Naturally light invisible axion and local $Z_{13}\otimes Z_3$ symmetries

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We show that by imposing local $Z_{13}\otimes Z_3$ symmetries in an $SU(2)\otimes U(1)$ electroweak model we can implement an invisible axion in such a way that (i) the Peccei-Quinn symmetry is an automatic symmetry of the classical Lagrangian, and (ii) the axion is protected from semiclassical gravitational effects. In order to be able to implement such a large discrete symmetry, and at the same time allow a general mixing in each charge sector, we introduce right-handed neutrinos and enlarge the scalar sector of the model. The domain wall problem is briefly considered.

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It has been known for a long time that the complex nature of the QCD vacuum solves the old $U(1)_A$ problem [1,2] but also implies the existence of the $\bar{\theta}F\tilde{F}$ term in the classical Lagrangian [3]. This *CP*-nonconserving $\bar{\theta}$ angle (which has also an electroweak contribution) should be smaller than 10^{-9} in order to be consistent with the measurement of the electric dipole moment of the neutron [4]. Why is *CP* only weakly violated in QCD? This is the strong *CP* problem and an elegant way to solve it is by introducing a chiral symmetry $U(1)_{\rm PQ}$ [5]. This Peccei-Quinn (PQ) symmetry implies also the existence of a pseudo Goldstone boson—the axion [6]. The invisible axion is almost a singlet (here denoted by ϕ) under the $SU(2)\otimes U(1)$ gauge symmetry [7]. In addition, since this particle can occur in the early Universe in the form of a Bose condensate which never comes into thermal equilibrium, it can be a significant component of the cold dark matter if its mass is of the order of 10^{-5} eV [8,9], which makes it important in its own right. However, such a small mass for the axion can be spoiled by semiclassical gravity effects since it could induce renormalizable or nonrenormalizable effective interactions which break explicitly any global symmetry, and in particular the PQ symmetry. The most dangerous of these effective operators are of the form ϕ^D, where D is the mass dimension of the effective operator. In this case the axion could gain a mass which is greater than the mass coming from instanton effects and also the $\bar{\theta}$ angle is not less than 10^{-9} in a natural way. This can be avoided if the dimension of the effective operators is $D \gtrsim 12$ [10,11]. Hence, unless D is high enough, invisible axion models do not solve the strong *CP* problem in a natural way. Thus the invisible (very light) axion must be protected against gravity effects.

Some years ago Krauss and Wilczek [12] pointed out that local symmetries can masquerade as discrete global symmetries to an observer equipped with only low-energy probes. We can see this as follows. Consider a $U(1)$ gauge theory with two complex scalar fields η and ξ carrying charge Ne and e, respectively. It is possible, for instance, that η undergoes condensation at some very high energy v, but ξ does not condensate and produces quanta of relatively small mass. Before the condensation the theory is invariant under the transformation $\eta'(x)=\exp[iNe\Lambda(x)]\eta(x)$, $\xi'(x)=\exp[ie\Lambda(x)]\xi(x)$ and $A'_\mu(x)=A_\mu(x)-\partial_\mu\Lambda(x)$, here A_μ is the $U(1)$ gauge field. The condensate characterized by the vacuum expectation value $\langle\eta(x)\rangle=v$ in the homogeneous ground state is invariant only when Λ is an integer multiple of $2\pi/Ne$. This residual transformation still acts nontrivially on ξ but now as a discrete Z_N group. The effective theory well below v will be the theory of the single complex scalar field ξ, neither the gauge field nor the scalar η will appear in the effective theory since these fields are very heavy. The only implication of the original gauge symmetry for the low energy effective theory is the absence of interaction terms forbidden by the Z_N symmetry. For instance, if there were more charged scalar fields in the theory, the discrete symmetry would forbid many couplings that were otherwise possible. Hence, since no processes like black-hole evaporation or wormhole tunneling can violate a discrete gauge symmetry it means that local Z_N symmetries violate the no-hair theorem [13]. These symmetries may be the consequences of gauge $U(1)$'s symmetries which are embedded in a larger grand unified theory or from a fifth dimension as it was shown for the case of $U(1)_Y$ in Ref. [14] or even in superstring inspired models [15–17].

