Intermediate Scale Accidental Axion and ALPs

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We discuss the problem of constructing models containing an axion and axion-like particles, motivated by astrophysical observations, with decay constants at the intermediate scale ranging from 10^9GeV to 10^{13}GeV. We present examples in which the axion and axion-like particles arise accidentally as pseudo Nambu-Goldstone bosons of automatic global chiral symmetries, in models having exact discrete symmetries.

Pseudoscalar bosons very weakly interacting and having low mass – below the eV scale for example – are common in the particle spectra of theories aiming to answer questions left open by the Standard Model (SM) like, for example, the CP conservation of the strong interactions, and the nature of dark matter. The axion is a prominent example occurring in extensions of the SM constructed to solve the strong CP problem [1, 2, 3]. Not connected with this last problem, but with interactions similar to the axion, are the axion-like particles (ALPs). For a review see [4].

Axions and ALPs arise in models containing global symmetries that, besides being spontaneously broken, are also explicitly broken conferring small masses for those particles characterizing them as pseudo Nambu-Goldstone bosons. There are astrophysical phenomena motivating the construction of models containing at last one ALP in addition to the axion [5]. Thus, we consider first a simple case of SM extensions containing two global chiral symmetries, $\mathrm{U}(1)_1 \times \mathrm{U}(1)_2$ with each factor broken spontaneously by vacuum expectation values (vev) $\langle\sigma_i\rangle = v_i/\sqrt{2}$ of SM singlets complex $\sigma_i(x) = [v_i + \rho_i(x)]e^{i\,a'_i(x)/f_{a'_i}}/\sqrt{2}$, $i = 1,\,2$, where the decay constants $f_{a'_i}$ depend on v_i and the vev of other scalar fields carrying charge of the $\mathrm{U}(1)_{is}$. At energies much below the scales $v_i \sim f_{a'_i}$, the low energy effective Lagrangian contains the $a'_i(x)$ fields interactions with the gluons and electromagnetic field, through the field strengths $G_{\mu\nu}$ and $F_{\mu\nu}$,

$$\mathcal{L} \supset \frac{1}{2}\sum_{i=1}^{2}\partial_\mu a'_i\,\partial^\mu a'_i - \frac{\alpha_s}{8\pi}\sum_{i=1}^{2} C_{ig}\frac{a'_i}{f_{a'_i}}\,G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} - \frac{\alpha}{8\pi}\sum_{i=1}^{2} C_{i\gamma}\frac{a'_i}{f_{a'_i}}\,F_{\mu\nu}\tilde{F}^{\mu\nu}\,. \tag{1}$$

We have omitted the $a'_i(x)$ interactions with fermionic fields since we are not going to discuss them here. The anomaly coefficients, C_{ig} and $C_{i\gamma}$ are model dependent but typically of order one in common models [5]. It is observed in Eq. (1) that the fields $a'_i(x)$ can be made very weakly interacting if the decay constants $f_{a'_i}$ are sufficiently high – much above the electroweak scale ~ 246 GeV. Equation (1) has the axion as the particle excitation of the field $A(x) = C_{1g}\,a'_1(x)f_A/f_{a'_1} + C_{2g}\,a'_2(x)f_A/f_{a'_2}$, with the ALP the one of the field $a(x) = C_{2g}\,a'_1(x)f_a/f_{a'_2}$ - $C_{1g}\,a'_2(x)f_a/f_{a'_2}$, and the decay constants $1/f_A^2 = 1/f_a^2 = (C_{1g}/f_{a'_1})^2 + (C_{2g}/f_{a'_2})^2$. The axion and the ALP couplings with the photon are defined through $-\frac{g_{\phi\gamma}}{4}\,\phi\,F_{\mu\nu}\widetilde{F}^{\mu\nu}$, where $\phi = A,\,a$, from Eq. (1) as $g_{A\gamma} = \frac{\alpha\,f_A}{2\pi}\left(C_{1g}C_{1\gamma}/f_{a'_2} + C_{2g}C_{2\gamma}/f_{a'_2} - 1.95\right)$ and $g_{a\gamma} = \frac{\alpha\,f_A}{2\pi}\left(C_{1g}C_{2\gamma} - C_{1\gamma}C_{2g}\right)/f_{a'_1}f_{a'_2}$.

