Axions in Type IIA Superstring Theory and Dark Matter

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Abstract
Motivated by the M-theory compactification physics, we study a type IIA superstring quiver model with an open string axion field associated with the $U(1)_{PQ}$ Peccei-Quinn global symmetry using D6-brane physics. This realization extends the symmetry of the SM-Like and contributes to the mediation of the electroweak symmetry breaking. The associated axion energy scales are approached in terms of D2 and D6-branes in type IIA compactifications on Calabi-Yau threefolds. Using the fermion mass scales as well as string theory results, the allowed axion window is discussed in terms of intersecting D6-branes wrapping 3-cycles belonging to the middle cohomology of the type IIA internal space. The non-perturbative effect of the open string axion sector is dealt with using a D2-brane wrapping a 3-cycle producing (1+3)-dimensional stringy instantons. According to the known data, the vacuum expectation value of the axion and the mass scale of the involved scalar provide a probe of the stringy physics effect in the SM and a possible axionic dark matter candidate.

Keywords: Type IIA superstring, D-branes, Calabi-Yau spaces, Open string axions, Dark Matter.

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1 Introduction

It has been shown that the physics of low-energy phenomena is successfully described by the so-called Standard Model (SM) of particle physics. With the recent observations including the one associated with the Higgs boson, a large amount of experimental data is in a good agreement with SM physics[1, 2, 3]. However, certain famous issues mostly related to the hierarchy problem, fermion masses and Dark Matter (DM) are still open scientific subjects [4, 5]. To deal with such questions, models beyond SM have been built using theories based on extra dimensions of spacetime and supersymmetry in the context of string/M-theory. In this way, the extra dimensions should be compact in such models producing (3+1)-dimensional physics with the presence of massless pseudo scalar axion like fields. To examine the physics of such fields, many stringy inspired models have been proposed using either geometric engineering method in M-theory on G2 manifolds or intersecting type II D-branes wrapping non trivial cycles embedded in complicated geometries including orbifold Calabi-Yau manifolds [6-26]. In particular, interesting type II superstring models in the presence of various types of axionic fields have been studied using different ways. It has been shown that such fields can play a primordial rôle in the physics beyond the SM and cosmology [17, 18]. Indeed, globally consistent D6-brane models with SM spectrum in the type IIA orientifold compactification scenario have been constructed. Moreover, different energy scales have been examined including the Peccei-Quinn U(1)$_{PQ}$ symmetry corresponding to the electroweak and the supersymmetry breaking scales in the context of closed and open string theory sectors [10-16].

The axion fields are characterized by two parameters: the axion decay constant and an energy scale derived from non-perturbative effect. This effect is associated with instantons in superstring theory. Moreover, it has been remarked that the number of such axions depends on the topology of the corresponding internal geometries in string/M-theory. More recently, DM axions in such theories have been investigated using hidden particle sectors[27, 28]. In particular, a study from M-theory compactified on G2-manifolds has been conducted. Using string duality, this could be related to intersecting numbers of 3-cycles in Calabi-Yau manifolds in the presence of D6-branes.

The objective of this paper is to contribute to these investigations by studying type IIA superstring quivers with an open string axion field associated with the U(1)$_{PQ}$ Peccei-Quinn global symmetry. In the case of standard singularities, this realization extends the symmetry of the SM-Like and contributes to the mediation of the electroweak symmetry breaking. The associated, open string, axion energy scales are discussed in terms of D2 and D6-branes in type IIA compactification. Using the fermion mass scales as well as string theory data, the allowed axion window is treated in terms of intersecting D6-branes wrapping on 3-
cycles belonging to the middle cohomology of the type IIA internal space. However, the non perturbative effect in the open string axion field is approached using a D2-brane wrapping on a 3-cycle producing stringy instantons in 1+3 dimensions. According to the known results, the vacuum expectation value of the axion and the mass scale of the involved new scalar provide a probe of the stringy physics effect in the SM and a possible axionic DM candidate.

