Flavored axions and the flavor problem

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Outline

- CP problem
- Five texture-zero mass matrices
- Particle content
- Minimal Higgs content
- Effective Lagrangian
- Low Energy constraints
- Conclusions

The CP problem

- In the limit $m_f \to 0$ the QCD lagrangian has the symmetry $U(N)_V x\, U(N)_A$ sin the up and down masses satisfy $m_u, m_d << \Lambda_{QCD}$, one expect that the strong interactions to be approximately $U(2)_V x\, U(2)_A$ invariant
- Experimentally $U(2)_V = SU(2)_V \times U(1)_V \equiv$ Isospin x Baryon # however, quark condensates break $U(2)_A$ down spontaneously

The CP problem

- however, quark condensates break down $U(2)_A$ spontaneously, one expects now 4 Nambu-Goldstone bosons (π, η). Although pions are light, there is no clue of another light state in the hadronic spectrum
- Weinberg dubbed this the U(1)_A problem, suggesting that, somehow, there was no U(1)_A symmetry in QCD.

The strong CP problem

- ‘t Hooft realized that the current associated with the U(1)_A symmetry is anomalous

$$\partial_\mu J_5^\mu = \frac{g^2 N}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}:$$

where N is the number of massless quarks. From this it is possible to add to te lagrangian the term:

$$L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

Strong CP problem

- This termproduces an electric dipole moment for the neutron of order:

  with $d_n \approx e\, m_q/M_n^2\, \theta \approx 10^{-16}\, \theta$ ecm

  $d_n < 2.9 \times 10^{-26}$ ecm

  which requires $\theta < 10^{-9} - 10^{-10}$

  why θ is so small ?, this is the Strong CP problem.

A solution

- Pecce and Quinn proposed a solution suggesting that the SM had an additional U(1) chiral symmetry which drives $\theta_{total} \to 0$

The five-texture mass matrices

- Our aim is to propose a PQ symmetry that generates this texture for the quark masses.

$$M^U = \begin{pmatrix} 0 & 0 & C_u \\ 0 & A_u & B_u \\ C_u^* & B_u^* & D_u \end{pmatrix},$$

$$M^D = \begin{pmatrix} 0 & C_d & 0 \\ C_d^* & 0 & B_d \\ 0 & B_d^* & A_d \end{pmatrix}.$$

Minimal Higgs content

- From the Lagrangian

$$\mathcal{L} \supset -\left(\bar{q}_{Li} y_{ij}^{D\alpha} \Phi^{\alpha} d_{Rj} + \bar{q}_{Li} y_{ij}^{U\alpha} \tilde{\Phi}^{\alpha} u_{Rj} + \text{h.c}\right),$$

it is possible to obtain the mass functions

$$M^U = \begin{pmatrix} 0 & 0 & x \\ 0 & x & x \\ x & x & x \end{pmatrix} \longrightarrow \begin{pmatrix} S_{11}^{U\alpha} \neq 0 & S_{12}^{U\alpha} \neq 0 & S_{13}^{U\alpha} = 0 \\ S_{21}^{U\alpha} \neq 0 & S_{22}^{U\alpha} = 0 & S_{23}^{U\alpha} = 0 \\ S_{31}^{U\alpha} = 0 & S_{32}^{U\alpha} = 0 & S_{33}^{U\alpha} = 0 \end{pmatrix},$$

$$M^D = \begin{pmatrix} 0 & x & 0 \\ x & 0 & x \\ 0 & x & x \end{pmatrix} \longrightarrow \begin{pmatrix} S_{11}^{D\alpha} \neq 0 & S_{12}^{D\alpha} = 0 & S_{13}^{D\alpha} \neq 0 \\ S_{21}^{D\alpha} = 0 & S_{22}^{D\alpha} \neq 0 & S_{23}^{D\alpha} = 0 \\ S_{31}^{D\alpha} \neq 0 & S_{32}^{D\alpha} = 0 & S_{33}^{D\alpha} = 0 \end{pmatrix},$$

where $S_{ij}^{U\alpha} = (-x_{q_i} + x_{u_j} - x_{\phi_\alpha})$ and $S_{ij}^{D\alpha} = (-x_{q_i} + x_{d_j} + x_{\phi_\alpha})$.

Minimal Higgs content

- To reproduce these mass functions at least 4 higgs doublets are needed.