The number -1.95 in the above is a universal contribution from the axion-neutral pion mixing. $g_{A\gamma}$ and $g_{a\gamma}$ are the main couplings of the axion and ALPs, respectively, giving rise to notable phenomena like photon-axion/ALP oscillations [4]. Intermediate energy scales for the decay constants such that $10^9\text{GeV} \lesssim f_{a_i'} \lesssim 10^{13}\text{GeV}$ are specially interesting. This furnishes the values of $g_{A\gamma}$ and $g_{a\gamma}$ within the ranges to be probed directly in new experiments, required to potentially explain some phenomena hinted by astrophysical observations. Depending on their masses, the axion and the ALP could also be cold dark matter candidates.

The pseudo-Nambu-Goldstone field $A(x)$ is associated to the Peccei-Quinn symmetry, $\text{U}(1)_{PQ}$ ($\subset \text{U}(1)_1 \times \text{U}(1)_2$), which is a chiral global symmetry with the special property of being anomalous – explicitly broken by non-perturbative effects – in the quarks sector leading to the interaction term $\frac{1}{f_A} A\, G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$. This allows the elimination of the CP violation term $\bar{\theta}\, G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$ absorbing the $\bar{\theta}$-parameter into the axion field as $A + \bar{\theta}\, f_A \to A$ [1]. Also, it is generated a potential $V(A) \simeq m_A^2 f_A^2 \left[1 - \cos\left(\frac{A}{f_A}\right)\right]$, in which the axion mass is $m_A = \frac{m_\pi f_\pi}{f_A}\frac{\sqrt{z}}{1+z} \simeq 6\,\text{meV} \times \left(\frac{10^9\,\text{GeV}}{f_A}\right)$, with m_π the mass of the pion, f_π its decay constant, and $z \approx 0.56$ [2]. $V(A)$ leads to the result that the effective CP violation parameter turns out to be zero by the fact that $\langle \frac{A}{f_A} \rangle = \theta_{eff} = 0$. This solves the strong CP problem, which is a fine tuning problem once $\bar{\theta}$ must be very small, arising due the non-observation of a electric dipole moment of the neutron, whose actual measurements limits $|\bar{\theta}| \lesssim 10^{-10}$ [6].

Differently from the axion the ALP remains massless – as Nambu-Goldstone boson of the combined $\text{U}(1)_i$ out of $\text{U}(1)_{PQ}$ – unless there are additional interactions explicitly breaking its associate global symmetry and, thus, generating an extra potential $\delta V(a_i')$. Massive ALPs have been implemented in ultra-violet completions of the SM for several purposes [5]. But the explicit breakdown of the global symmetries must occur in a controlled way to get appropriate ALPs masses and preserve the solution of the strong CP problem. In fact, it is not expected that gravitational interactions conserve global symmetries. It is known that operators suppressed by the Planck scale M_{Pl} like $\sigma_1^n \sigma_2^k / M_{\text{Pl}}^{D-4}$, with $D = n + k > 4$, might bring corrections to the axion potential such that $\delta\bar{\theta} > 10^{-10}$ if not forbidden until a certain dimension $D \gtrsim 9/\left[1 - 0.1 \log\left(f_A/10^9\text{GeV}\right)\right]$ [7]. Discrete gauge symmetries Z_N [8], with $N = D+1$, have been used to resolve the problem of having dangerous effective operators in axion models [9], and also in models containing axion plus ALPs [5]. Another compelling reason for these Z_N symmetries is that if they are appropriately postulate anomalous symmetries like $\text{U}(1)_{PQ}$ may arise as automatic quasi exact symmetries. This avoids the non-natural impositions of global continuous symmetries which are already explicitly broken, as is the case of the $\text{U}(1)_{PQ}$ symmetry.

