Physics Letters B 735 (2014) 95–100

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Calculation of axion–photon–photon coupling in string theory

Jihn E. Kim

Department of Physics, Kyung Hee University, 26 Gyungheedaero, Dongdaemun-Gu, Seoul 130-701, Republic of Korea

ARTICLE INFO

Article history:
Received 22 May 2014
Accepted 9 June 2014
Available online 11 June 2014
Editor: M. Cvetič

Keywords:
QCD axion
Axion–photon–photon coupling
$\mathbf{Z}_{12-I}$ orbifold compactification
Flipped SU(5) GUT

ABSTRACT

The axion search experiments invite a plausible estimation of the axion–photon–photon coupling constant $\bar{c}_{a\gamma\gamma}$ in string models with phenomenologically acceptable visible sectors. We present the calculation of $\bar{c}_{a\gamma\gamma}$ with an exact Peccei–Quinn symmetry. In the Huh–Kim–Kyae $\mathbf{Z}_{12-I}$ orbifold compactification, we obtain $\bar{c}_{a\gamma\gamma} = \frac{1123}{388}$, and the low-temperature axion search experiments will probe the QCD corrected coupling, $c_{a\gamma\gamma} \simeq \bar{c}_{a\gamma\gamma} - 1.98 \simeq 0.91$.

1. Introduction

It seems that the Universe once passed the grand unification (GUT) scale energy region with its imprint survived until now [1]. If this BICEP2 result on the B-mode polarization survives on the matter of GUT scale energy density during inflation, it has a far-reaching implication in axion cosmology [2,3]. Firstly, the implied high scale inflation nullifies the dilution idea of topological defects, strings and domain walls of axion models [4]. Secondly, if the QCD axion accounts for most of cold dark matter (CDM) in the Universe, the constraint from isocurvature perturbation rules out the anthropic region [5] of the axion parameter space [6]. If axion accounts for some fraction of CDM, then it may be possible to detect it by low temperature Sikivie-type detectors [7]. If we accept this high scale inflation scenario, there are two urgent issues to be clarified.

The first is to introduce the trans-Planckian value of inflaton, the so-called Lyth bound [8], within a well-motivated theory. Recently, Lyth argued for a rationale of any specific term working for a large *e*-fold number [9]. There are three widely different classes of theories on this, the natural inflation completed with two non-abelian forces [10,11], appropriate quantum numbers under string-allowed discrete symmetries [12], and M-flation [14]. Discrete symmetries are favored compared to global symmetries in string compactification [13], which is thus welcome in obtaining a large *e*-folding by this method. If we rely on a single field inflation, it is generally very difficult to put the *e*-fold number at the bull's eye on the BICEP2 point [12]. However, there are some attempts to obtain the large *e*-folding from single field inflation [15].

The second issue which motivated this paper is the domain wall problem in some axion models. Accepting high scale inflation, a string theory solution of the domain wall problem is possible [4] using a discrete subgroup of the anomalous U(1) symmetry in string models. In string models with anomalous U(1) [16], the model-independent (MI) axion becomes the longitudinal degree of the anomalous U(1) gauge boson, rendering it massive above 10^{16} GeV [17]. Below 10^{16} GeV, there results a global symmetry whose quantum numbers have descended from the original anomalous U(1) symmetry [18,19]. Thus, string models with the anomalous U(1) is suitable for introducing a spontaneously broken Peccei–Quinn (PQ) symmetry at the intermediate scale, to have an invisible axion [20,21]. Now, because of the high scale inflation, it is a dictum to have the axion domain wall number one: $N_{\rm DW} = 1$. In string compactification, we found a solution of the domain wall problem [4] by identifying vacua in terms of discrete subgroups of the anomalous U(1), which is the Choi–Kim (CK) mechanism [22].