In fact, it has long been known that superstring theories exhibit PQ-like symmetries. It happens that in the reduction of a ten-dimensional theory to four dimensions an arbitrary large number of massless (up to the effect of the coupling $F\tilde{F}$) scalar four-dimensional fields, which cannot be gauged away, arise [18,19]. On the other hand, in superstring theory, also naturally local discrete symmetries arise [15–18]. These facts are welcome since superstring theory is considered a good candidate for the unification of the four interactions.

Hence it is reasonable to require that any global or local symmetry that is introduced in low energy models can be derived from the superstring theory. However, since we already do not know the details of the theory that describes quantum gravity, we will apply the ideas above in a more conservative scenario: a multi-Higgs extension of the standard model.

We show below that in this situation, the axion, as a solution to the strong *CP* problem, can be achieved by introducing appropriated discrete symmetries and also the PQ symmetry arises as an automatic or accidental symmetry of the classical Lagrangian in the sense that it is not imposed on the Lagrangian but it is just a consequence of the particle content, renormalizability, and the gauge and Lorentz invariance of the model [10]. The automatic PQ symmetry has been also considered up to now only in the context of grand unified or supersymmetric theories [20] or, recently, in 3-3-1 models [21,22]. The same can be said with respect to the axion protection from gravity effects [11,16,17,22].

The model we will put forward can be viewed as a way of stabilizing the Dine-Fischler-Srednicki (DFS) axion [7]. As is well known the DFS axion suffers from two difficulties: (i) the PQ symmetry has to be imposed by hand and (ii) the axion is not stable from the gravitational effects as discussed before. With respect to the first problem we expect that the PQ symmetry is not an *ad hoc* symmetry but an accidental one. It could be the consequence of discrete symmetries Z_N which in addition, if N is large enough, it can stabilize the axion from the classical gravity effect. In this vain a large Z_N symmetry solves both difficulties of the DFS axion model. The lowest order effective operator contributing to these parameters have $D=13$ since operators with dimension up to $D=12$ are forbidden by the local discrete symmetry $Z_{13}\otimes Z_3$. Moreover, after imposing these discrete symmetries the PQ chiral symmetry is automatically implemented in a model with $SU(3)_C\otimes SU(2)_L\otimes U(1)_Y$ gauge symmetry (a similar analysis for avoiding *B*- and *L*-violating operators in supersymmetric versions of this model was done in Ref. [23]).

The axion is made invisible if it is almost a singlet under the gauge group and for this reason we add a singlet ϕ which gets a vacuum expectation value denoted by v_ϕ [7]. The suppression of the explicit breakdown of the PQ symmetry by gravity is obtained by adding a large Z_N symmetry among the matter multiplets, in such a way that effective operators like $\phi^{N-1}/M_{\rm Pl}^{(N-1)-4}$, where $M_{\rm Pl}$ is the Planck mass, are automatically suppressed. At the same time this local discrete symmetry makes the PQ symmetry an automatic symmetry of the classical Lagrangian. For instance, a Z_{13} symmetry implies that the first nonforbidden operator is of dimension thirteen and the first contribution to the axion mass square is proportional to $v_\phi^{11}/M_{\rm Pl}^9\approx 10^{-21}$ eV^2 or $10^{-11}m_a^2$, if $m_a\sim\Lambda_{\rm QCD}^2/v_\phi\approx 10^{-5}$ eV is the instanton induced mass (we have used $M_{\rm Pl}=10^{19}$ GeV and $v_\phi=10^{12}$ GeV). We see also that the naturalness of the PQ solution to the $\bar{\theta}$-strong problem is not spoiled since in this case we have $\theta_{\rm eff}\propto v_\phi^N/M_{\rm Pl}^{N-4}\Lambda_{\rm QCD}^4$ [24] and it means also that $\theta_{\rm eff}\propto 10^{-11}$ for $N=13$.

