Origins of CP phases in GUT models

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1. Introduction

Experimentally:

- B factory experiments $\longrightarrow \sin 2\phi_1 = 0.78 \pm 0.08$
- ν factory etc in the future $\longrightarrow$ CP phases in lepton sector(?)
- EDM experiments, super B factory, LHC, LC... $\longrightarrow$ CP phases appear in BSM(?)

Theoretically:

- In the standard model – CP phases in Yukawa couplings, strong phase
- MSSM – SM phase + many phases
- ....

CP phases in many models are dealt as some kind of parameters at high energy scale (not controllable).

For example, quark sector in a model with U(1) flavor symmetry,

$$M_u \sim \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} , \quad M_d \sim \begin{pmatrix} \lambda^4 & \lambda^3 & \lambda \\ \lambda^3 & \lambda^2 & 1 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

Here, there are $\mathcal{O}(1)$ factor(they are complex numbers) in all elements.

$\longrightarrow 9 \times 2 \times 2$ parameters

What is the origin(s) of CP phases in the standard model ?

- Some origins in gravity (or string) side ?
- Geometrically breaking ?
- VEV of some scalar field ?
- ......

There may be many many possibilities (?).

As a first step, we focus on the CP phase in quark sector (KM phase)

2. Trial and error (U(1) flavor symmetry)

IDEA: We consider the case that a flavon field have complex vev.

Simplest model – a model with U(1) flavor symmetry

$$-\mathcal{L} = (Y_u)_{ij}\bar{u}_i h_u \cdot q_j \left(\frac{\Theta}{M_P}\right)^{-Q_{u_i}+Q_{q_j}+Q_{h_u}} + (Y_d)_{ij}\bar{d}_i h_d \cdot q_j \left(\frac{\Theta}{M_P}\right)^{-Q_{d_i}+Q_{q_j}+Q_{h_d}}$$

All $Y_{u,d}$ are real parameters in some phase convention of fields!!

Then $\langle\Theta\rangle/M_P = \lambda e^{i\alpha}$

However, all CP phases are unphysical phases

$$q_i \rightarrow e^{-iQ_{q_i}\alpha} q_i \; u_i \rightarrow u_i e^{-iQ_{u_i}} \; d_i \rightarrow d_i e^{-iQ_{d_i}} \; ...$$

$$\Downarrow$$

M_u and M_d are real matrix

i.e.

Though $\langle \Theta \rangle$ seems to violate CP, the model remains the non-CP violating class.

Two U(1) flavon case:

$\langle\Theta_1\rangle = \lambda e^{i\alpha_1}, \quad \langle\Theta_2\rangle = R\lambda e^{i\alpha_2}$

$$M_u \sim \begin{pmatrix} a_{11}P_6\lambda^6 & a_{12}P_5\lambda^5 & a_{13}P_3\lambda^3 \\ a_{21}P_5\lambda^5 & a_{22}P_4\lambda^4 & a_{23}P_2\lambda^2 \\ a_{31}P_3\lambda^3 & a_{32}P_2\lambda^2 & a_{33} \end{pmatrix}$$

$$M_d \sim \begin{pmatrix} b_{11}P_4\lambda^4 & b_{12}P_3\lambda^3 & b_{13}P_2\lambda \\ b_{21}P_3\lambda^3 & b_{22}P_2\lambda^2 & b_{23} \\ b_{31}P_3\lambda^3 & b_{32}P_2\lambda^2 & b_{33} \end{pmatrix}$$

where $P_k = \sum_n R^n \exp[i((k-n)\alpha_1 + n\alpha_2)]$ and a_{ij} are real

One CP phas in m_u and m_d reminds physically !

We want to consider more predictable model

3. Restricted models

Assumptions:

- Two U(1) flavon fields are introduced
- They have complex VEVs
- We based on the U(1) flavor symmetry
- All $\mathcal{O}(1)$ coefficients are 1 ($\forall a_{ij} = 1$)

1. U$(1) \times$ Z$_2$

$$\mathcal{L} = (Y_u)^{ij} U_i^c H_u \cdot Q_j + (Y_d)^{ij} D_i^c H_d \cdot Q_j$$
$$= y_u \left(\frac{\langle \Theta_k \rangle}{M} \right)^{Q_{Ui}+Q_{Qj}} U_i^c H_u \cdot Q_j + y_d \left(\frac{\langle \Theta_k \rangle}{M} \right)^{Q_{Di}+Q_{Qj}} D_i^c H_d \cdot Q_j$$

Matter contents

$U_1^c(3,+)$ $D_1^c(2,+)$ $Q_1(3,+)$

$U_2^c(2,+)$ $D_2^c(1,+)$ $Q_2(2,+)$

$U_3^c(0,-)$ $D_3^c(1,-)$ $Q_3(0,-)$

$H_u(0,+)$ $H_d(0,-)$

$\Theta_1(-1,+)$ $\Theta_2(-1,-)$

VEVs: $\langle \Theta_1 \rangle = \lambda M$, $\langle \Theta_2 \rangle = R\lambda M e^{i\alpha}$