Particles	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Q_{PQ}	$U(1)_{PQ}$
ϕ_1	0	1	2	1/2	s_1	x_{ϕ_1}
ϕ_2	0	1	2	1/2	s_2	x_{ϕ_2}
ϕ_3	0	1	2	1/2	$-s_1 + 2s_2$	x_{ϕ_3}
ϕ_4	0	1	2	1/2	$-3s_1 + 4s_2$	x_{ϕ_4}
S	0	1	1	0	$x_S \neq 0$	x_S
Q_L	1/2	3	0	0	$x_{Q_L} - x_{Q_R} \neq 0$	x_{Q_L}
Q_R	1/2	3	0	0		x_{Q_R}

TABLE III: Beyond standard model scalar and fermion fields and their respective PQ charges. The parameters s_1, s_2 and α are reals, with $s_1 \neq s_2$, where: $s_1 = \frac{N}{9}\hat{s}_1$ and $s_2 = \frac{N}{9}(\epsilon + \hat{s}_1)$.

Model particle content

- The PQ charges of quarks to reproduce the mass textures are

Particles	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$Q_{PQ}(i=1)$	$Q_{PQ}(i=2)$	$Q_{PQ}(i=3)$	$U(1)_{PQ}$
q_{Li}	1/2	3	2	1/6	$-2s_1+2s_2+\alpha$	$-s_1+s_2+\alpha$	α	x_{q_i}
u_{Ri}	1/2	3	1	2/3	$s_1+\alpha$	$s_2+\alpha$	$-s_1+2s_2+\alpha$	x_{u_i}
d_{Ri}	1/2	3	1	-1/3	$2s_1-3s_2+\alpha$	$s_1-2s_2+\alpha$	$-s_2+\alpha$	x_{d_i}

TABLE II: The columns 6-8 are the PQ Q_{PQ} charges for the SM quarks in each family. The subindex $i=1,2,3$ stands for the family number in the interaction basis. The parameters s_1, s_2 and α are reals, with $s_1 \neq s_2$, where: $s_1 = \frac{N}{9}\hat{s}_1$ and $s_2 = \frac{N}{9}(\epsilon + \hat{s}_1)$.

- by chosing the VEVs in a convenient way it is possible to reproduce the quark masses and the CKM mixing matrix.

Effective Lagrangian

- $$\mathcal{L} = (D_\mu \Phi^\alpha)^\dagger D^\mu \Phi^\alpha + \sum_\psi i\bar{\psi}\gamma^\mu D_\mu \psi + \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2$$
$$- \left(\bar{q}_{Li} y_{ij}^{D\alpha} \Phi^\alpha d_{Rj} + \bar{q}_{Li} y_{ij}^{U\alpha} \tilde{\Phi}^\alpha u_{Rj} + \bar{\ell}_{Li} y_{ij}^{E\alpha} \Phi^\alpha e_{Rj} + \bar{\ell}_{Li} y_{ij}^{N\alpha} \tilde{\Phi}^\alpha \nu_{Rj} + \text{h.c} \right)$$
$$+ c_{a\Phi^\alpha} O_{a\Phi^\alpha} + c_1 \frac{\alpha_1}{8\pi} O_B + c_2 \frac{\alpha_2}{8\pi} O_W + c_3 \frac{\alpha_3}{8\pi} O_G,$$

  where

- $$O_{a\Phi} = i\frac{\partial^\mu a}{\Lambda} \left((D_\mu \Phi^\alpha)^\dagger \Phi^\alpha - \Phi^{\alpha\dagger} (D_\mu \Phi^\alpha) \right), \qquad O_B = -\frac{a}{\Lambda} B_{\mu\nu} \tilde{B}^{\mu\nu},$$
$$O_W = -\frac{a}{\Lambda} W_{\mu\nu}^a \tilde{W}^{a\mu\nu}, \qquad O_G = -\frac{a}{\Lambda} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}.$$

Effective Lagrangian

- It is possible to obtain the dimension five effective lagrangians by means of the non-linear transformation

$$\Phi^{\alpha} \longrightarrow e^{i\frac{x_{\Phi^{\alpha}}}{\Lambda}a}\Phi^{\alpha},$$

$$\psi_L \longrightarrow e^{i\frac{x_{\psi_L}}{\Lambda}a}\psi_L,$$

$$\psi_R \longrightarrow e^{i\frac{x_{\psi_R}}{\Lambda}a}\psi_R,$$

Down quark Vector and axial couplings

- $$\Delta\mathcal{L}_{K^D} + \Delta\mathcal{L}_{Y^D} \quad \equiv - \partial_\mu a \, \bar{d}_i \gamma^\mu \left(g^V_{ad_i d_j} + \gamma^5 g^A_{ad_i d_j} \right) d_j .$$

