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Protecting the axion with local baryon number

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ABSTRACT

The Peccei–Quinn (PQ) solution to the Strong CP Problem is expected to fail unless the global symmetry $U(1)_{PQ}$ is protected from Planck-scale operators up to high mass dimension. Suitable protection can be achieved if the PQ symmetry is an automatic consequence of some gauge symmetry. We highlight that if baryon number is promoted to a gauge symmetry, the exotic fermions needed for anomaly cancellation can elegantly provide an implementation of the Kim–Shifman–Vainshtein–Zakharov 'hidden axion' mechanism with a PQ symmetry protected from Planck-scale physics.
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1. Introduction

In principle one expects that the QCD Lagrangian should contain a CP-violating term of the form

$$\mathcal{L}_{\rm QCD} \supset -\bar{\theta}\,\frac{\alpha_S}{8\pi} G_{\mu\nu}\widetilde{G}^{\mu\nu}\,. \tag{1}$$

This would imply a non-vanishing neutron electric-dipole moment $d_n \simeq 5.2\times 10^{-16}\bar{\theta}$ e cm [1], which has been constrained to be $d_n < 3.0\times 10^{-26}$ e cm at 90 % C.L. by experimental searches [2]. Satisfying this experimental upper limit on d_n requires $\bar{\theta} \lesssim \bar{\theta}_{\rm lim} \simeq 10^{-10}$ and the unexplained smallness of $\bar{\theta}$ is the Strong CP Problem.

Fortunately, there is an elegant resolution due to Peccei and Quinn (PQ) [3,4] in which $\bar{\theta}$ is promoted to a dynamical field and the scalar potential is minimised for $\bar{\theta}=0$. The PQ mechanism involves a global symmetry $U(1)_{PQ}$ which is spontaneously broken by a vacuum expectation value (VEV) and explicitly broken by the QCD chiral anomaly. If in addition $U(1)_{PQ}$ is explicitly broken by other sources, then generically $\bar{\theta}\neq 0$. One potential concern in this context is that continuous global symmetries are expected to be explicitly broken by Planck-scale ($M_{\rm Pl}$) physics [5, and references therein]. Indeed, unless Planck-scale suppressed operators with mass dimension $D \lesssim 9$ are absent, then generically $\bar{\theta} > \bar{\theta}_{\rm lim}$, in conflict with observation [6,7]. Thus for the PQ mechanism to be successful these PQ violating operators must be forbidden or highly suppressed. Manners of forbidding these PQ violating Planck-scale operators include imposing discrete symmetries, or embedding $U(1)_{PQ}$ into a local symmetry or GUT [7–12].

Here we consider models with the gauge symmetry

$$SU(3)\times SU(2)_L \times U(1)_Y \times U(1)_{\mathcal{B}}\,, \tag{2}$$

where $U(1)_{\mathcal{B}}$ is *generalised baryon number*, under which the Standard Model quarks carry charge 1/3, whilst other Standard Model fields are neutral. Promoting the accidental U(1) symmetries of the Standard Model to gauge symmetries is an interesting idea with roots in the work of [13–15]. Recently such models have received a marked growth in interest following the explicit models of Fileviez Perez and Wise [16,17] (see also [18]). The quantum numbers of the Standard Model fermions (with three right-handed neutrinos N_R) are

$$\begin{aligned} Q_L &= (\mathbf{3},\mathbf{2},1/3,1/3)_{\times 3}\,, & L_L &= (\mathbf{1},\mathbf{2},-1,0)_{\times 3}\,,\\ u_R &= (\mathbf{3},\mathbf{1},4/3,1/3)_{\times 3}\,, & e_R &= (\mathbf{1},\mathbf{1},-2,0)_{\times 3}\,,\\ d_R &= (\mathbf{3},\mathbf{1},-2/3,1/3)_{\times 3}\,, & N_R &= (\mathbf{1},\mathbf{1},0,0)_{\times 3}\,, \end{aligned} \tag{3}$$

with notation $(\mathbf{d_3},\mathbf{d_2},q_y,q_{\mathcal{B}})_{\times n}$ where $\mathbf{d_N}$ is the dimension of the representation under SU(N), the q_i are $U(1)_i$ charges and the subscript $\times 3$ indicates the number of families. The quantum numbers of the Higgs are $H=(\mathbf{1},\mathbf{2},1,0)_{\times 1}$. In the Standard Model global baryon number $U(1)_B$ is anomalous with non-vanishing anomaly coefficients

$$\mathcal{A}_{U(1)_B\times SU(2)^2} = 3/2\,,\qquad \mathcal{A}_{U(1)_B\times U(1)_Y^2} = -6\,. \tag{4}$$

An anomaly-free theory of gauged baryon number therefore requires new chiral fermions transforming under the Standard Model gauge group as well as $U(1)_{\mathcal{B}}$.

