Flavourful Axion and the Peccei-Quinn Symmetry

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Outline


5X VECES MÁS PODER
PRECIO ESPECIAL 900mL
AXION
100% EFECTIVO ARRANCAGRASA
Limón
Lemon

Axions and the Peccei-Quinn Symmetry $U(1)_{PQ}$

- CP-violating term in QCD Lagrangian $\theta \frac{g_s^2}{32\pi^2} G\widetilde{G}$, where $\widetilde{G}^{a\,\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} G^a_{\rho\sigma}$.
- $\overline{\theta} = \theta + \mathrm{Arg}\left(\mathrm{Det}(M^u M^d)\right) < 10^{-10}$ by neutron EDM[1].
- Unnaturally small?
- Introduce $U(1)_{PQ}$ and scalar field to SM[2].
- Axion appears as pseudo-Goldstone boson of $U(1)_{PQ}$[3], and $\mathcal{L}_{QCD+axion} \supset \frac{a}{f_a} \frac{g_s^2}{32\pi^2} G\widetilde{G} + \overline{\theta} \frac{g_s^2}{32\pi^2} G\widetilde{G}$.
- Quasi shift-symmetry of axion, $a \to a - f_a\overline{\theta}$, solves strong CP problem.

[1] Abel et al. 2020.
[2] R. D. Peccei and Quinn 1977.
[3] Weinberg 1978; Wilczek 1978.

$U(1)_{PQ}$ as a Flavour Symmetry

- $U(1)_{PQ}$ can be a flavour symmetry.
- Identified with the Froggatt-Nielsen symmetry $U(1)_{FN}$.
- This gives rise to a *flavourful axion* or *axión sabroso*.
- FN symmetry can explain fermion mass hierarchy[4].
- Flavon field σ couples to fermions like $\frac{C^f_{ij}}{\Lambda^n}\overline{F^i_L} H\, f^j_R\, \sigma^n$ or $\frac{C^f_{ij}}{\Lambda^n}\overline{F^i_L}\widetilde{H}\, f^j_R\, \sigma^n$.
- After FN symmetry breaking $y^f_{ij}\varepsilon^n\overline{F^i_L} H\, f^j_R$ are the SM Yukawa terms, and $\varepsilon = \frac{v_\sigma}{\Lambda} \sim 0.2$, hierarchy comes form powers of n.

[4] Froggatt and Nielsen 1979.

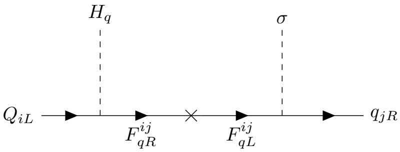
Quark Sector

Field/Symmetry	Q_{iL}	u_{iR}	d_{iR}	H_u	H_d	σ
$SU(2)_L \times U(1)_Y$	(2, 1/6)	(1, 2/3)	(1, -1/3)	(2, -1/2)	(2, 1/2)	(1, 0)
$U(1)_{PQ}$	(9/2, -5/2, 1/2)	(-9/2, 5/2, -1/2)	(-9/2, 5/2, -1/2)	1	1	1

- Flavon σ is coupled to quark sector.
- Couplings up to dimension 5 are:
  $$\mathcal{L} \supset \frac{C^u_{12}}{\Lambda}\overline{Q}_{1L}H_u u_{2R}\sigma + \frac{C^u_{21}}{\Lambda}\overline{Q}_{2L}H_u u_{1R}\sigma + \frac{C^u_{23}}{\Lambda}\overline{Q}_{2L}\widetilde{H}_d u_{3R}\sigma^* + \frac{C^u_{32}}{\Lambda}\overline{Q}_{3L}\widetilde{H}_d u_{2R}\sigma^* + y^u_{33}\overline{Q}_{3L}H_u u_{3R} + (u \to d).$$
- Next order is dimension 8.
- NNI texture, with the (3, 3) entry generated at dimension 4
  $$M^{u/d} = \begin{pmatrix} 0 & \varepsilon v_{u/d} C^{u/d}_{12} & 0 \\ \varepsilon v_{u/d} C^{u/d}_{21} & 0 & \varepsilon v_{d/u} C^{u/d}_{23} \\ 0 & \varepsilon v_{d/u} C^{u/d}_{32} & y^{u/d}_{33} v_{u/d} \end{pmatrix}.$$