2 D-brane model and field content

In this section, we elaborate a stringy axion model using string theory approach. It has been argued that open strings stretched to different stacks of type II D-branes generate the SM particle spectrum. More precisely, an unitary group $U(N) \sim SU(N) \times U(1)$ is obtained by considering $N$ coincident type II D-branes. Typically, this gauge group model can be extended by introducing extra abelian factors \cite{9, 10}. Generically, these abelian fields involve (1+3)-dimensional anomalies canceled via the Green-Schwarz mechanism generating a mass to the anomalous U(1) fields by breaking the associated gauge symmetry \cite{10}. This gives an acceptable effective low-energy description reproducing either SM-like or more generally some possible extensions \cite{20, 21}. In such models, the gauge and the matter fields could be encoded in quivers representing stacks of coinciding D-branes in type II superstrings. Working at the level of quivers one might investigate the Yukawa-like couplings as well as their strengths from the quiver data rather than concentrating on the whole geometrical and physical data derived from string theory. Here, we build a type IIA quiver model involving an axion-like particle using the intersecting D-brane method. Type IIA D-brane configurations with orientifold geometries have been considered to produce non trivial components associated with SM-like theories. To get this model, we consider a set of three stacks of D6-branes which can accommodate the $U(3) \times Sp(1) \times U(1)$ gauge symmetry and SM matter fields. A way to deal with the axion field is to use the $U(1)_{PQ}$ symmetry. It has been observed that there are many roads to handle such a symmetry considered either as a local or as a global one depending on the model in question. To consider this symmetry, we can enlarge the $U(3) \times Sp(1) \times U(1)$ gauge symmetry by thinking about an extra abelian gauge factor corresponding to the $U(1)_{PQ}$ symmetry. However, this symmetry will be viewed as as a global one. Precisely, the present proposed system will be constructed form four blocks of intersecting type IIA D6-branes in the presence of a flavor-dependent symmetry. It has been shown that the symmetry distinguishes various fermions from each other. In type IIA superstring theory, the intersecting D6-brane configurations produce the gauge group

$$U(3)_a \times Sp(1)_b \times U(1)_c \times U(1)_{PQ}.$$  \hspace{1cm} (2.1)
In this D-brane industry, the intersections between such D6-branes generate matter fields. Investigations reveal that the associated physics can be encoded nicely in a quiver diagram, considered as a possible generalization of Dynking diagrams of Lie symmetries. The $U(1)_{\text{PQ}}$ symmetry will be broken by incorporating a complex scalar field $\phi = \rho \exp\left(\frac{i}{f_\sigma} \sigma\right)$ where $f_\sigma$ denotes the axion decay constant. Here, the field $\sigma$ will be considered as an open string axion obtained from type IIA superstring using intersecting D6-brane associated with the $U(1)_{\text{PQ}}$ symmetry. It is noted that $\rho$ can be associated with fluctuations of the corresponding open string sector. The complex scalar $\phi$ gets a non-zero vacuum expectation value $\langle \phi \rangle = f_\sigma$. It has been shown that the lagrangian involving this open string axion field $\sigma$ has the following terms

$$\mathcal{L}_\sigma \simeq \partial_\mu \sigma \partial^\mu \sigma + \frac{\sigma}{f_\sigma} F_{\mu\nu} \wedge F^{\mu\nu},$$

(2.2)

where $\sigma$ is the phase of the complex scalar field $\phi$ charged under the $U(1)_{\text{PQ}}$ symmetry. In what follows, $F_{\mu\nu}$ will be associated with the corresponding abelian gauge field strength obtained from the quantization of the open string living on the D6-brane world volume. It is noted that the vanishing of the non-abelian anomalies is related to the tadpole conditions. However, the Green-Schwarz mechanism kills the abelian and mixed anomalies. On the perturbative level, the anomalous $U(1)'s$ become massive and can survive only if they are considered as global symmetries which cancel various couplings in the theory in question. In the corresponding gauge symmetry, the hypercharge can be identified with a massless remained linear combination of the global symmetries. The SM fermion charges can be obtained by using the vanishing of anomaly constraints imposed by the flavor conditions associated with the complex scalar field $\phi$. In 1+3 dimensions, the complex field gives allowed invariant coupling terms. Concretely, there are many ways to implement such interaction coupling terms. It is possible to write down a general form which can be embedded in SM-like

$$y_f \left( \frac{\phi}{M_s} \right)^{n_f} h f^f.$$

(2.3)