The early (and so-far the only) example of the CK method using the anomalous U(1) was Ref. [18], which however was based on a toy model. Here, we present the second example based on a phenomenologically acceptable grand unification (GUT) model from the heterotic string theory, leading to an $N_{\rm DW} = 1$ solution. In addition, we calculate the axion–photon–photon coupling strength, which is needed as a guideline in the axion detection experiments. It is in the Huh–Kim–Kyae (HKK) double SU(5) model

http://dx.doi.org/10.1016/j.physletb.2014.06.021
0370-2693/

[23,24] from $\mathbf{Z}_{12-I}$ orbifold compactification. We may consider the $\mathbf{Z}_{12-I}$ compactification as the simplest one among the thirteen different orbifolds of the heterotic string [25]. One may be tempted to regard the $\mathbf{Z}_3$ orbifold compactification as the simplest one, but it is not so because the $\mathbf{Z}_3$ orbifold has twenty-seven fixed points while the $\mathbf{Z}_{12-I}$ orbifold has only three fixed points. If one follows the orbifold selection rules carefully, the $\mathbf{Z}_{12-I}$ orbifold compactification leads to the easiest way of obtaining a string model [25,26]. The most complicated orbifolds are from $\mathbf{Z}_{6-II}$ [27]. The *double SU(5)* model is defined here as the model having three ($\overline{\mathbf{10}}$ plus $\mathbf{5}$) families under one SU(5) and one ($\overline{\mathbf{10}}'$ plus $\mathbf{5}'$) family under the other SU(5)′ toward a successful low energy supersymmetry (SUSY). One family SU(5)′ is needed for dynamical breaking of SUSY with confining force SU(5)′ [28].[1] There does not exist any *double SU(5)* model in the $\mathbf{Z}_3$ orbifold compactification [25], and we have not found any other *double SU(5)* model yet beyond the HKK model in the computer scan of $\mathbf{Z}_{12-I}$ orbifolds.

Phenomenologically interesting orbifold models, in particular the standard-like models with gauge group $SU(3)_c \times SU(2)_W \times U(1)^n$ are interesting [30], but for the study of anomalous U(1) they are too complicated because there are thirteen U(1) directions to consider. A simpler model with the GUT-type gauge coupling unification is the flipped-SU(5) GUT, $SU(5)_{flip}$ [31], in which a 16-dimensional set is obtained from the spinor representation **16** of SO(10). In this paper, the rank 5 gauge group $SU(5)\times U(1)_X$ is denoted as $SU(5)_{flip}$. The fermionic construction of $SU(5)_{flip}$ was given in [32]. The *double SU(5)* model contains $SU(5)_{flip}$ as the visible sector, and a successful phenomenology of the HKK model was discussed in Ref. [23].

In Section 2, we obtain the anomalous charge operator Q_{anom} which is used for the PQ charges and list the charges for the $SU(5)_{flip}$ non-singlet representations. For the representations of the E_8' sector non-abelian groups, the charges are listed in Appendix A. In Section 3, we list the charges for electromagnetically charged singlet representations and compute the axion–photon–photon coupling $\bar{c}_{a\gamma\gamma}$. Section 4 is a conclusion.

2. $SU(5)\times U(1)_X \times SU(5)' \times U(1)_{anom}$ without domain wall problem

Recently, we emphasized that the early history of the Universe does not take the possibility of inflating away the topological defects of axion models [4]. This implies that the axion solution of the strong CP problem via the spontaneous breaking of the Peccei–Quinn (PQ) symmetry is cosmologically disfavored if the axion domain wall number is not one [33]. The solution by introducing $N_{DW}=1$ via the model-independent (MI) axion by the CK mechanism in string models is the following [4]. The MI axion has the anomaly coupling to gauge fields,

$$\frac{a_{MI}}{32\pi^2 F_{MI}}(G\tilde{G}+F_h\tilde{F}_h) \tag{1}$$

where $G\tilde{G}$ and $F_h\tilde{F}_h$ are the QCD and hidden sector anomalies, respectively. With the anomalous $U(1)_{ga}$ gauge symmetry, below the $U(1)_{ga}$ gauge boson scale a global symmetry survives and its spontaneous symmetry breaking allows the second axion coupling as

$$\frac{\mathcal{N}a_2}{32\pi^2 f_2}G\tilde{G}+\frac{\mathcal{N}a_2}{32\pi^2 f_2}F_h\tilde{F}_h, \tag{2}$$

where $\mathcal{N}$ is common to $G\tilde{G}$ and $F_h\tilde{F}_h$. Here, we assumed only one extra axion a_2 beyond the discrete subgroup of the MI axion direction. The fact that $\mathcal{N}$ is common to $G\tilde{G}$ and $F_h\tilde{F}_h$ is essential to have an $N_{DW}=1$ solution. In this section, we show that indeed this is the case even though $G\tilde{G}$ occurs from E_8 and $F_h\tilde{F}_h$ occurs from E_8'. Identifying the same $\mathcal{N}$ is the $N_{DW}=1$ solution via a discrete subgroup of $U(1)_{anom}$ [4].