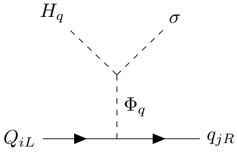
UV Completion of the Quark Sector

Type-I seesaw:
Heavy vector-like fermions F_q^{ij}



$$\mathcal{Y}^u_{ij}\overline{Q}_{iL}H_qF^{ij}_{qR} + \mathcal{M}^q_{ij}\overline{F^{ij}_{qR}}F^{ij}_{qL} + \mathcal{Y}'^q_{ij}\,\overline{F^{ij}_{qL}}\sigma q_{iR}$$

Type-II seesaw:
Heavy $SU(2)_L$ doublet scalars Φ_q



$$\mathcal{Y}^q_{ij}\overline{Q}_{iL}\Phi_q q_{jR} + \kappa_q H_q \Phi_q^\dagger \sigma$$

Can limit mass-generating terms!

Lepton Sector

Field/Symmetry	L_{iL}	ℓ_{iR}	N_i	σ'
$SU(2)_L \times U(1)_Y$	(2, -1/2)	(1, -1)	(1, 0)	(1, 0)
$U(1)_{PQ}$	(1, -3, 0)	(0, -2, -1)	(0, -2, -1)	2

- Second flavon σ' is introduced.
- Neutrino masses generated in a type-I seesaw scenario, from $\mathcal{L} \supset y_1^\nu \overline{L}_{eL} H_u N_1 + y_2^\nu \overline{L}_{\mu L} \widetilde{H}_d N_2 + y_3^\nu \overline{L}_\tau H_u N_3 + \frac{M_1}{2} \overline{N_1^c} N_1 + \frac{y_{12}^N}{2} \overline{N_1^c} N_2 \sigma' + \frac{y_{13}^N}{2} \overline{N_1^c} N_3 \sigma + \frac{y_{33}^N}{2} \overline{N_3^c} N_3 \sigma'$.
- The neutrino mass matrix gets an A_2 structure $\begin{pmatrix} 0 & a & 0 \\ a & b & c \\ 0 & c & d \end{pmatrix}$.
- Charged leptons mass matrix is diagonal at leading order.
- $0\nu\beta\beta$ at tree-level, and normal ordering.

Scalar Sector and the Axion

- The 4 or 6 scalar fields present lead to a complex scalar potential.
- Axion is the PQ Goldstone, orthogonal to the Z-boson Goldstone, i.e. $a = A_{PQ} - \left[\frac{\sum_i X_i Y_i v_i^2}{\sqrt{\sum_i Y_i^2 v_i^2}\sqrt{\sum_i X_i^2 v_i^2}} \right] A_Z$.
- Axion mass and axion-photon coupling depend on f_a[5], as $m_a \approx 5.70 \left(\frac{10^{12}\text{ GeV}}{f_a}\right) \mu\text{eV}$ and $g_{a\gamma} \approx \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$.
- Strong hierarchy between the scalars' *vevs* leads to $f_a \approx \frac{v_\sigma}{\sqrt{2}N}$.
- Here $N = 5$ and $E = \frac{28}{3}$.
- Compared to the $SU(5)$ GUT[6], where $\frac{E}{N} = \frac{8}{3}$, $\frac{|g_{a\gamma}^{SU(5)}|}{|g_{a\gamma}^{Flaxion}|} \approx 14$.

[5] Grilli di Cortona et al. 2016.
[6] Georgi and Glashow 1974.