In this equation, $f$ denotes the SM fermion fields and the coupling parameters $y_f$ indicate the Yukawa constants. $M_s$ is the string scale mass while $n_f$ is a number which will be fixed later by considering SM and string theory known data. The global $U(1)_{\text{PQ}}$ symmetry which acts on the fields as follows

$$\phi \to e^{i\eta/\alpha} \phi, \quad h \to e^{i\eta/\alpha} h, \quad f \to e^{i\eta/\alpha} f,$$

(2.4)
can be used to establish constraints on $n_f$ and th gauge charges. The invariance of the equation (2.3) gives the expression of $n_f$

\[ n_f = -\frac{q_h + q_f + q_T}{q_\phi}. \]  

Using the SM fields, this equation can be solved using a possible physical configuration based on intersecting D6-brane charge assignments of type IIA superstring compactification. In the present work, we propose a particular system obtained from the intersecting 3-cycles belonging to the middle cohomology of the internal space. This model can be supported by the known result of intersecting D6-brane model building using the toroidal orientifold compactification. To get the above stringy gauge symmetry, we consider four stacks of D6-branes indicated by $D_6^{a,b,c,PQ}$-branes. In this way, the intersecting numbers $I_{\alpha\beta} = \Sigma_\alpha \circ \Sigma_\beta$ between the $D_6^{a,b,c,PQ}$-brane and $D_6^{\beta=a,b,c,PQ}$-brane can be given in terms of the 3-cycles $\Sigma_{\alpha,\beta}$ intersections. It has been remarked that type IIA superstring theory compactified on a factorized six dimensional tori $T^6 = T_1^2 \times T_2^2 \times T_3^2$ can be exploited to compute the number $I_{\alpha\beta}$ by exploring winding numbers. The model we study here requires D6-brane configurations with the following intersection numbers

\[
\begin{align*}
I_{D_aD_b} &= 3, \\
I_{D_aD_c} &= -2, \\
I_{D_aD_c^*} &= -1, \\
I_{D_aD_{PQ}} &= -1, \\
I_{D_{PQ}D_b} &= 3, \\
I_{D_{PQ}D_c^*} &= -3.
\end{align*}
\]  

These intersection numbers can produce the associated spectrum. In particular, the gauge fields, the leptons, the quarks and scalar fields can be represented by a non trivial graph called a quiver as illustrated in figure 1.

In this graph, the arrows represent the gauge fields and the nodes indicate the matter fields with the arrows indicate their fundamental (antifundamental) representations. This stringy system, which is based on the above intersecting D6-branes, is determined by a particular choice of the charges which are listed in the table 1.

| Fields | $q_i^L$ | $\pi^1_R$ | $\bar{d}^{1,2}_R$ | $\pi^{2,3}_R$ | $\bar{d}^2_R$ | $l_i^1$ | $\bar{\pi}^i_R$ | $h$ | $\phi$ |
|--------|---------|-----------|-------------------|--------------|------------|-------|---------------|----|------|
| $U(1)_c$ | 0 1 -1 0 0 1 -1 0 -1 |
| $U(1)_{PQ}$ | 0 0 0 1 -1 0 -1 1 -1 |
| $U(1)_Y$ | 1/6 -2/3 1/3 -2/3 1/3 -1/2 1 -1/2 0 |

Table 1: field content corresponding to the Hypercharge combination $Y = \frac{1}{6}Q_a - \frac{1}{2}Q_c - \frac{1}{4}Q_{PQ}$. The index $i(= 1, 2, 3)$ denotes the family index.
3 Axion and coupling scalar-matter terms