A model in which the axion and ALPs have their masses and couplings controlled by discrete symmetries is the $\mathbb{Z}_{13} \otimes \mathbb{Z}_5 \otimes \mathbb{Z}_5'$ model proposed in [5]. It is a hybrid of invisible axion models [10] plus an ALP. The field content of the model beyond the SM one is: four SM Higgs doublets H_b, an $\text{SU}(2)_L$ triplet T, a vector-like color triplet (Q_L, Q_R), three right-handed neutrinos N_{iR}, and two SM singlet fields $\sigma_{1,2}$. The fields charges of the imposed discrete symmetry $\mathbb{Z}_{13} \otimes \mathbb{Z}_5 \otimes \mathbb{Z}_5'$ are shown in Table 1. It can be shown that both the Yukawa interaction terms and the renormalizable scalar potential of this model have two accidental global chiral symmetries and, thus, an axion and one ALP. Additionally, the interaction terms $\overline{L}_i \widetilde{H}_N N_{jR}$ and $\overline{(N_{iR})^c} \sigma_1 N_{jR}$, allowed by the discrete symmetries of the model lead to a seesaw mechanism for generating small masses to the active neutrinos.

The lowest dimensional effective operator invariant by the discrete symmetry, but breaking $\text{U}(1)_1 \otimes \text{U}(1)_2$ explicitly is $\frac{g}{M_{\text{Pl}}^{10}} H_N^\dagger H_d \sigma_1^{*5} \sigma_2^7$. This generates a tiny mass $m_a \sim 10^{-33}$ eV to

ψ_i	q_L	u_R	d_R	L	N_R	l_R	H_u	H_d	H_l	H_N	σ_2	T	Q_L	Q_R	σ_1
$\mathbb{Z}_{13}$	ω_{13}^5	ω_{13}^3	ω_{13}^8	ω_{13}^9	ω_{13}^3	ω_{13}^7	ω_{13}^{11}	ω_{13}^{10}	ω_{13}^2	ω_{13}^7	ω_{13}^{12}	ω_{13}^9	1	ω_{13}^6	ω_{13}^7
$\mathbb{Z}_5$	1	ω_5	ω_5^4	1	ω_5	ω_5^4	ω_5	ω_5	ω_5	ω_5	1	ω_5^2	ω_5	ω_5^3	ω_5^3
$\mathbb{Z}_5'$	1	ω_5^4	1	1	ω_5^2	ω_5^4	ω_5^4	1	ω_5	ω_5^2	ω_5	ω_5^3	1	ω_5^4	ω_5

Table 1: $\mathbb{Z}_N$ charges of the $\mathbb{Z}_{13} \otimes \mathbb{Z}_5 \otimes \mathbb{Z}_5'$ model, where $\omega_{13} \equiv e^{i2\pi/13}$ and $\omega_5 \equiv e^{i2\pi/5}$.

the ALP, assuming the values $v_1 \simeq f_A \simeq 10^{10}$ GeV, $v_1 \simeq 7.5 \times 10^{10}$ GeV, taking the Higgses doublets vevs $v_W \simeq 100$ GeV, the Planck scale $M_{\rm Pl} = 10^{19}$ GeV, and $g = 1$. The axion mass is approximately $m_a \simeq 0.6$ meV, not been affected in a significantly manner by the Planck suppressed effective operators. For the couplings $g_{A\gamma}$, $g_{a\gamma}$, the coefficients entering in them are $C_{1g} = 1$, $C_{2g} = 3$, $C_{1\gamma} = 6$, $C_{2\gamma} = 4$, where we assume the electric charge of $Q_{L,R}$ equal to one. This furnishes $|g_{A\gamma}| \simeq 4 \times 10^{-13}$ GeV^{-1}, and $|g_{a\gamma}| \simeq 2 \times 10^{-13}$ GeV^{-1}. With these values for the coupling to photons and mass the axion can be a dark matter candidate, but still outside the region to be probed directly by present experiments. The ALP in this model has the coupling to photons and mass within the range required explanation for the soft X-ray excess from Coma cluster [11], and also being in the reach of proposed experiments [5].