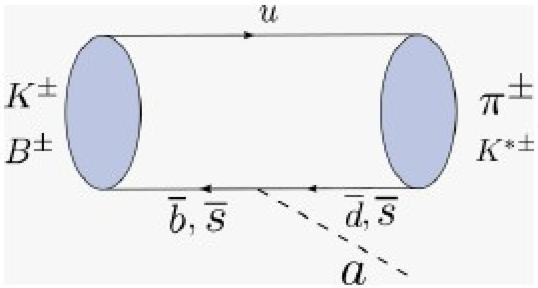
$$g^{V,A}_{ad_i d_j} = \frac{1}{2 f_a c_3^{\rm eff}} \left(2\Delta^{Dij}_{V,A} + \frac{\hat{v}\Delta^{\gamma 1}_{\Phi} Y^{D\gamma ij}_{V,A}}{(m^D_i \mp m^D_j)} \right), \qquad (35)$$

where $\Delta^{Dij}_{V,A} = \Delta^{Dij}_{RR}(d) \pm \Delta^{Dij}_{LL}(q)$ with $\Delta^{Fij}_{LL}(q) = \left(U^D_L x_q \, U^{D\dagger}_L \right)^{ij}$ and $\Delta^{Fij}_{RR}(d) = \left(U^D_R x_d \, U^{D\dagger}_R \right)^{ij}$. The parameters associated with the FCNC due to the differences between the Higgs charges are: $\Delta^{\gamma\beta}_{\Phi} = (R x_\Phi R^T)^{\gamma\beta}$, $\hat{v} = v/\sqrt{2}$ and $Y^{D\gamma ij}_{V,A} = \left(Y^{D\gamma}_{ij} \mp Y^{D\gamma\dagger}_{ij} \right)$. The term with $\gamma = 1$ does not contribute to the FCNC since $Y^{D1} = \frac{2}{v} m^D$ is a diagonal

Constraints from Semileptonic decays

$$\Gamma(K^+ \to \pi^+ a) = \frac{m_K^3}{16\pi}\left(1 - \frac{m_\pi^2}{m_K^2}\right)^2 \lambda_{K\pi a}^{1/2} f_0^2(m_a^2)|g_{ads}^V|^2.$$

$$\Gamma(B \to K^* a) = \frac{m_B^3}{16\pi}\lambda_{BK^*a}^{3/2} A_0^2(m_a^2)|g_{asb}^A|^2.$$



Constraints from semileptonic decays

Collaboration	upper bound
E949+E787 [48, 49]	$\mathcal{B}\left(K^+ \to \pi^+ a\right) < 0.73 \times 10^{-10}$
CLEO [50]	$\mathcal{B}\left(B^\pm \to \pi^\pm a\right) < 4.9 \times 10^{-5}$
CLEO [50]	$\mathcal{B}\left(B^\pm \to K^\pm a\right) < 4.9 \times 10^{-5}$
BELLE [51]	$\mathcal{B}\left(B^\pm \to \rho^\pm a\right) < 21.3 \times 10^{-5}$
BELLE [51]	$\mathcal{B}\left(B^\pm \to K^{*\pm} a\right) < 4.0 \times 10^{-5}$

(36)

TABLE IV: These inequalities come from the window for new physics in the branching ratio uncertainty of the meson decay in a pair $\bar{\nu}\nu$.

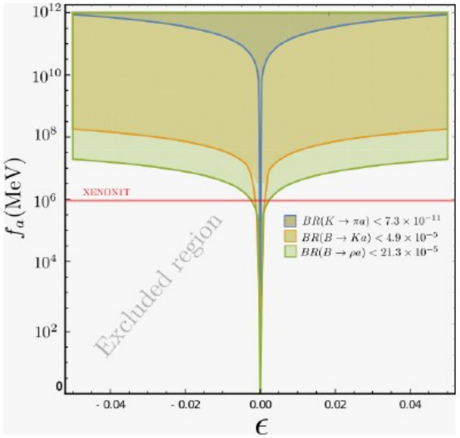


FIG. 2: Allowed regions by semileptonic meson decays.

Conclusions

- In this work we have proposed a PQ symmetry that gives rise to Hermitian mass matrices with five texture-zeros. This texture can adjust in a non-trivial way the six masses of the quarks and the three CKM mixing angles and the CP violating phase.
- we showed that this texture requires at least four Higgs doublets to be generated from a PQ symmetry. We proposed a general parameterization for the PQ charges which is consistent with the texture.

Conclusions

- We calculated the FCNC coming from the effective Lagrangian of interaction between the Yukawa term and the axion. This calculation poses some technical problems due to the multi-Higgs sector. To solve this, we proposed a generalized Georgi rotation for an arbitrary number of Higgs doublets.
- As a bonus, we showed that our model can adjust the axion mass required to explain the anomaly recently reported by XENON1T~\cite{Aprile:2020tmw}.