In order to be able to implement this rather large symmetry the representation content of the model is augmented: we add right-handed neutrinos and several scalar Higgs multiplets. Presently, right-handed neutrinos may be a necessary ingredient of any electroweak model if, as indicated by recent experimental solar [25] and atmospheric [26] data, neutrinos are massive particles. On the other hand, each of the extra Higgs scalar multiplets that we will introduce has already been considered, separately, as viable extensions of the minimal $SU(2)_L\otimes U(1)_Y$ model [27–29]. However, in general the doublets can be coupled to all fermion doublets, having flavor changing neutral currents if we will. In other words, there is not an underlying reason to constraint the interactions of the multi-Higgs extensions. Below we will show how this reason arises in an extension of the DFS axion model.

The representation content is the following: $Q_L=(ud)_L^T\sim(\mathbf{2},1/3)$, $L_L=(\nu l)_L^T\sim(\mathbf{2},-1)$ denote any quark and lepton doublet; $u_R\sim(\mathbf{1},4/3)$, $d_R\sim(\mathbf{1},-2/3)$, $l_R\sim(\mathbf{1},-2)$, $\nu_R\sim(\mathbf{1},0)$ are the right-handed components; and we will assume that each charge sector gain mass from a different scalar doublets, i.e., Φ_u, Φ_d, Φ_l, and Φ_ν generate Dirac masses for *u*-like, *d*-like quarks, charged leptons and neutrinos, respectively [all of them of the form $(\mathbf{2},+1)=(\varphi^+,\varphi^0)^T$]. We also add a neutral complex singlet $\phi\sim(\mathbf{1},0)$ as in [7], a singly charged singlet $h^+\sim(\mathbf{1},+2)$, as in the Zee's model [27] and finally, a triplet $\vec{\mathcal{T}}\sim(\mathbf{3},+2)$ that can be written as [28]

$$T\equiv\epsilon\vec{\tau}\cdot\vec{\mathcal{T}}=\begin{pmatrix}\sqrt{2}T^0 & -T^+\\ -T^+ & -\sqrt{2}T^{++}\end{pmatrix},\tag{1}$$

where $\epsilon=i\tau_2$.

Next, we will impose the following Z_{13} symmetry among those fields:

$$\begin{aligned}&Q\to\omega_5 Q,\;\; u_R\to\omega_3 u_R,\, d_R\to\omega_5^{-1}d_R,\\ &L\to\omega_6 L,\;\;\nu_R\to\omega_0\nu_R,\;\; l_R\to\omega_4 l_R,\\ &\Phi_u\to\omega_2^{-1}\Phi_u,\;\;\Phi_d\to\omega_3^{-1}\Phi_d,\;\;\Phi_l\to\omega_2\Phi_l,\\ &\Phi_\nu\to\omega_6^{-1}\Phi_\nu,\;\;\phi\to\omega_1^{-1}\phi,\;\; T\to w_4^{-1}T,\\ &h^+\to\omega_1 h^+,\end{aligned}\tag{2}$$

with $\omega_k=e^{2\pi ik/13}$, $k=0,1,\ldots,6$.

With this representation content and the Z_{13} symmetry defined in Eq. (2) the allowed Yukawa interactions are given by

$$\begin{aligned}-\mathcal{L}_Y=&\overline{Q}_{iL}(F_{i\alpha}u_{\alpha R}\tilde{\Phi}_u+\tilde{F}_{i\alpha}d_{\alpha R}\Phi_d)+\overline{L_{aL}}(G_{ab}\nu_{bR}\tilde{\Phi}_\nu\\&+\tilde{G}_{ab}l_{bR}\Phi_l)+f^{ab}\overline{(L_{aiL})^c}L_{bjL}\epsilon_{ij}h^++\text{H.c.},\end{aligned}\tag{3}$$

where $\tilde{\Phi}=\epsilon\Phi^*$, with $i=1,2,3$ and $a=e,\mu,\tau$; $G,\tilde{G},F,\tilde{F}$ are arbitrary 3×3 matrices and f^{ab} is a 3×3 antisymmetric matrix. Notice that we have the Zee's interaction [27] but the interaction $\overline{(L_{iaL})^c}F_{ab}(\epsilon\vec{\tau}\cdot\vec{T})_{ij}L_{bLj}$ is not allowed by the Z_{13} symmetry, i.e., this is not an automatic symmetry of the model. Moreover, the Z_{13} symmetry also implies that there is no flavor changing neutral currents since there is a doublet for each charge sector in Eq. (3). The neutrino interactions with the doublet Φ_ν imply a Dirac bare mass; while the singlet h^+ induces, through the radiative corrections, like in the Zee's model, Majorana masses to the left-handed neutrinos [30].