In the $\mathbf{Z}_{12-I}$ HKK orbifold model, we have $SU(5)\times U(1)_X \times SU(5)'\times U(1)_{anom}$, and the key field contents under $SU(5)\times SU(5)'$ are $3\times\mathbf{16}+\{\mathbf{10},\overline{\mathbf{10}}\}+\{\mathbf{10}',\bar{\mathbf{5}}'\}$. The set $\{\mathbf{10},\overline{\mathbf{10}}\}$ is needed for spontaneous breaking of $SU(5)_{flip}\times U(1)_X$ down to the standard model gauge group. The set $\{\mathbf{10}',\bar{\mathbf{5}}'\}$ is useful for SUSY breaking. Three copies of **16** constitute three families of $SU(5)_{flip}$.

The shift vector V of $\mathbf{Z}_{12-I}$ is composed of sixteen fractional numbers which are integer multiples of $\frac{1}{12}$, satisfying the modular invariance conditions. With the twist vector of the six internal dimensions with three complex numbers, $\phi=(\frac{5}{12},\frac{4}{12},\frac{1}{12})$, the condition is $12(V^2-\phi^2)=$ even integer. The Wilson line W should satisfy the modular invariance conditions, $12(V^2-\phi^2)=$ even integer, $12V\cdot W=$ even integer, and $12W^2=$ even integer. The HKK model is [23],

$$\begin{aligned} V&=\left(0\,0\,0\,0\,0\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\right)\left(0\,0\,0\,0\,0\,\frac{1}{4}\,\frac{1}{4}\,\frac{-2}{4}\right)'\\ W&=\left(\frac{2}{3}\,\frac{2}{3}\,\frac{2}{3}\,\frac{2}{3}\,\frac{2}{3}\,0\,\frac{-2}{3}\,\frac{2}{3}\right)\left(\frac{2}{3}\,\frac{2}{3}\,\frac{2}{3}\,\frac{2}{3}\,0\,\frac{-2}{3}\,0\,0\right)'. \end{aligned} \tag{3}$$

In this model, the SU(5) charge raising and lowering generators are

$$SU(5):\quad F_a\,(a=1,\dots,20)=(\underline{1\,{-1}\,0\,0\,0};0\,0\,0)(0^8)', \tag{4}$$

where the underline means permutations of the entries above the line. The SU(5)′ charge raising and lowering generators are

$$SU(5)':\quad \begin{cases} \Lambda_\alpha\,(\alpha=1,\dots,12)=(0^8)(\underline{1\,{-1}\,0\,0}\,0;0\,0\,0)', \\ \Lambda_\alpha\,(\alpha=13,\dots,16)=(0^8)(\underline{+\,+\,+\,-}\,+;-\,-\,-)', \\ \Lambda_\alpha\,(\alpha=17,\dots,20)=(0^8)(\underline{+\,-\,-\,-}\,-;+\,+\,+)'. \end{cases} \tag{5}$$

The SU(2)′ charge raising and lowering generators are

$$SU(2)':\quad \begin{cases} T^+=(0^8)(+\,+\,+\,+\,+\,+\,+\,+)', \\ T^-=(0^8)(-\,-\,-\,-\,-\,-\,-\,-)'. \end{cases} \tag{6}$$