In this section, we discuss the coupling scalar-matter terms of the above proposed model. These terms will allow us to get the open string axion window appearing in the axion mass expression. Indeed, the fermion fields are distinguished by their $U(1)_{c,PQ}$ charges. This symmetry usually forbids the renormalizable Yukawa couplings for the $U(1)_{PQ}$ charged quarks, but it would allow them via certain effective highly suppressed couplings through the complex field $\phi$ carrying an appropriate charge under $U(1)_{PQ}$. In this set-up, this can be done upon the simultaneous spontaneous breaking of the Peccei-Quinn and electro-weak symmetry by the vevs of $\phi$ and $v_{EM}$ respectively. We will see later that string theory requires positive numbers for $n_f$. Indeed, the effective Yukawa couplings appearing in (2.3) can be obtained by considering $n_f$ solving the charge equations given in (2.5).

The intersection numbers can be used to determine the low-energy effective Yukawa lagrangian. It has been revealed that the allowed couplings take the following form

$$\zeta_{Yuk} = y_u^i h^i q_L \bar{u}_R^i + y_d^i h^i q_L \bar{d}_R^i + y_e^i h^i l_L^i \bar{l}_R^i + y_u^i \frac{\phi}{M_s} h^i q_L^i$$

$$+ y_d^i \frac{\phi^*}{M_s} h^i d^i_R + y_d^i \frac{\phi}{M_s} h^i d^i_R + y_e^i \frac{\phi^2}{M^3_s} h^i t^i_l l^i_L + h.c.$$ (3.1)

The heavy fermions, which are directly related to the electroweak symmetry breaking sector, have (1+3)-dimensional Yukawa couplings. However, the lighter ones are associated with the electroweak symmetry breaking sector via the complex field $\phi$. They have higher dimensional suppressed Yukawa-like couplings involving powers of $(\phi/M_s)$ or $(\phi^*/M_s)$. The corresponding powers are required by flavor charges and certain SM physical data. Using
the approximation $\phi^2 h / M_s^3 \sim (\phi / M_s)^3$, $n_f$ should take 0, 1 and 3. It is observed that $n_f = 0$ corresponds to the absence of the open string axion field. Deeper investigations of the stringy origin of the axion field can be explored to give more information on $n_f$.

The values of $n_f$ will be used to investigate the electroweak symmetry breaking associated with the lagrangian (3.1). After such a breaking symmetry with $\langle h \rangle = v_{EW}$, and using a simple scaling, the resulting lagrangian for the mass coupling term takes the form

$$\bar{\zeta}_{\text{mass}} = y_f \epsilon v_{EW} f_f$$  \hspace{1cm} (3.2)

If we forget about the fermion mass hierarchy which could be encoded in the corresponding Yukawa constants $y_f, \epsilon = (\langle \phi \rangle / M_s)^{n_f}$ is a suppression factor related to the open string axion decay constant $f_\sigma$ and the $M_s$ via the relation

$$e^{\frac{1}{n_f}} = \frac{f_\sigma}{M_s}.$$  \hspace{1cm} (3.3)

This shows that the decay constant of the open string axion is proportional to the mass string scale. Breaking the electroweak symmetry at the usual scale $v_{EW} \simeq 10^2 \text{GeV}$, and using the ratio of certain suitable fermion masses, we can estimate the suppression factor $\epsilon$. In fact, it could be approached by strange and top quark masses report. It is given by

$$\epsilon \simeq \frac{m_s}{m_t} \simeq 10^{-3},$$  \hspace{1cm} (3.4)

where $m_s$ and $m_t$ are the strange and the top quark masses.

Taking $M_s = 10^{12} \text{GeV}$, the so-called open string axion window can be obtained for the above mentioned values of $n_f$. Using the above data, one can find the associated energy scales. For $n_f = 1$, we obtain $f_\sigma = 10^9 \text{GeV}$ while we get $10^{11}$ for $n_f = 3$. This is in a good argument with the astrophysical observations and the cosmological considerations made on the axion decay constant region $[22, 23]$

$$10^9 \text{GeV} \leq f_\sigma \leq 10^{12} \text{GeV}.$$ \hspace{1cm} (3.5)