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In this work we highlight that the PQ symmetry can be protected from $M_{\rm Pl}$ operators by $\mathrm{U}(1)_{\mathscr{B}}$ gauge invariance.[1] This is a well motivated example of the case that $\mathrm{U}(1)_{\rm PQ}$ arises as an accidental symmetry due to a gauge symmetry. Moreover, the chiral fermions needed for anomaly cancellation can naturally yield the field content to implement the Kim–Shifman–Vainshtein–Zakharov (KSVZ) mechanism for 'hiding' the axion [19,20]. Since baryon number is intimately tied to the QCD sector, it is aesthetically pleasing to connect the resolution of the Strong CP Problem to a baryonic symmetry.

2. Gauge-embedded PQ symmetries

The PQ mechanism dynamically sets $\bar\theta \approx 0$ provided there is some global $\mathrm{U}(1)_{\rm PQ}$ for which the main source of explicit breaking is due to the QCD chiral anomaly, $\mathcal{A}_{\mathrm{U}(1)_{\rm PQ}\times \mathrm{SU}(3)^2} \neq 0$. In the following we discuss how such an anomalous global U(1) can arise in models with gauged baryon number $\mathrm{U}(1)_{\mathscr{B}}$.

We supplement the Standard Model with exotic fermions charged under the Standard Model gauge group as well as $\mathrm{U}(1)_{\mathscr{B}}$. If cross-terms involving both Standard Model quarks and exotics are forbidden by gauge invariance and the choice of particle content, the model exhibits a global 'exotics' symmetry $\mathrm{U}(1)_X$ which is independent of global Standard Model baryon number $\mathrm{U}(1)_B$. Nevertheless, the baryon and exotics sectors are linked by the underlying $\mathrm{U}(1)_{\mathscr{B}}$ symmetry. It is insightful to fix the global $\mathrm{U}(1)_X$ and $\mathrm{U}(1)_B$ charges to match the corresponding $\mathrm{U}(1)_{\mathscr{B}}$ charges. Given this choice, the cancellation of the $\mathrm{U}(1)_{\mathscr{B}} \times \mathcal{G}^2$ gauge anomaly implies that the anomalies of the global symmetries with some gauge group $\mathcal{G}$ must be equal and opposite:

$$\mathcal{A}_{\mathrm{U}(1)_{\mathscr{B}}\times\mathcal{G}^2} = 0 \quad\Rightarrow\quad \mathcal{A}_{\mathrm{U}(1)_B\times\mathcal{G}^2} = -\mathcal{A}_{\mathrm{U}(1)_X\times\mathcal{G}^2}. \tag{5}$$

With only the Standard Model quarks carrying global baryon number, $\mathrm{U}(1)_B$ does not have a QCD anomaly ($\mathcal{A}_{\mathrm{U}(1)_B\times \mathrm{SU}(3)^2} = 0$) and hence also $\mathcal{A}_{\mathrm{U}(1)_X\times \mathrm{SU}(3)^2} = 0$, impeding an identification of exotics number $\mathrm{U}(1)_X$ with the PQ symmetry.

One can however easily envision two independent global 'exotics' symmetries, which we call suggestively $\mathrm{U}(1)_{\rm PQ}$ and $\mathrm{U}(1)'_{\rm PQ}$. Independent global symmetries occur if there are no cross-terms between sets of fermions. With the $\mathrm{U}(1)_{\mathscr{B}}$ induced normalisation the anomalies of these two individual global symmetries are related to the anomaly of global exotics number by

$$\mathcal{A}_{\mathrm{U}(1)_X\times\mathcal{G}^2} = \mathcal{A}_{\mathrm{U}(1)_{\rm PQ}\times\mathcal{G}^2} + \mathcal{A}_{\mathrm{U}(1)'_{\rm PQ}\times\mathcal{G}^2}. \tag{6}$$

By eq. (5) it remains that $\mathcal{A}_{\mathrm{U}(1)_X\times\mathcal{G}^2} = 0$, however with appropriate charge assignments one can arrange for

$$\mathcal{A}_{\mathrm{U}(1)_{\rm PQ}\times \mathrm{SU}(3)^2} = -\mathcal{A}_{\mathrm{U}(1)'_{\rm PQ}\times \mathrm{SU}(3)^2} \neq 0\,, \tag{7}$$

and thus these global symmetries are suitable for implementing the PQ mechanism.

