THE AXION-FLAVOR CONNECTION

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OUTLINE

- STRONG CP PROBLEM
- AXION SOLUTION AND BENCHMARK AXION MODELS

  Focus on the PQ origin and quality issues
- THE AXION-FLAVOR CONNECTION

STRONG CP PROBLEM

The QCD Lagrangian contains a CP-violating term:

$$\mathcal{L}_{QCD} = \sum_f \bar{\psi}_f (i\not{D} - m_f)\psi_f - \frac{1}{4}(G_{\mu\nu}, G^{\mu\nu}) + \theta \frac{1}{32\pi^2}(G_{\mu\nu}, \tilde{G}^{\mu\nu})$$

However, experimental bounds indicate that, in strong interactions, $\vartheta < 10^{-10}$. How can we explain this?

- Anthropic reasons? No…
- Mechanism that constrains $\vartheta < 10^{-10}$ or drives ϑ to 0:
  1. *Vanishing fermion masses;*
  2. *Nelson-Barr Mechanism.*

AXION SOLUTION

In 1977, Peccei and Quinn devised a mechanism to dispose of CP violation in strong interactions. Introducing a new anomalous, spontaneously broken, global U(1) invariance at the Lagrangian level and imposing that at least one quark flavor acquires its mass by coupling to a scalar field with non-vanishing vacuum expectation value (VEV), they managed to preserve CP invariance in strong interactions.

We will focus on the benchmark axion models, explaining the *origin* and *quality* problems of the PQ symmetry.

STEAL A GLANCE ON THE AXION MASS

Just to show some numbers, the axion mass turns out to be

$$m_a^2 = \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2} \Longrightarrow m_a \approx 5.7 \left(\frac{10^{12}\mathrm{GeV}}{f_a} \right) \mu\mathrm{eV}$$

BENCHMARK AXION MODEL

Different ways of implementing the PQ mechanism can be classified in three large classes:

1. The Peccei-Quinn-Weinberg-Wilczek (PQWW) model;
2. The Dine-Fishler-Srednicki-Zhitnitsky (DFSZ) model;
3. The Kim-Shifman-Vainshtein-Zakharov (KSVZ) model.

PQWW MODEL

In the PQWW model, the SM is extended by adding a new complex scalar field, namely a second Higgs doublet.

The Lagrangian is written as:

$$\mathcal{L} \supset -y_u \bar{q}_L H_u u_R - y_d \bar{q}_L H_d d_R - V(H_u, H_d) + \text{h.c.}$$

$$V = \frac{\lambda_u}{4}\left(|H_u|^2 - \frac{v_u^2}{2}\right)^2 + \frac{\lambda_d}{4}\left(|H_d|^2 - \frac{v_d^2}{2}\right)^2 + \lambda_{ud}\left(H_u^\dagger H_d\right)\left(H_d^\dagger H_u\right) + \ldots$$

One could naively say that, since there are two Higgs fields, there are two independent symmetries, which can be redefined to obtain the hypercharge and an orthogonal *accidental* Peccei-Quinn symmetry. Is it true? NO!

PQWW MODEL

The general two Higgs doublet model potential, in fact, can be written as

$$
\begin{aligned}
V(H_u, H_d) = {} & m_u^2 H_u^\dagger H_u + m_d^2 H_d^\dagger H_d - \cancel{\left[m_{ud}^2 H_u^\dagger H_d + \text{h.c.}\right]} + \frac{1}{2}\lambda_1 \left(H_u^\dagger H_u\right)^2 + \\
& + \frac{1}{2}\lambda_2 \left(H_d^\dagger H_d\right)^2 + \lambda_3 \left(H_u^\dagger H_u\right)\left(H_d^\dagger H_d\right) + \lambda_4 \left(H_u^\dagger H_d\right)\left(H_d^\dagger H_u\right) + \\
& + \left[\cancel{\frac{1}{2}\lambda_5 \left(H_u^\dagger H_d\right)^2} + \lambda_6 \cancel{\left(H_u^\dagger H_u\right)\left(H_u^\dagger H_d\right)} + \lambda_7 \cancel{\left(H_d^\dagger H_d\right)\left(H_u^\dagger H_d\right)} + \text{h.c.}\right],
\end{aligned}
$$

Therefore, if we want a PQ symmetry, we must *impose* that some terms are absent. *No accidental PQ symmetry.*

ACHTUNG!

In general, all the aforementioned axion models DO NOT feature an *accidental* PQ symmetry.

«But, Clemente, why did we focus on the fact that the PQ symmetry was not *accidental?».*

For two reasons:

- Global symmetries are widely believed not to be fundamental in QFT;
- Being anomalous, $U(1)_{PQ}$ is not a symmetry of the quantum world.

Therefore, we should account for the *origin.* It would be desirable that the PQ came accidentally, as a result of imposing «sacred» principles: Lorentz and gauge invariance.

ORIGIN AND QUALITY OF THE PQ SYMMETRY

Moreover, experimental bounds constrain $\vartheta < 10^{-10}$, so our symmetry must be highly protected. This is commonly referred to as the *PQ quality* issue.

Various constructions that enforce a *high quality, accidental* PQ symmetry have been proposed, but they all rely on imposing the dimension of the first PQ-breaking operator *by hand.*

Not satisfying!

AND NOW?

We need a mechanism that enforces a *high quality, accidental* PQ symmetry without imposing any condition by hand.

THE FLAVOR PUZZLE

On a completely different note, the fermion mass hierarchy problem represents one among the most puzzling features of the Standard Model. In two lines, there is a 5 order of magnitude difference between the Yukawa couplings of the top quark and of the up quark.