Quark Sector

Parameter	Best fit
$A_u/(10^{-2}$ GeV)	1.519
$B_u/(10^{-2}$ GeV)	−5.368
$C_u/$ GeV	−3.004
$D_u/(10^{1}$ GeV)	3.562
$E_u/(10^{2}$ GeV)	1.679
$A_d/(10^{-2}$ GeV)	−1.233
$B_d/(10^{-2}$ GeV)	1.228
$C_d/(10^{-1}$ GeV)	−3.074
$D_d/(10^{-1}$ GeV)	−4.782
$E_d/$ GeV	−2.793
$\alpha_u/^\circ$	96.56
$\beta_u/^\circ$	98.23

Observable	Global-fit value		Model best-fit
	Best-fit value	1σ range	
$\theta^q_{12}/^\circ$	13.09	13.06 → 13.12	12.988
$\theta^q_{13}/^\circ$	0.207	0.202 → 0.213	0.2000
$\theta^q_{23}/^\circ$	2.32	2.29 → 2.37	2.381
$\delta^q/^\circ$	68.53	66.06 → 71.10	68.720
$m_u/(10^{-3}$ GeV)	1.288	0.766 → 1.550	1.2743
$m_c/(10^{-1}$ GeV)	6.268	6.076 → 6.459	6.2592
$m_t/$ GeV	171.68	170.17 → 173.18	171.687
$m_d/(10^{-3}$ GeV)	2.751	2.577 → 3.151	2.7330
$m_s/(10^{-2}$ GeV)	5.432	5.153 → 5.728	5.4311
$m_b/$ GeV	2.854	2.827 → 2.880	2.8501
χ^2_q			1.0901

Lepton Sector

Parameter	Best fit
$a/(10^{-3}\,\text{eV})$	9.933
$b/(10^{-2}\,\text{eV})$	2.646
$c/(10^{-2}\,\text{eV})$	2.475
$d/(10^{-2}\,\text{eV})$	2.264
$\phi_a/^\circ$	29.87
$\phi_b/^\circ$	91.88
$\phi_c/^\circ$	3.03
$\phi_d/^\circ$	-109.97

Observable	Global-fit value		Model best-fit
	Best-fit value	1σ range	
$\theta^l_{12}/^\circ$	34.5	$33.5 \to 35.7$	34.85
$\theta^l_{13}/^\circ$	8.45	$8.31 \to 8.61$	8.432
$\theta^l_{23}/^\circ$	47.7	$46.0 \to 48.9$	48.11
$\delta^l/^\circ$	218	$191 \to 256$	258.8
$\alpha/^\circ$			65.27
$\beta/^\circ$			265.08
$\Delta m^2_{21}/(10^{-5}\,\text{eV}^2)$	7.55	$7.39 \to 7.75$	7.571
$\Delta m^2_{32}/(10^{-3}\,\text{eV}^2)$	2.424	$2.394 \to 2.454$	2.4221
$\sum m_\nu/(10^{-2}\,\text{eV})$			6.453
$m_e/$ MeV	0.4865763	$0.4865735 \to 0.4865789$	-
$m_\mu/$ GeV	0.10271897	$0.10271866 \to 0.10271931$	-
$m_\tau/$ GeV	1.74618	$1.74602 \to 1.74633$	-
χ^2_l			2.0053