Spontaneous breaking of the two independent global PQ symmetries will lead to two Nambu–Goldstone bosons. The physical axion a will be an admixture of these two Goldstone bosons while the orthogonal field will be eaten by the $\mathrm{U}(1)_{\mathscr{B}}$ gauge boson Z' resulting in a non-zero mass $m_{Z'}$. The effective axion decay constant f_a is given by [21]

$$f_a = \frac{ff'}{\sqrt{f^2 + f'^2}}\,, \tag{8}$$

where f and f' are the breaking scales of $\mathrm{U}(1)_{\rm PQ}$ and $\mathrm{U}(1)'_{\rm PQ}$. The 'axion window' in which f_a is appropriate to avoid cosmological and astrophysical limits is roughly 10^9 GeV $\lesssim f_a \lesssim 10^{12}$ GeV [22]. The axion obtains a mass from the QCD chiral anomaly and a contribution Δ_a from Planck-scale breaking

$$m_a^2 \simeq (m_a^{\rm QCD})^2 + \Delta_a^2\,. \tag{9}$$

For the case that the leading $M_{\rm Pl}$ breaking operator is mass dimension D, the correction Δ_a is of order [6,10]

$$\Delta_a^2 \sim g\cos\delta M_{\rm Pl}^2 \left(\frac{f_a}{M_{\rm Pl}}\right)^{D-2}, \tag{10}$$

where g is a coupling associated to gravitational interactions and δ is the rotation of the phase of the fermion mass matrix into $\bar\theta$. Breaking of $\mathrm{U}(1)_{\rm PQ}$ by gravitational effects leads to $\bar\theta \propto \Delta_a^2$ which is generically non-zero. Specifically, (for $\Delta_a^2 \ll m_a^2$) the Planck-scale breaking of the PQ symmetry leads to

$$\bar\theta \simeq \frac{\Delta_a^2}{m_a^2}\tan\delta \sim g\sin\delta \frac{M_{\rm Pl}^2}{m_a^2}\left(\frac{f_a}{M_{\rm Pl}}\right)^{D-2}. \tag{11}$$

For $g,\delta \sim \mathcal{O}(1)$ and $f_a \sim 10^{11}$ GeV the dimension D of the gravity induced operator should be $D \gtrsim 10$ in order to ensure $\bar\theta \leq \bar\theta_{\rm lim}$. We note in passing that there are two potential caveats: further *ad-hoc* symmetries could forbid these operators up to some order or, alternatively, if $g \ll 1$ Planck-scale breaking may not be important. There are some arguments in the literature that these operators could potentially be exponentially suppressed [23], however, it is far from clear that this is the case and naïvely one might expect gravitationally induced operators with $\mathcal{O}(1)$ coefficients. Thus, in general protection from Planck-scale symmetry violation should be considered an important requirement for successful implementations of the PQ mechanism.

3. PQ protection from $\mathbf{U(1)}_{\mathscr{B}}$

As was discussed in the last section, to implement a protected PQ symmetry with gauged baryon number one needs at least two pairs of fermion exotics that can be associated with two accidental PQ symmetries. Moreover, one requires that at least one exotic fermion pair transforms non-trivially under $\mathrm{SU}(2)_L$ in order to cancel the $\mathrm{SU}(2)_L^2\times\mathrm{U}(1)_{\mathscr{B}}$ anomaly. However, if the fermion exotics carry SU(3) colour and are chiral under $\mathrm{U}(1)_{\mathscr{B}}$ one cannot simultaneously cancel the $\mathrm{SU}(2)_L^2\times\mathrm{U}(1)_{\mathscr{B}}$ and $\mathrm{SU}(3)^2\times\mathrm{U}(1)_{\mathscr{B}}$ anomalies if all the exotic fermions transform in the same $\mathrm{SU}(2)_L$ representation. To allow simple mass terms for the fermion exotics, we limit ourselves to pairs that are vector-like under the Standard Model gauge group.

The Planck-scale operators which dominantly cause $\bar\theta$ to deviate from zero are those involving only scalars with high scale VEVs, while operators involving fields that do not obtain VEVs are expected to be subdominant [24]. Therefore for a given PQ model it is important to determine the leading scalar operator which violates the PQ symmetry.

Consider the following set of n fermion pairs,[2] which we label by the dimension $\lambda_i \in \mathbb{N}$ of their $\mathrm{SU}(2)_L$ representation,

$$\begin{aligned}
\lambda_{1L} &= (\mathbf{3}, \boldsymbol{\lambda_1}, Y_1, B_1), & \lambda_{1R} &= (\mathbf{3}, \boldsymbol{\lambda_1}, Y_1, B'_1),\\
&\ \ \vdots & &\ \ \vdots\\
\lambda_{nL} &= (\mathbf{3}, \boldsymbol{\lambda_n}, Y_n, B_n), & \lambda_{nR} &= (\mathbf{3}, \boldsymbol{\lambda_n}, Y_n, B'_n),
\end{aligned} \tag{12}$$

[1] Associating a PQ symmetry to local baryon number was briefly remarked on in an early paper of Foot, Joshi, and Lew [15].

[2] A new family of quarks which are vector-like under the Standard Model gauge group, as studied in [17], corresponds to $n = 3$ pairs with $\boldsymbol{\lambda_1} = \mathbf{2}$ and $\boldsymbol{\lambda_2} = \boldsymbol{\lambda_3} = \mathbf{1}$.

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