The rank 5 gauge group $SU(5)\times U(1)_X$ is denoted as $SU(5)_{flip}$, where the hypercharge $Y_5\in SU(5)$ and X are denoted as

$$Y_5=\left(\frac{-1}{3}\,\frac{-1}{3}\,\frac{-1}{3}\,\frac{+1}{2}\,\frac{+1}{2};0\,0\,0\right)(0^8)', \tag{7}$$

$$X=(-2\,-2\,-2\,-2\,-2;0\,0\,0)(0^8)', \tag{8}$$

with the convention presented in Ref. [25]. To get $U(1)_{anom}$, consider the rank 16 gauge group $SU(5)_{flip}\times U(1)_1\times U(1)_2\times U(1)_3$ from E_8 and $SU(5)'\times SU(2)'\times U(1)_4'\times U(1)_5'\times U(1)_6'$ from E_8'. The six U(1) charges are given by

$$\begin{aligned} Q_1&=(0^5;12\,0\,0)(0^8)', &\tilde{Q}_1&=\frac{1}{12}Q_1,\\ Q_2&=(0^5;0\,12\,0)(0^8)', &\tilde{Q}_2&=\frac{1}{12}Q_2,\\ Q_3&=(0^5;0\,0\,12)(0^8)', &\tilde{Q}_3&=\frac{1}{12}Q_3,\\ Q_4&=(0^8)(0^4,0;12\,-12\,0)', &\tilde{Q}_4&=\frac{1}{12\sqrt{2}}Q_4,\\ Q_5&=(0^8)(0^5;-6\,-6\,12)', &\tilde{Q}_5&=\frac{1}{6\sqrt{6}}Q_5, \end{aligned}$$

[1] If one assumes gravity effects with gaugino condensation in SUSY breaking, one family SU(5)′ may not be needed [29].

Table 1
The $SU(5)_{flip}$ states. Here, $+$ represents $+\frac{1}{2}$ and $-$ represents $-\frac{1}{2}$. In the Label column, 3 is multiplied for **10** and $\overline{\mathbf{10}}$ each of which houses three quark and antiquarks. The PQ symmetry, being chiral, counts quark and antiquark in the same way. The right-handed states in T_3 and T_5 are converted to the left-handed ones of T_9 and T_7, respectively.

Sect.	Colored states	$SU(5)_X$	Multiplicity	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_{anom}	Label	$Q_a^{\gamma\gamma}$
U	$(\underline{+++--};--+)(0^8)'$	$\overline{\mathbf{10}}_{-1}$		−6	−6	+6	0	0	0	−1638	$3C_2$	−3276
U	$(\underline{+----};+--)(0^8)'$	$\mathbf{5}_3$		+6	−6	−6	0	0	0	−126	C_1	−294
T_4^0	$(\underline{+----};\frac{-1}{6}\frac{-1}{6}\frac{-1}{6})(0^8)'$	$\mathbf{5}_3$	2	−2	−2	−2	0	0	0	−378	$2C_3$	−882
T_4^0	$(\underline{+++--};\frac{-1}{6}\frac{-1}{6}\frac{-1}{6})(0^8)'$	$\overline{\mathbf{10}}_{-1}$	2	−2	−2	−2	0	0	0	−378	$6C_4$	−756
T_4^0	$(\underline{10000};\frac{1}{3}\frac{1}{3}\frac{1}{3})(0^8)'$	$\mathbf{5}_{-2}$	2	+4	+4	+4	0	0	0	+756	$2C_5$	+1008
T_4^0	$(\underline{-10000};\frac{1}{3}\frac{1}{3}\frac{1}{3})(0^8)'$	$\bar{\mathbf{5}}_2$	2	+4	+4	+4	0	0	0	+756	$2C_6$	+1008
T_6^0	$(\underline{10000};000)(0^5;\frac{-1}{2}\frac{+1}{2}0)'$	$\mathbf{5}_{-2}$	3	0	0	0	−12	0	0	0	$3C_7$	0
T_6^0	$(\underline{-10000};000)(0^5;\frac{+1}{2}\frac{-1}{2}0)'$	$\bar{\mathbf{5}}_{+2}$	3	0	0	0	+12	0	0	0	$3C_8$	0
T_3^0	$(\underline{+++--};000)(0^5;\frac{-1}{4}\frac{-1}{4}\frac{+2}{4})'$	$\overline{\mathbf{10}}_{-1}$	1	0	0	0	0	+9	+3	−594	$3C_9$	−1188
T_9^0	$(\underline{++---};000)(0^5;\frac{+1}{4}\frac{+1}{4}\frac{-2}{4})'$	$\mathbf{10}_{+1}$	1	0	0	0	0	−9	−3	+594	$3C_{10}$	+1188
T_7^0	$(\underline{-10000};\frac{-1}{6}\frac{-1}{6}\frac{-1}{6})(0^5;\frac{-1}{4}\frac{-1}{4}\frac{+2}{4})'$	$\bar{\mathbf{5}}_{-2}$	1	−2	−2	−2	0	+9	+3	−972	C_{11}	−1296
T_7^0	$(\underline{+10000};\frac{-1}{6}\frac{-1}{6}\frac{-1}{6})(0^5;\frac{-1}{4}\frac{-1}{4}\frac{+2}{4})'$	$\mathbf{5}_{+2}$	1	−2	−2	−2	0	+9	+3	−972	C_{12}	−1296
			$\sum_i Q(q_i)n(q_i) =$	−16	−28	+8	0	+18	+6	−6984	$\sum_i =$	−17058