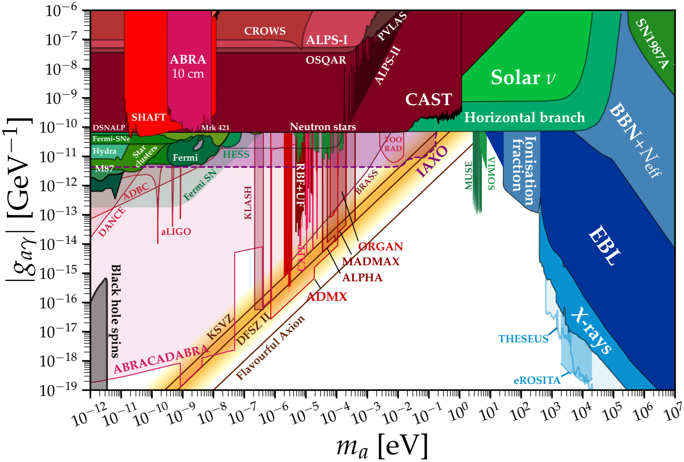
Flavour Violating Decays with Axions

- Flavour violating Yukawa couplings can lead to $q_i \to q_j\, a$.
- Can be probed through meson decays.
- $\Gamma(K^+ \to \pi^+ a) \approx \frac{1.9\times 10^{-9}\,\mathrm{GeV}^3}{v_\sigma^2}$.
- E949 Collaboration constrain $\frac{\Gamma(K^+ \to \pi^+ a)}{\Gamma_{Total}(K^+)} < 7.3 \times 10^{-11}$[7].
- Relationship $f_a \approx \sqrt{2} v_\sigma N$ implies $f_a \gtrsim 7 \times 10^9$ GeV.
- $m_a < 0.7 \times 10^{-3}$ eV and $|g_{a\gamma}(\mathrm{GeV}^{-1})| < 0.8 \times 10^{-14}$.
- $B^+ \to K^+\, a$ (Belle-II[8]) provides $f_a \gtrsim 6 \times (10^6 - 10^7)$ GeV.

[7] Adler et al. 2008.
[8] Calibbi et al. 2017.

Flavour Violating Decays with Axions

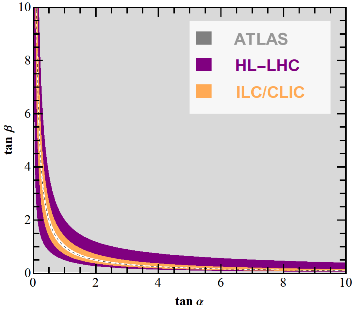
Flavourful axion and experiments[9]



[9] O'Hare 2020.

Flavour Violating Higgs Couplings

- $v_{u/d} \ll v_{\sigma/\sigma'}$.
- Two Higgs bosons:
  $h \approx h_0^u \cos\alpha + h_0^d \sin\alpha$ and
  $H \approx -h_0^u \sin\alpha + h_0^d \cos\alpha$.
- $v_{SM} = v_u \sin\beta + v_d \cos\beta$.
- Flavour conservation if $\tan\alpha = \cot\beta$.
- $t \to h\,c$ sets bounds[10].
- Effective Lagrangian and χ^2 fit:
  $\left|\frac{\cos\alpha}{\sin\beta}(1-\tan\alpha\tan\beta)\right| \leq 17\frac{\Gamma^{Exp}_{t\to hc}}{[GeV]}$.



[10] ATLAS 2016; Vos et al. 2016.

Flavourful Axion as a Dark Matter Candidate

- Through the misalignment mechanism[11] cold axions can be produced, with $\Omega_a h^2 \approx 2 \times 10^4 \left(\frac{f_a}{10^{16}\text{GeV}}\right)^{7/6} \langle\theta_i^2\rangle$.
- Relic density can be matched to $\Omega_{DM} h^2 \sim 0.12$.
- For $\theta_i \in (0, 2\pi)$ and 5×10^{10} GeV $< f_a < 1 \times 10^{15}$ GeV.
- $N > 1$ implies formation of domain walls, which have to be destabilized or inflated away.

[11] Fox, Pierce, and Thomas 2004.

Conclusions

- $U(1)_{PQ}$ can be identified with $U(1)_{FN}$.
- Mass and vev hierarchies.
- At leading order mass quark mass matrix gets NNI structure and neutrino mass matrix gets A_2 structure.
- Theoretical predictions match χ^2 fit.
- Flavourful axion arises after PQ symmetry breaking.
- Flavour violating decays with the axion set bounds on f_a, m_a, and $g_{a\gamma}$.
- Possibility of FCNCs being present.
- Flavourful axion can account for dark matter.
- Future possibilities: KSVZ-like model, gauge symmetries.

Thank you for listening!