We present another construction containing, in addition to the axion, two photophilic ALPs is the $Z_{11} \otimes Z_9 \otimes Z_7$ model. It is motivated by distinct ranges of coupling to photons and mass required to explain the anomalous transparency of the Universe [12] (see [5] and references therein), and the unidentified X-ray line of 3.55 keV found in recent observations [13]. With the latter supposed to be due a two photon decay of a dark matter ALP with mass of 7.1 keV [15]. The field content of the $Z_{11} \otimes Z_9 \otimes Z_7$ model has beyond the SM fields: one vector-like color triplet (Q_L, Q_R); two noncolored vectorial charged fermions $(E_L,\, E_R)$, $(E_L',\, E_R')$; three right-handed neutrinos N_{iR}; and three SM singlet fields σ_i. The fields charges of the discrete symmetry are shown in Table 2.

	q_L	u_R	d_R	L	l_R	N_R	H	Q_L	Q_R	σ_1	σ_2	E_L	E_R	σ_3	E_L'	E_R'
$\mathbb{Z}_7$	1	ω_7^3	ω_7^4	1	ω_7^4	ω_7^3	ω_7^3	ω_7^5	ω_7^3	ω_7	1	ω_7^5	ω_7^4	ω_7^1	ω_7^5	ω_7^3
$\mathbb{Z}_9$	1	ω_9^5	ω_9^4	ω_9^6	ω_9	ω_9^2	ω_9^5	1	ω_9^8	ω_9^5	ω_9	ω_9^6	1	1	ω_9^1	ω_9^5
$\mathbb{Z}_{11}$	1	ω_{11}^3	ω_{11}^8	ω_{11}^2	ω_{11}^{10}	ω_{11}^5	ω_{11}^3	ω_{11}^9	ω_{11}^7	ω_{11}	1	1	ω_{11}^{10}	1	ω_{11}^{10}	ω_{11}^9

Table 2: $\mathbb{Z}_N$ charges of the $\mathbb{Z}_7 \otimes \mathbb{Z}_9 \otimes \mathbb{Z}_{11}$ model.

It is shown in [5] that the Yukawa interaction terms and the renormalizable scalar potential allowed by the discrete symmetry have three global chiral symmetries, $\mathrm{U}(1)_1 \otimes \mathrm{U}(1)_2 \otimes \mathrm{U}(1)_3$. Each one of them is spontaneously broken by the respective singlet vevs $\langle \sigma_i \rangle = v_1/\sqrt{2}$, with the axion being related to related to $\mathrm{U}(1)_1$, the ALP a_2 to $\mathrm{U}(1)_2$, and the ALP a_3 to $\mathrm{U}(1)_3$. There is no one relevant Planck suppressed operator correcting the axion mass. The lowest dimension operators breaking $\mathrm{U}(1)_2$ and $\mathrm{U}(1)_3$ are $\frac{g}{M_{\rm Pl}^5}(\sigma_2)^9$ and $\frac{g'}{M_{\rm Pl}^3}(\sigma_2)^7$, respectively. In order to give an example we set $v_2 = 10^9$ GeV, $v_3 = 3 \times 10^9$ GeV, $g = 1$, and $g' \approx 0.1$. This furnishes $m_{a_2} \approx 10^{-7}$ eV, $g_{a_2\gamma} \approx 2.2 \times 10^{-11}$ GeV^{-1} to the ALP a_2 making it able to explain the anomalous transparency of the Universe [12], and also in the search range of the experiment

ALPS II [14]; and $m_{a_3} \approx 7.1$ keV, $g_{a_3\gamma} \approx 7.7 \times 10^{-13}$ GeV^{-1} to the ALP a_3 so that it can explain the 3.55 keV line through its two photons decay [15].

For other developments on discrete symmetries originating from string theory see [16].

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