$$Q_6 = (0^8)(-6\,-6\,-6\,-6\;18;0\,0\,6)',$$
$$\tilde{Q}_6 = \frac{1}{6\sqrt{14}} Q_6, \tag{9}$$

where tilded charges are the properly normalized U(1) charges, and norms of these charges are

$$Q_1^2 = Q_2^2 = Q_3^2 = 144, \qquad Q_4^2 = 288,$$
$$Q_5^2 = 216, \qquad Q_6^2 = 504. \tag{10}$$

In Table 1, we list fields containing the standard model quarks (and antiquarks), where the U(1) charges are also shown. The PQ symmetry, being chiral, counts quark and antiquark in the same way, and we took into account the factor 3 for **10** and $\overline{\mathbf{10}}$ in the Label column. The five anomaly free U(1)s are

$$P_1 = \frac{1}{12\sqrt{5}}(Q_1 + 2Q_3), \qquad P_2 = \frac{1}{6\sqrt{22}}(-Q_1 + Q_2 + 2Q_6),$$
$$P_3 = \frac{1}{72}(Q_5 - 3Q_6), \qquad P_4 = \frac{1}{12\sqrt{2}} Q_4,$$
$$P_5 = \frac{1}{12\sqrt{74}}(3Q_3 - 4Q_6). \tag{11}$$

The sixth U(1), which is orthogonal to Eq. (11) and carries the anomaly, is

$$Q_{anom} = 84Q_1 + 147Q_2 - 42Q_3 - 63Q_5 - 9Q_6. \tag{12}$$

For the non-abelian gauge groups from E_8', we present two tables in Appendix A, Table 3 and Table 4. Comparing Table 1 and Tables 3 and 4 of Appendix A, we note that the anomaly sum of these U(1) charges are the same for three non-abelian groups, SU(5), SU(5)′ and SU(2)′. In particular, the anomaly charges are the same, −6984, and we obtain the $N_{DW} = 1$ solution as commented above [4].

3. Axion–photon–photon coupling

For singlet fields, non-vanishing charges arise for non-vanishing X quantum number of Eq. (8). Complete lists of the spectrum is found in the preprint version [24] of Ref. [23]. Singlets with non-vanishing X charges are listed in Table 2. For the non-singlets, we also list the electromagnetic charges in the last columns of Tables 1, 3, and 4. The electromagnetic charge Q_{em} belongs to $SU(5)_{flip}$, not depending on SU(5)′ and SU(2)′. The $SU(5)_{flip}$ assignments $(Y_5)_X$ are

$$\mathbf{5}_3 = \begin{pmatrix} u^c \\ \nu_e \\ e^- \end{pmatrix} = \begin{pmatrix} (\frac{-1}{3})_3 \\ (\frac{+1}{2})_3 \\ (\frac{+1}{2})_3 \end{pmatrix},$$
$$\overline{\mathbf{10}}_{-1} = \begin{pmatrix} d^c & \begin{matrix} u \\ d \end{matrix} & N \end{pmatrix} = \begin{pmatrix} (\frac{2}{3})_{-1} & \begin{matrix} (\frac{-1}{6})_{-1} \\ (\frac{-1}{6})_{-1} \end{matrix} & (-1)_{-1} \end{pmatrix},$$
$$\mathbf{1}_{-5} = (e^+), \tag{13}$$

