Flavour symmetry as the origin of the axion

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The Quest for New Physics

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Abstract

Based on:

$U(1)$ flavour symmetries as Peccei-Quinn symmetries
FB, L Di Luzio, F Mescia, E Nardi,
[1811.09637 [hep-ph]]

Q: What, if anything, does flavour have to do with a solution to the strong CP problem?

Recent developments:

[Celis, Fuentes-Martin, Serôdio '14] [Ahn '14 & '18]
[Ema, Hamaguchi, Moroi, Nakayama '16] [Calibbi, Goertz, Redigolo, Ziegler, Zupan '16]
[FB, Chun, King '17 & '18] [Linster, Ziegler '18]
[Reig, Valle, Wilczek '18] [Alanne, Blasi, Goertz '18]

Assume

- 2HDM with $Y(H_{1,2}) = -1/2$
- Global $U(1)$ symmetry acting on quarks and Higgs
- Quark $U(1)$ charges can be generation-dependent

Define $U(1)$ charges $\mathcal{X}$

- $\mathcal{X}(H_{1,2}) = \mathcal{X}_{1,2}$
- $\mathcal{X}(Q) = \{-x, -y, 0\}$
- $\mathcal{X}(u) = \{a, b, c\}$
- $\mathcal{X}(d) = \{m, n, p\}$

We may write combined charges of quark bilinears as matrices:

$$\mathcal{X}_{\overline{Q}u} = \begin{pmatrix} a+x & b+x & c+x \\ a+y & b+y & c+y \\ a & b & c \end{pmatrix}, \quad \mathcal{X}_{\overline{Q}d} = \begin{pmatrix} m+x & n+x & p+x \\ m+y & n+y & p+y \\ m & n & p \end{pmatrix}$$

If

$$(\mathcal{X}_{\overline{Q}u})_{ij} + \mathcal{X}_{1\,\mathrm{or}\,2} = 0 \quad \mathrm{or} \quad (\mathcal{X}_{\overline{Q}d})_{ij} - \mathcal{X}_{1\,\mathrm{or}\,2} = 0$$

the corresponding Yukawa coupling

$$\mathcal{L} \supset H_{1\,\mathrm{or}\,2}\overline{Q}_i u_j \ \mathrm{or}\ \tilde{H}_{1\,\mathrm{or}\,2}\overline{Q}_i d_j$$

is allowed. Conversely, if $\cdots \neq 0$, Yukawa matrix has texture zero.

What is the minimal set of non-zero Yukawa operators compatible with this $U(1)$ symmetry?

Conditions for a physically viable Yukawa sector

1. $U(1)$ charge consistency
2. Non-zero quark masses

$$\det M_u \neq 0, \quad \det M_d \neq 0$$

3. Non-vanishing Jarlskog invariant (i.e. a "full" CKM matrix)

$$J \propto \mathcal{D} \equiv \det[M_d M_d^\dagger, M_u M_u^\dagger] \neq 0$$

NB: with 9 quark fields, we can perform 8 relative phase redefinitions to remove phases in M_u, M_d. We must have $8+1=9$ non-zero terms across $M_u \oplus M_d$ to have CP violation.

Structures that don't work

We need 9 non-zero Yukawa couplings: $M_n \oplus M_{9-n}$

Ex 1: $M_1 \oplus M_8$

$$M_u = M_1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}, \quad M_d = M_8 = \begin{pmatrix} 0 & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}$$

$\Rightarrow det M_u = 0!$

Ex 2: $M_4 \oplus M_5$

$$M_u = M_4 = \begin{pmatrix} \times & \times & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix}, \quad M_d = M_5 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix}$$

$\Rightarrow J \propto \sin\theta_{13} = \sin\theta_{23} = 0!$

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>> proof.get()
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There are only 2 viable structures, both like $M_4 \oplus M_5$

$$\mathcal{T}_1 = \begin{pmatrix} \times & \times & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \oplus \begin{pmatrix} \times & \times & 0 \\ 0 & \times & \times \\ 0 & 0 & \times \end{pmatrix}$$

$$\mathcal{T}_2 = \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & 0 \\ \times & \times & 0 \end{pmatrix} \oplus \begin{pmatrix} \times & \times & 0 \\ 0 & \times & \times \\ 0 & 0 & \times \end{pmatrix}$$