The most general scalar potential among the several scalar multiplets introduced above must be invariant under the gauge $SU(2)_L\otimes U(1)_Y$ and also under the discrete Z_{13} symmetry. However, an extra discrete Z_3 symmetry will be added in order to avoid an interaction in the scalar potential and in Eq. (3). We then have

$$\begin{aligned}V=&\mu_k^2\Phi_k^\dagger\Phi_k+\mu_\phi^2\phi^*\phi+\mu_T^2\mathrm{Tr}(T^\dagger T)+\mu_h^2h^+h^-+\lambda^k(\Phi_k^\dagger\Phi_k)^2+\lambda^{kk'}|\Phi_k^\dagger\Phi_{k'}|^2+\lambda^{k\phi}(\Phi_k^\dagger\Phi_k)\phi^*\phi\\&+\lambda_1^{kT}\Phi_k^\dagger\Phi_k\mathrm{Tr}(T^\dagger T)+\lambda_2^{kT}(\Phi_k^\dagger T^\dagger)(T\Phi_k)+\lambda^{kh}\Phi_k^\dagger\Phi_kh^-h^++\lambda_1(\phi^*\phi)^2+\lambda_2(\mathrm{Tr}T^\dagger T)^2\\&+\lambda_3\mathrm{Tr}(T^\dagger T)^2+\lambda_4\mathrm{Tr}(T^\dagger T)|\phi|^2+\lambda_5(h^-h^+)^2+\lambda_6\mathrm{Tr}(T^\dagger T)h^-h^++[\tilde\lambda_1\Phi_d^\dagger\Phi_l\Phi_\nu^\dagger\Phi_l+\tilde\lambda_2\tilde\Phi_d^TT\tilde\Phi_u\phi\\&+\tilde\lambda_3\Phi_u^\dagger\Phi_\nu\Phi_u^\dagger\Phi_l+f_1\Phi_u^\dagger\Phi_d\phi^*+f_2\tilde\Phi_u^TT\tilde\Phi_u+f_3\tilde\Phi_l^TT\tilde\Phi_\nu+f_4\Phi_d^\dagger\Phi_uh^-+\mathrm{H.c.}],\end{aligned}\tag{4}$$

where $k\neq k'$ run over all doublets, i.e., $k,k'=u,d,l,\nu$ and we have omitted summation symbols. The trilinear $\Phi_u\epsilon\Phi_lh^-\phi^*$ is allowed by the Z_{13} symmetry but it is forbidden by the Z_3 symmetry with parameters denoted by $\tilde\omega_0$, $\tilde\omega_1$, and $\tilde\omega_1^{-1}$ if Φ_l transform with $\tilde\omega_1^{-1}$ and Φ_ν,ν_R,l_R transform with $\tilde\omega_1$ while all the other fields remain invariant i.e., transform with $\tilde\omega_0$. This Z_3 symmetry forbids also a Majorana mass term $\overline{(\nu_{aR})^c}M_{ab}\nu_{bR}$ in Eq. (3). It is in this context that the PQ symmetry is an automatic symmetry of the classical Lagrangian of the model and the axion mass and the $\bar\theta$ angle are protected against gravitational effects, as discussed in the Introduction.

We have confirmed that the axion is an invisible one. After redefining the neutral fields as usual $\Phi_k^0=(v_k+\mathrm{Re}\,\Phi_k^0+i\,\mathrm{Im}\,\Phi_k^0)/\sqrt{2}$, $T^0=(v_T+\mathrm{Re}\,T^0+i\,\mathrm{Im}\,T^0)/\sqrt{2}$, and $\phi=(v_\phi+\mathrm{Re}\,\phi+i\,\mathrm{Im}\,\phi)/\sqrt{2}$ there are only two neutral Goldstone bosons: one which is eaten by the Z^0, G^0, and another one which has a small mixture with the G^0, the axion which is almost singlet, i.e., $a\simeq\mathrm{Im}\,\phi$. This has been done considering the full 6×6 mass matrix in the pseudoscalar sector.