and we have the electromagnetic charge operator as

$$Q_{em} = W_3 + \frac{1}{5} Y_5 - \frac{1}{5} X, \tag{14}$$

where W_3 is the third component of the weak isospin and the electroweak hypercharge is $Y = Y_5 - \frac{1}{5}X$. Thus, the electromagnetic charges of the $SU(5)_{flip}$ representations are

$$\overline{\mathbf{10}}_{-1} = \left(\left(\frac{1}{3}\right)_\alpha, \left(\frac{2}{3}\right)_\alpha, \left(\frac{-1}{3}\right)_\alpha, 0\right),$$
$$\mathbf{10}_{+1} = \left(\left(\frac{-1}{3}\right)_\alpha, \left(\frac{-2}{3}\right)_\alpha, \left(\frac{1}{3}\right)_\alpha, 0\right),$$
$$\mathbf{5}_3 = \left(\left(\frac{-2}{3}\right)_\alpha, 0, -1\right), \qquad \mathbf{1}_X = \left(-\frac{1}{5}X\right),$$
$$\mathbf{5}_{-2} = \left(\left(\frac{1}{3}\right)_\alpha, 1, 0\right), \qquad \bar{\mathbf{5}}_{+2} = \left(\left(\frac{-1}{3}\right)_\alpha, 0, -1\right),$$
$$\bar{\mathbf{5}}_{-2} = \left(\left(\frac{7}{15}\right)_\alpha, \frac{4}{5}, \frac{-1}{5}\right), \qquad \mathbf{5}_{+2} = \left(\left(\frac{-7}{15}\right)_\alpha, \frac{1}{5}, \frac{-4}{5}\right), \tag{15}$$

where α is the color index and $-X/5$ for an $SU(5)_{flip}$ singlet is the electromagnetic charge of the singlet. For the $SU(5)_{flip}$ non-singlet representations, the traces are

Table 2
Electromagnetically charged singlets.