### 4 Axion mass spectrum and dark matter

Despite the axion directly results from the $U(1)_{PQ}$ breaking at the scale $\langle \phi \rangle = f_\sigma$ as a solution to the strong CP problem $[29]$. It has also been considered as a significant DM candidate $[30]$. It naturally meets the dark matter particle requirements, i.e. cold even though they are so light, non-baryonic and with extremely weak coupling to ordinary matter as being inversely proportional to its decay constant (3.5). Thus, the only significant long-range interactions are
gravitational. In spite of the fact that the exact mass of the axion is not known, its mass has been constrained by cosmic observation and particle physics experiments \cite{31, 32, 33}. The mass of the axion is predicted such as

\[ m_\sigma \simeq 10^{-6} eV \left( \frac{10^{12} GeV}{f_\sigma} \right). \]  

(4.1)

According to the range of the decay constant in our quiver based on a D6-brane model, it corresponds to the open string axion mass

\[ 10^{-2} meV \lesssim m_\sigma \lesssim 1 meV. \]  

(4.2)

This is a mass range for a small elementary particles so that the previous detectors did not have enough sensibility to coin them. A direct way of the detection of this kind of particles may be directly by studying their interaction within the detector. This corresponds to the tiny shocks with its atomic nuclei, even if this path seems to be more difficult, if not impossible, due to the axion particle characteristics. Let us make an estimate of such direct detection. DM axions are supposed to be flying around the halo of our galaxy with typical speed \( v_\sigma = 10^{-3} c \) \cite{34}, and because they are only very weakly interacting, they can go through everything, just like neutrinos with little trouble. The corresponding maximal kinetic energy for \( m_\sigma \simeq 1 meV \) reads

\[ K_\sigma \simeq \frac{1}{2} 10^{-6} eV \left( \frac{10^{12} GeV}{f_\sigma} \right) v_\sigma^2 \sim 10^{-3} \mu eV. \]  

(4.3)

This value scatters off an atomic nuclei. The energy deposit is only a highly small recoiling energy; and most of this order of magnitude. It is extremely a tiny energy deposit that is very difficult to pick out against background from natural radioactivity which typically \( \sim MeV \). Therefore, a detector with very low energy threshold will be needed for the hunt for such a dark matter target.

In D-brane models, two important physical processes can describe the axion mass scale as well as its behaviour. In fact, after the breaking of the U(1)\(_{PQ}\) symmetry at some high scale \( f_\sigma \) establishing the axion as a massless Goldstone boson, the non-perturbative physics, in terms of instantons, obtined from D-branes wrapped on cycles, becomes relevant at some scale \( \Lambda_\sigma \ll f_\sigma \) and provides a potential for the axion and thus a tiny mass. The axions then obtain mass by non-perturbative effects, such as instantons, and are extremely generic prediction of string theory at low energies. We know read easily that due to the the large scale hierarchies \( \Lambda_\sigma \ll f_\sigma \lesssim M_\sigma \), the axion mass is thus parametrically small. Because the scale of the induced axion potential energy depends exponentially on details of the internal geometry, and large hierarchies between the non-perturbative scale \( \Lambda_\sigma \) and the string scale
\( M_s \) can easily be achieved. Explicitly, we have

\[
\Lambda_\sigma \sim \mu e^{-S},
\]

where \( \mu \) is the hard non-perturbative scale, i.e., GUT scale, SUSY breaking. This could be associated with fermionic zero modes obtained from open strings living on some branes. \( S \) is an instanton string moduli action describing, in string units, the size of the 3-cycle \( \Sigma \) on which the relevant euclidian D-branes are wrapped. In type II superstring theory, the non-perturbative effects are principally produced from Euclidean Dp-branes wrapping \((p + 1)\)-cycles [35, 36]. The Calabi-Yau compactification topology, in type IIA superstring, requires that the relevant instantons are D2-branes wrapped on three-cycles intersecting with the 3-cycle associated with the D6_{PQ}-brane. In this way, there are D2-D2 and D2-D6_{PQ} open string sectors producing the instanton zero modes over which one should integrate. This integration generate an action given in terms the Dirac Born-Infeld action on the D2-brane wrapping on \( \Sigma \) in the presence of the WZ term. This, which involves also the R-R 3-form coupled to such a D2-brane on \( \Sigma \), produces a complex quantity where its real part is identified with \( S \). In this picture, small changes in \( S \) produce large changes in \( \Lambda_\sigma \) for fixed \( \mu \) by controlling fermionic zero mode contributions. In this scenario, the mass behavior (4.1) could be written using two parameters: the axion decay constant \( f_\sigma \), and the non-perturbative physics scale \( \Lambda_\sigma \) as follows,