Besides, the fact that the Peccei-Quinn chiral symmetry is an automatic symmetry of the model, the discrete Z_{13} symmetry suppresses also gravitational effects up to operators of dimension twelve. It means that the contributions to the axion mass and to the $\bar\theta$ angle are like those we have shown above. The assignment of the PQ charges for all the fermion and scalar fields in the model are the following (using the notation $\psi'=e^{-i\alpha X_\psi}\psi$ with X_ψ the PQ charge of the multiplet ψ): $X_Q=-3$, $X_{u_R}=3$, $X_{d_R}=3$, $X_L=-6$, $X_{l_R}=-8$, $X_{\nu_R}=4$, $X_{\Phi_u}=6$, $X_{\Phi_d}=-6$, $X_{\Phi_l}=2$, $X_{\Phi_\nu}=10$, $X_T=12$, $X_{h^+}=12$, $X_\phi=-12$. It is straightforward to verify that the Yukawa interactions in Eq. (3) and the scalar potential in Eq. (4) are invariant under the PQ transformations given above. In the present model we have still a global discrete symmetry, namely $Z_{18}\subset U(1)_{\mathrm{PQ}}$. Hence, the model has the domain wall problem [31] and the usual mechanism for avoiding it can be applied [32,33].

Larger Z_N symmetries are possible if we add more fields in any electroweak model. However, notice that if N is a prime number the axion can transform under this symmetry with any assignment (but the trivial one); otherwise, we have to be careful with the way we choose the singlet ϕ transforms under the Z_N symmetry.

In the present model the axion couples to quarks and leptons (including neutrinos). Those couplings are proportional to $X_fm_fv_\phi^{-1}$, where X_f and m_f are the PQ charge and the mass of the fermion f. On the other hand, the axion-photon coupling $c_{a\gamma\gamma}$ is, in general, proportional to $2N_{\mathrm{DW}}^{-1}\Sigma_fX_fQ_f^2-1.95$, where the sum is over all generations and the numerical factor comes from the light quarks through a Fujikawa relation [34] and it is the same in the present model; N_{DW} is the domain wall factor which is equal to 18 in the present model. We have $c_{a\gamma\gamma}\approx-0.62$, and not 0.75 as in the invisible axion of Refs. [7,35,36]. The coupling of the axion with neutrinos in the present model may have astrophysics and/or cosmological consequences.

It is still possible to assign the PQ charge as in Sec. II of Ref. [22] and the PQ charges are quantized. However, in that case it appears as an extra Goldstone boson coupling with leptons and photons. Thus, in order to avoid such an extra Goldstone we have to break softly the Z_3 symmetry, say, by adding $\mu^2\Phi_l\Phi_\nu$ in the scalar potential.

Summarizing, we have obtained a model with an automatic PQ symmetry, with an invisible axion which is protected against gravitational effects in the context of a multi-Higgs extension of the standard model. This is important for three reasons. First, multi-Higgs extensions, with or without supersymmetry, are used by the experimentalists as reference models for searching extra scalar particles [29,37]. Second, these models are used by phenomenologists to get an appropriate mass matrix in the lepton and quark sectors. In fact, as we said before, all the extra fields that we have added to the minimal version of the model have already been introduced in the literature with different goals; we have just put all of them together. The necessity of protecting the invisible axion from gravitational effects, as we have done above, gives a rationale for those scalar multiplets. Finally, we would like to mention that one of the issues that remains arbitrary in most multi-Higgs extensions is the flavor violating neutral currents in the scalar sector. We can implement it or not at will. However, in our case these effects are automatically avoided since the Yukawa interactions are already determined for the Z_{13} symmetry. Then, our model automatically does not have flavor changing neutral currents in all sectors of the model.

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