- Equivalent SM physics for any column or (simultaneous) row permutations, i.e. by redefinitions of quark fields
- One quark has no mixing: it is "sequestered"
- New Physics depends on sequestered quark $\Rightarrow 2 \times 6$ physically distinct textures

- It is possible to completely reconstruct the Yukawa matrices in terms of measured observables:
  - 9 (real) + 1 (phase) Yukawa parameters
  - 6 quark masses + 3 CKM mixing angles + 1 CP phase
  - At high scales ($\mu \sim 10^{12}$ GeV):

Observable	Value	Observable	Value
m_u /MeV	$0.61^{+0.19}_{-0.18}$	θ_{12}	0.22735 ± 0.00072
m_c /GeV	$0.281^{+0.02}_{-0.04}$	θ_{13}	0.00364 ± 0.00013
m_t /GeV	82.6 ± 1.4	θ_{23}	0.04208 ± 0.00064
m_d /MeV	1.27 ± 0.22	δ	1.208 ± 0.054
m_s /MeV	26^{+8}_{-5}		
m_b /GeV	$1.16^{+0.07}_{-0.02}$		

[Xing et al '11, Antusch, Maurer '13]

- Exact analytical expressions are possible, but ugly
- Solutions are stable under perturbations

The U(1) flavour symmetries are Peccei-Quinn symmetries!

- Anomaly

$$N = \frac{1}{2}\sum_i \left[\mathcal{X}(u) + \mathcal{X}(d) - 2\mathcal{X}(Q)\right]_i$$

- With normalization $\mathcal{X}_2 - \mathcal{X}_1 = 1$, we obtain

$$N(\mathcal{T}_1) = 1, \quad N(\mathcal{T}_2) = 1/2$$

- The Goldstone of the broken flavour $U(1)$ is an axion
- To be compatible with low-energy pheno, we make it *invisible*
  - $U(1)$ broken at high scale by new scalar ϕ
- Couplings are generation-dependent $\Rightarrow$ the axion is *flavoured*

Flavoured axions couple to fermions like

$$\mathcal{L}_{af} = -\frac{\partial_\mu a}{v_{PQ}} \sum_{f=u,d,e} \bar{f}_i \gamma^\mu (V^f_{ij} - A^f_{ij}\gamma_5) f_j,$$

where $v_{PQ} = f_a N_{DW}$ and

$$V^f = \frac{1}{2}\left(U^\dagger_{Lf} x_{f_L} U_{Lf} + U^\dagger_{Rf} x_{f_R} U_{Rf}\right)$$
$$A^f = \frac{1}{2}\left(U^\dagger_{Lf} x_{f_L} U_{Lf} - U^\dagger_{Rf} x_{f_R} U_{Rf}\right)$$

- $x_{f_L} = \mathrm{diag}(x_{f_{L1}}, x_{f_{L2}}, x_{f_{L3}})$, $x_{f_R} = \mathrm{diag}(x_{f_{R1}}, x_{f_{R2}}, x_{f_{R3}})$
- $V_{\mathrm{CKM}} = U^\dagger_{Lu} U_{Ld}$
- The sequestered quark has no FV axion couplings

Decay: $P \to P'a$, where $P = (\bar{q}_P q')$, $P' = (\bar{q}_{P'} q')$.
Branching ratio

$$\mathrm{Br}(P \to P'a) = \frac{1}{16\pi\Gamma(P)} \frac{\left|V^f_{q_P q_{P'}}\right|^2}{v_{PQ}^2} m_P^3 \left(1 - \frac{m_{P'}^2}{m_P^2}\right)^3 |f_+(0)|^2 \,,$$