\[
m_\sigma \simeq \mu e^{-S} \frac{M_s}{f_\sigma}.
\]

Thus stringy models are expected to possess a large number of axions, where each axion is associated with a different modulus \( S \). In connection with superstring theory, one may consider models with various modulus. These can be identified with R-R 3-form on 3-cycles of the internal Calabi-Yau geometries. The corresponding number can be related to the number of the complex deformations of such geometries. These stringy axions thus have a mass spectrum spanning a vast number of orders of magnitude from the string scale down to zero

\[
0 \lesssim m_\sigma \lesssim M_s.
\]

This is the "string axiverse" idea which corresponds to the theoretical expectation stating that some large number of light and stable axions should exist given the potential complexity of the internal geometry.
5 Conclusion and open questions

It has been highlighted that the axion fields are characterized by two parameters: the axion decay constant and an energy scale obtained from non-perturbative effect. This effect is associated with instantons in superstring theory. Besides such energy scales, it has been remarked that the number of such axions, in M-theory, depends on the topology of the corresponding internal geometries. Using string duality, this could be related to intersecting numbers of 3-cycles in Calabi-Yau manifolds in the presence of D6-branes.

In this work, we have proposed a type IIA superstring quiver with an open string axion field associated with the $U(1)_{PQ}$ global symmetry. In the case of standard singularities, the Peccei-Quinn realization extends the symmetry of the SM-Like and contributes to the mediation of the electroweak symmetry breaking. The associated open string axion scales have been investigated in terms of D2 and D6-branes in type IIA compactifications. Using the fermion mass scales as well as string theory data, we have first approached the allowed axion window in terms of intersecting D6-branes wrapping 3-cycles belonging to the middle cohomology of the internal space. Then we have discussed the non-perturbative effect on the open string axion field using a D2-brane wrapping a 3-cycle producing 1+3 dimensional instantons. According to the known data, we have shown that the vacuum expectation value of the axion and the mass scale of the involved new scalar provide a probe of the stringy physics effect in the SM and a possible axionic DM candidate.

Our work comes up with many open questions. A natural question is think about a mirror dual version in type IB superstring. In this way, the D2-D6 brane systems could be replaced by D3-D7 ones using the geometry of 4-cycles. Another question is to go beyond the present study by introducing extra axion fields from D6-brane models. This allows one to think about multi-instantons by considering a set of D2-branes on 3-cycles producing non-perturbative string contributions. These could induce superpotential coupling involving chiral charged matter fields given in terms of fermionic zero modes living at the intersection of D6 and D2-branes. We expect that such intersections bring new light on the axionic dark matter discussions. Alternatively, axions can be derived from closed string sectors. In superstring theory, such fields can be obtained either from the NS-NS or R-R forms wrapping appropriate cycles of the internal space. In the case of type IIA superstring theory, the closed string axion fields can be associated with the R-R 3-form wrapping 3-cycles. These scalar fields can carry charge under the gauge fields living on the D6-brane wrapping on the same 3-cycles including the one associated with the $U(1)_{PQ}$ symmetry. In particular, the analogue of the last term of the lagrangian (2.2) can be obtained from the Chern Simon actions corresponding to the same D6-brane world-volume. It should be useful to introduce such fields in the ADM discussions by combing the open and closed sectors of string theory. We believe that this
study deserves a better understanding, and hope to report elsewhere on the corresponding questions.

Acknowledgements: The authors would like to thank M. P. Garcia del Moral for the collaboration on related topics.

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