THE AXION-FLAVOR CONNECTION: A TOP-DOWN APPROACH

We will assume that the SM flavor pattern is generated by a spontaneously broken flavor symmetry, which will be identified requiring that

- it must automatically enforce an *accidental* global anomalous PQ symmetry;
- it must protect $U(1)_{PQ}$ up to a sufficiently large operator dimension.

Then, we will analyze whether it reproduces, after SSB, the observed pattern of quark mass hierarchies and CKM mixings

THE AXION-FLAVOR CONNECTION: MODEL-BUILDING

Let us consider the following examples of flavor symmetries:

- $SU(N)_L x SU(N)_R$: Y in the bifundamental, det(Y) is PQ-violating;
- $SU(M)_L x SU(N)_R$, $M \neq N$: Y in the bifundamental, we cannot write det(Y)

Therefore, rectangular symmetries are more effective, as for the *quality* issue.

THE AXION-FLAVOR CONNECTION: MODEL-BUILDING

In order to construct a sensible model, our *modus operandi* will be oriented by the following pillars and requirements:

- *Simplicity:* look for the simplest consistent gauge group and for the smallest number of fermions;
- *Phenomenology:*

1. ***Masses:*** top mass at tree level from renormalizable coupling to Higgs. Up and charm from effective operators.
2. ***Mixings:*** field content sufficiently rich to generate all the masses and mixings of the quarks

- *Gauge anomalies:* gauge symmetries must be anomaly-free.
- *PQ origin and quality:* the PQ-symmetry should be accidental and protected up to a suitably large operator dimension.

THE AXION-FLAVOR CONNECTION: MODEL-BUILDING

The «simplest» model complying with all these requirements is a 2HDM containing 4 scalars and a 7x7 fermion mass matrix transforming under the $G_{SM} \times SU(3) \times SU(2)_u \times SU(2)_d \times U(1)$ gauge group.

THE AXION FLAVOR CONNECTION: RESULTS

In the models analyzed, we were able to retrieve the quark mass hierarchies from non-hierarchical (or mildly hierarchical) input parameters without imposing any number *by hand.* We were also able to obtain the CKM, although not simultaneously with the correct mass ratios.

	num	exp
m_c(GeV)	0.35	0.35
m_u(GeV)	0.72	0.69
m_b(GeV)	1.50	1.50
m_s(GeV)	0.041	0.030
m_d(MeV)	1.50	1.52

Numerical (num) values of the quark masses obtained and their experimental values evolved at the scale 10^8 GeV. $m_t = 102.5$ GeV.

- The accidental PQ symmetry is protected up to a large operator dimension, complying with the PQ quality requirement

THE AXION-FLAVOR CONNECTION: CONCLUSIONS AND PROSPECTS

- As we have shown, the axion-flavor connection is a sensible ansatz to tackle the SM flavor puzzle and the strong CP problem in one fell swoop.
- Moreover, the QCD-axion could also be a good CDM candidate.

  →I have a dream! Flavor + Strong CP problem + CDM (at once).
- Research strategies:

1. Implement powerful minimization routines and try to obtain CKM + Hierarchies simultaneously
2. Extend to the lepton sector
3. Dream! (and pray…)

THANK YOU FOR
THE ATTENTION!

AXION EFFECTIVE LAGRANGIAN

The underlying idea of the PQ solution is based on the introduction of a *spinless axion field*

$$\mathcal{L}_a = \frac{1}{2}\left(\partial_\mu a\right)^2 + \mathcal{L}\left(\partial_\mu a, \psi\right) + \frac{1}{32\pi^2}\frac{a}{f_a}\left(G_{\mu\nu}, \tilde{G}^{\mu\nu}\right)$$

endowed with a *quasi-shift symmetry*

$$a \to a + \kappa f_a$$

$$\delta S = \frac{\kappa}{32\pi^2}\int d^4x \left(G_{\mu\nu}, \tilde{G}^{\mu\nu}\right)$$

Does the action shift remind you of something?

AXION EFFECTIVE LAGRANGIAN

Of course, the ϑ-term!

$$\theta \frac{1}{32\pi^2} \int d^4x \, (G_{\mu\nu}, \tilde{G}^{\mu\nu})$$

Using the quasi shift symmetry, we can write

$$\mathcal{L}_{QCD+a} = \mathcal{L}_{QCD} + \frac{1}{32\pi^2} \frac{a}{f_a} \left(G_{\mu\nu}, \tilde{G}^{\mu\nu} \right)$$

where we have chosen the value of κ that cancels the ϑ-term, so that the QCD Lagrangian includes only CP-invariant contributions.

Minimization of the scalar potential (ChPT techniques) guarantees that the theory has a minimum in the CP-conserving a = 0, thus solving the Strong CP problem.

THE AXION-FLAVOR CONNECTION: 2HDM

General strategy:

- making an initial choice of the gauge-allowed Yukawa terms and scalar non-hermitian operators;
- computing the anomaly, which will depend on two charges, and then identifying:

1. the flavor U(1) gauge symmetry, associated to the anomaly-free combination of the two charges;
2. the PQ global $U(1)_{PQ}$ symmetry, anomalous and orthogonal to the flavor gauge U(1);

- verifying that no operator with charge equal to the anomaly can be written;
- minimizing the scalar potential;
- seeing whether minimization of the scalar potential with non-hierarchical coupling constants allows for SM-like hierarchies among the quarks and, hopefully, also for CKM.