Then the mass matrices are

$$M_u = \frac{v_u}{1-R^2} \begin{pmatrix} (1-\tilde{R}^8)\lambda^6 & (1-\tilde{R}^6)\lambda^5 & \tilde{R}(1-\tilde{R}^4)\lambda^3 \\ (1-\tilde{R}^6)\lambda^5 & (1-\tilde{R}^6)\lambda^4 & \tilde{R}(1-\tilde{R}^2)\lambda^2 \\ \tilde{R}(1-\tilde{R}^4)\lambda^3 & \tilde{R}(1-\tilde{R}^2)\lambda^2 & 1-\tilde{R}^2 \end{pmatrix}$$

$$M_d = \frac{v_d}{1-R^2} \begin{pmatrix} \tilde{R}(1-\tilde{R}^6)\lambda^5 & \tilde{R}(1-\tilde{R}^4)\lambda^4 & (1-\tilde{R}^4)\lambda^2 \\ \tilde{R}(1-\tilde{R}^4)\lambda^4 & \tilde{R}(1-\tilde{R}^4)\lambda^3 & (1-\tilde{R}^2)\lambda \\ (1-\tilde{R}^6)\lambda^4 & (1-\tilde{R}^4)\lambda^3 & \tilde{R}(1-\tilde{R}^2)\lambda \end{pmatrix}$$

2. U(1) $\times$ Z$_3$ (unlike GUT assignment ?)

$$\begin{aligned}\mathcal{L} =&(Y_u)^{ij} U_i^c H_u \cdot Q_j + (Y_d)^{ij} D_i^c H_d \cdot Q_j \\ =& y_u \left(\frac{\langle \Theta_k \rangle}{M} \right)^{Q_{Ui} + Q_{Qj}} U_i^c H_u \cdot Q_j + y_d \left(\frac{\langle \Theta_k \rangle}{M} \right)^{Q_{Di} + Q_{Qj}} D_i^c H_d \cdot Q_j\end{aligned}$$

Matter contents

$$\begin{array}{lll} U_1^c(3,1) & D_1^c(2,1) & Q_1(3,1) \\ U_2^c(2,1) & D_2^c(1,1) & Q_2(2,1) \\ U_3^c(0,\omega) & D_3^c(1,\omega^*) & Q_3(0,\omega^*) \\ H_u(0,1) & H_d(0,\omega^*) & \\ \Theta_1(-1,1) & \Theta_2(0,\omega^*) & \end{array}$$

VEVs: $\langle \Theta_1 \rangle = \lambda M \ , \quad \langle \Theta_2 \rangle = R \lambda M e^{i\alpha}$

Then the mass matrices are

$$M_u = v_u \begin{pmatrix} (1+\tilde{R}^3+\tilde{R}^6)\lambda^6 & (1+\tilde{R}^3)\lambda^5 & \tilde{R}\lambda^3 \\ (1+\tilde{R}^3)\lambda^5 & (1+\tilde{R}^3)\lambda^4 & \tilde{R}\lambda^2 \\ \tilde{R}^2\lambda^3 & \tilde{R}^2\lambda^2 & 1 \end{pmatrix}$$

$$M_d = v_d \begin{pmatrix} \tilde{R}(1+\tilde{R}^3)\lambda^5 & \tilde{R}(1+\tilde{R}^3)\lambda^4 & \tilde{R}^2\lambda^2 \\ \tilde{R}(1+\tilde{R}^3)\lambda^4 & \tilde{R}\lambda^3 & 0 \\ \tilde{R}^2\lambda^4 & \tilde{R}^2\lambda^3 & \lambda \end{pmatrix}$$

3. U$(1) \times$ Z$_4$ (unlike GUT assignment ?)

$$\begin{aligned}\mathcal{L} =&(Y_u)^{ij} U_i^c H_u \cdot Q_j + (Y_d)^{ij} D_i^c H_d \cdot Q_j \\ =&y_u \left(\frac{\langle \Theta_k \rangle}{M} \right)^{Q_{Ui}+Q_{Qj}} U_i^c H_u \cdot Q_j + y_d \left(\frac{\langle \Theta_k \rangle}{M} \right)^{Q_{Di}+Q_{Qj}} D_i^c H_d \cdot Q_j\end{aligned}$$

Matter contents

$$\begin{array}{lll} U_1^c(3,i) & D_1^c(2,1) & Q_1(3,1) \\ U_2^c(2,i) & D_2^c(1,1) & Q_2(2,1) \\ U_3^c(0,1) & D_3^c(1,-1) & Q_3(0,-1) \\ H_u(0,1) & H_d(0,\omega^*) & \\ \Theta_1(-1,1) & \Theta_2(0,\omega^*) & \end{array}$$

VEVs: $\langle \Theta_1 \rangle = \lambda M \;, \quad \langle \Theta_2 \rangle = R \lambda M e^{i\alpha}$

Then the mass matrices are

$$M_u = v_u \begin{pmatrix} \tilde{R}(1+\tilde{R}^4)\lambda^6 & \tilde{R}(1+\tilde{R}^4)\lambda^5 & \tilde{R}^3\lambda^3 \\ \tilde{R}(1+\tilde{R}^4)\lambda^5 & \tilde{R}\lambda^4 & 0 \\ \tilde{R}^2\lambda^3 & \tilde{R}^2\lambda^2 & 1 \end{pmatrix}$$

$$M_d = v_d \begin{pmatrix} \tilde{R}(1+\tilde{R}^4)\lambda^5 & \tilde{R}\lambda^4 & 0 \\ \tilde{R}\lambda^4 & \tilde{R}\lambda^3 & 0 \\ \tilde{R}^3\lambda^4 & \tilde{R}^3\lambda^3 & \tilde{R}\lambda \end{pmatrix}$$

4. Summary

- Physical CP phase can be generate by the vev of flavon field

Future works

- Which model is more convincing ?
- More realistic model
- Various models can be considered
  - Other symmetry
  - Other ideas
- Lepton sector (quark $\leftrightarrow$ neutrino)
- SUSY (EDM etc)