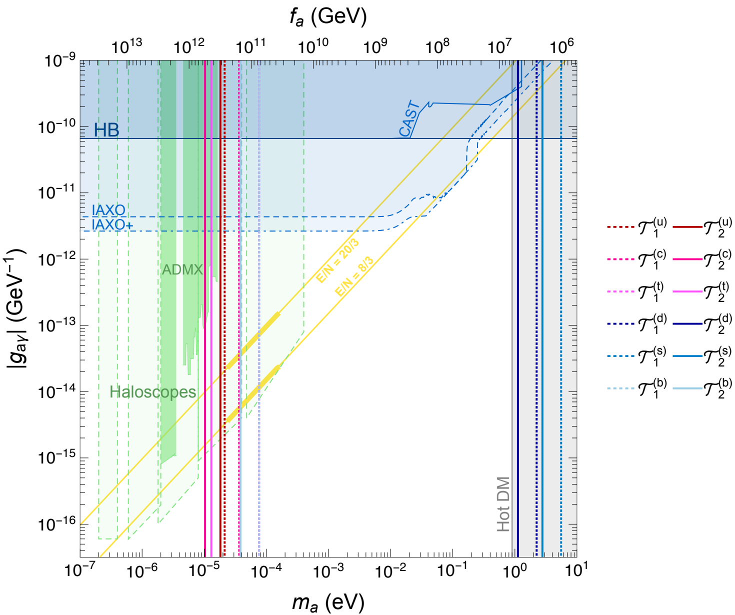
- $f_+(0)$ is a hadronic form factor
- Only unknown quantity is the ratio $|V^f|/v_{PQ}$
- Example: $K^+ \to \pi^+ a$ decay proceeds by $\bar{s} \to \bar{d} a$ with coupling strength $V^d_{sd} \equiv V^d_{21}$

Decay	$f_+(0)$
$K \to \pi$	1
$D \to \pi$	0.74(6)(4)
$D \to K$	0.78(5)(4)
$D_s \to K$	0.68(4)(3)
$B \to \pi$	0.27(7)(5)
$B \to K$	0.32(6)(6)
$B_s \to K$	0.23(5)(4)

Limits

Decay	Branching ratio	Experiment	$\tilde{c}_{P\to P'}$	v_{PQ}/GeV
$K^+ \to \pi^+ a$	$< 0.73 \times 10^{-10}$	E949 + E787	3.51×10^{-11}	$> 6.9 \times 10^{11} \lvert V_{21}^d \rvert$
	$< 0.01 \times 10^{-10}*$	NA62 (future)		$> 5.9 \times 10^{12} \lvert V_{21}^d \rvert$
	$< 1.2 \times 10^{-10}$	E949 + E787		
	$< 0.59 \times 10^{-10}$	E787		
$K_L^0 \to \pi^0 a$	$< 5 \times 10^{-8}$	KOTO	3.67×10^{-11}	$> 2.7 \times 10^{10} \lvert V_{21}^d \rvert$
$(K_L^0 \to \pi^0 \nu\bar{\nu})$	$(< 2.6 \times 10^{-8})$	E391a		
$B^\pm \to \pi^\pm a$	$< 4.9 \times 10^{-5}$	CLEO	5.30×10^{-13}	$> 1.0 \times 10^{8} \lvert V_{31}^d \rvert$
$(B^\pm \to \pi^\pm \nu\bar{\nu})$	$(< 1.0 \times 10^{-4})$	BaBar		
	$(< 1.4 \times 10^{-4})$	Belle		
$B^\pm \to K^\pm a$	$< 4.9 \times 10^{-5}$	CLEO	7.26×10^{-13}	$> 1.2 \times 10^{8} \lvert V_{32}^d \rvert$
$(B^\pm \to K^\pm \nu\bar{\nu})$	$(< 1.3 \times 10^{-5})$	BaBar		
	$(< 1.9 \times 10^{-5})$	Belle		
	$(< 1.5 \times 10^{-6})*$	Belle-II (future)		
$B^0 \to \pi^0 a$			4.92×10^{-13}	
$(B^0 \to \pi^0 \nu\bar{\nu})$	$(< 0.9 \times 10^{-5})$	Belle		$\gtrsim 2.3 \times 10^{8} \lvert V_{31}^d \rvert$
$B^0 \to K_{(S)}^0 a$	$< 5.3 \times 10^{-5}$	CLEO	6.74×10^{-13}	$> 1.1 \times 10^{8} \lvert V_{32}^d \rvert$
$(B^0 \to K^0 \nu\bar{\nu})$	$(< 1.3 \times 10^{-5})$	Belle		
$D^\pm \to \pi^\pm a$	< 1		1.11×10^{-13}	$> 3.3 \times 10^{5} \lvert V_{21}^u \rvert$
$D^0 \to \pi^0 a$	< 1		4.33×10^{-14}	$> 2.1 \times 10^{5} \lvert V_{21}^u \rvert$
$D_s^\pm \to K^\pm a$	< 1		4.38×10^{-14}	$> 2.1 \times 10^{5} \lvert V_{21}^u \rvert$
$B_s^0 \to \overline{K}^0 a$	< 1		3.64×10^{-13}	$> 6.0 \times 10^{5} \lvert V_{31}^d \rvert$

