qquad \bar{C} : \overline{16}$

$$\lambda^{\varphi_i+\varphi_j+2\bar{c}} \Psi_i \Psi_j \bar{C}^2$$

$$\Rightarrow \quad M_R = \lambda^{\varphi_i+\varphi_j+2\bar{c}} \langle \bar{C} \rangle^2 = \lambda^9 \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$M_\nu = M_e M_R^{-1} M_e^T = \lambda^{-5} \begin{pmatrix} \lambda^2 & \lambda\sqrt{\lambda} & \lambda \\ \lambda\sqrt{\lambda} & \lambda & \sqrt{\lambda} \\ \lambda & \sqrt{\lambda} & 1 \end{pmatrix} \langle H_u \rangle^2 \eta^2$$

$$U_{MNS} = \begin{pmatrix} 1 & \sqrt{\lambda} & \lambda \\ \sqrt{\lambda} & 1 & \sqrt{\lambda} \\ \lambda & \sqrt{\lambda} & 1 \end{pmatrix}$$

· $\sqrt{\lambda} \sim \frac{1}{2}$ ☺ This gives bi-maximal solution.

· $V_{e3} \sim \lambda$ $\qquad$ c.f CHOOZ $V_{e3} \lesssim 0.15$

· $\frac{m_{\nu_\mu}}{m_{\nu_\tau}} \sim \lambda \longrightarrow \frac{\Delta m^2_{solar}}{\Delta m^2_{atm}} \sim \lambda^2$

$$\lambda^2 \left(\begin{array}{l} 1.6 \times 10^{-3} \leq \Delta m^2_{atm} \leq 4 \times 10^{-3} \quad (eV)^2 \\ 2.5 \times 10^{-5} \leq \Delta m^2_{solar} \leq 1 \times 10^{-4} \quad (eV)^2 \end{array} \right.$$ LMA.

LMA solution is the most favored one.

$$m_{\nu_\tau} = \frac{1}{\lambda^5} \frac{\langle H_u \rangle^2 \eta^2}{M_p} \xrightarrow[\substack{M_p \sim 10^{18}\, GeV \\ \langle H_u \eta \rangle \sim 100\, GeV \\ \lambda \sim 0.2}]{} 3 \times 10^{-2}\, eV$$ good value!

V Summary

- We proposed an attractive GUT scenario.
  (Anomalous U(1) gauge sym.)

  ⊙ DT splitting is naturally realized.

    - proton decay is suppressed.
      (dim 5)

$\times HH$
$R<0$

$$\lambda^{2h} = M_C^{eff} > M_P.$$

  ⊙ Realistic quarks & lepton mass matrises

    - Neutrino
      - LMA
      - $U_{e3} \sim \lambda$

- No parameter

  Every scales are determined only by charges.

- coupling unification.

  Δ_G ? $\longrightarrow$ dim 6 proton decay