Bounds



f_a (GeV)
10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6}
10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15} 10^{-16}
$|g_{a\gamma}|$ (GeV^{-1})
HB
CAST
IAXO
IAXO+
ADMX
E/N = 20/3
E/N = 8/3
Haloscopes
Hot DM
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}
m_a (eV)
$\mathcal{T}_1^{(u)}$ $\mathcal{T}_2^{(u)}$
$\mathcal{T}_1^{(c)}$ $\mathcal{T}_2^{(c)}$
$\mathcal{T}_1^{(t)}$ $\mathcal{T}_2^{(t)}$
$\mathcal{T}_1^{(d)}$ $\mathcal{T}_2^{(d)}$
$\mathcal{T}_1^{(s)}$ $\mathcal{T}_2^{(s)}$
$\mathcal{T}_1^{(b)}$ $\mathcal{T}_2^{(b)}$

It is possible in this framework to suppress the couplings to protons and neutrons: *nucleophobia*

$$0 \approx C_p + C_n = 0.50(5)\,(C_u + C_d - 1) - 2\delta_s; \qquad |\delta_s| \lesssim 0.04$$

$$0 \approx C_p - C_n = 1.273(2)\left(C_u - C_d - \frac{1}{3}\right)$$

- $C_{u,d}$ are axion couplings to up, down quarks
  generically depend on Higgs vevs via $\tan\beta \equiv v_2/v_1$
  connect to earlier notation: $C_q = A^q_{11}/N$
- $C_u + C_d$ depends only on
  1) charge assignments
  2) quark mixing
- $C_u - C_d$ depends also on $\tan\beta$

Example model: $\mathcal{T}_2$ texture, with u or d quark sequestered

$$\mathcal{T}_2^{(u,d)}: \quad \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & 0 \\ \times & \times & 0 \end{pmatrix} \oplus \begin{pmatrix} \times & \times & 0 \\ 0 & \times & \times \\ 0 & 0 & \times \end{pmatrix}$$

- Without mixing, $C_u + C_d = 1$ (exactly)
- With mixing, $C_u + C_d \approx 1.1$
- To get $C_u - C_d \approx 1/3$, require $\tan\beta \approx 2^{\pm 1/2}$

Consequence: upper bound on m_a from supernovae can be relaxed.

Summary

- We have explored a $U(1)$ quark flavour symmetry, yielding maximal reduction in free Yukawa parameters.
- Our minimal approach is a compelling way to parametrize quark flavour.
- Only two basic structures are allowed in the minimal setup, both corresponding to PQ symmetries.
- The axion is necessarily flavoured, with testable predictions.

Future

- Leptons
- Electrophobia $\to$ astrophobia

Thank You!