Sect.	Singlet states	$U(1)_X$	Multiplicity	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_{anom}	Label	$Q_a^{\gamma\gamma}$
U	$(+ + + + +; - + -)(0^8)'$	$\mathbf{1}_{-5}$		−6	+6	−6	0	0	0	+630	S_1	+630
T_4^+	$(\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6};\,\frac{-1}{6}\,\frac{1}{6}\,\frac{1}{2})(\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{-1}{2};\,\frac{-1}{6}\,\frac{-1}{2}\,\frac{1}{2})'$	$\mathbf{1}_{-5/3}$	2	−2	+2	+6	+4	+10	−10	−666	$2S_2$	−74
	$(\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6};\,\frac{-1}{6}\,\frac{1}{6}\,\frac{1}{2})(\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{-1}{2};\,\frac{-1}{6}\,\frac{1}{2}\,\frac{-1}{2})'$	$\mathbf{1}_{-5/3}$	2	−2	+2	+6	−8	−8	−16	+522	$2S_3$	+58
T_4^-	$(\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6};\,\frac{-1}{6}\,\frac{-1}{2}\,\frac{1}{6})(\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{1}{2};\,\frac{1}{6}\,\frac{+1}{2}\,\frac{-1}{2})'$	$\mathbf{1}_{5/3}$	2	−2	−6	+2	−4	−10	+10	−594	$2S_4$	−68
	$(\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6};\,\frac{-1}{6}\,\frac{-1}{2}\,\frac{1}{6})(\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{1}{2};\,\frac{1}{6}\,\frac{-1}{2}\,\frac{+1}{2})'$	$\mathbf{1}_{5/3}$	2	−2	−6	+2	+8	+8	+16	−1782	$2S_5$	−198
T_2^+	$(\frac{1}{3}\,\frac{1}{3}\,\frac{1}{3}\,\frac{1}{3}\,\frac{1}{3};\,\frac{-1}{3}\,\frac{1}{3}\,0)(\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{1}{2};\,\frac{-1}{3}\,0\,\frac{1}{2})'$	$\mathbf{1}_{-10/3}$	1	−4	+4	0	−4	+8	+16	−396	S_6	−176
	$(\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6};\,\frac{1}{6}\,\frac{-1}{6}\,\frac{1}{2})(\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{1}{2};\,\frac{2}{3}\,0\,\frac{-1}{2})'$	$\mathbf{1}_{5/3}$	1	+2	−2	+6	+8	−10	+10	+162	S_7	+18
	$(\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6};\,\frac{1}{6}\,\frac{-1}{6}\,\frac{1}{2})(\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{1}{2};\,\frac{-1}{3}\,0\,\frac{1}{2})'$	$\mathbf{1}_{5/3}$	1	+2	−2	+6	−4	+8	+16	−1026	S_8	−114
T_2^-	$(\frac{-1}{3}\,\frac{-1}{3}\,\frac{-1}{3}\,\frac{-1}{3}\,\frac{-1}{3};\,\frac{-1}{3}\,0\,\frac{1}{3})(\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{-1}{2};\,\frac{1}{3}\,0\,\frac{-1}{2})'$	$\mathbf{1}_{10/3}$	1	−4	0	+4	+4	−8	−16	+144	S_9	+64
	$(\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6};\,\frac{1}{6}\,\frac{-1}{2}\,\frac{-1}{6})(\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{-1}{2};\,\frac{-2}{3}\,0\,\frac{1}{2})'$	$\mathbf{1}_{-5/3}$	1	+2	−6	−2	−8	+10	−10	−1170	S_{10}	−130
	$(\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6};\,\frac{1}{6}\,\frac{-1}{2}\,\frac{-1}{6})(\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{-1}{2};\,\frac{1}{3}\,0\,\frac{-1}{2})'$	$\mathbf{1}_{-5/3}$	1	+2	−6	−2	+4	−8	−16	+18	S_{11}	+2
T_1^+	$(\frac{-1}{3}\,\frac{-1}{3}\,\frac{-1}{3}\,\frac{-1}{3}\,\frac{-1}{3};\,\frac{-1}{6}\,\frac{1}{6}\,\frac{1}{2})(\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{-1}{2};\,\frac{1}{12}\,\frac{-1}{4}\,0)'$	$\mathbf{1}_{10/3}$	1	−2	+2	+6	+4	+1	−13	−72	S_{12}	−32
	$(\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6};\,\frac{-2}{3}\,\frac{2}{3}\,0)(\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{-1}{2};\,\frac{1}{12}\,\frac{-1}{4}\,0)'$	$\mathbf{1}_{-5/3}$	1	−8	+8	0	+4	+1	−13	+558	S_{13}	+62
	$(\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6};\,\frac{1}{3}\,\frac{-1}{3}\,0)(\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{-1}{2};\,\frac{1}{12}\,\frac{-1}{4}\,0)'$	$\mathbf{1}_{-5/3}$	2	+4	−4	0	+4	+1	−13	−198	$2S_{14}$	−22
T_1^-	$(\frac{1}{3}\,\frac{1}{3}\,\frac{1}{3}\,\frac{1}{3}\,\frac{1}{3};\,\frac{-1}{6}\,\frac{1}{2}\,\frac{1}{6})(\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{1}{2};\,\frac{5}{12}\,\frac{-1}{4}\,0)'$	$\mathbf{1}_{-10/3}$	1	−2	+6	+2	+8	−1	+13	+576	S_{15}	+256
	$(\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6};\,\frac{-2}{3}\,0\,\frac{-1}{3})(\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{1}{2};\,\frac{5}{12}\,\frac{-1}{4}\,0)'$	$\mathbf{1}_{5/3}$	1	−8	0	−4	+8	−1	+13	−558	S_{16}	−62
	$(\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6};\,\frac{1}{3}\,0\,\frac{2}{3})(\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{1}{2};\,\frac{5}{12}\,\frac{-1}{4}\,0)'$	$\mathbf{1}_{5/3}$	1	+4	0	+8	+8	−1	+13	−54	S_{17}	−6
T_7^+	$(\frac{-1}{3}\,\frac{-1}{3}\,\frac{-1}{3}\,\frac{-1}{3}\,\frac{-1}{3};\,\frac{-1}{6}\,\frac{1}{6}\,\frac{-1}{2})(\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{-1}{2};\,\frac{-5}{12}\,\frac{1}{4}\,0)'$	$\mathbf{1}_{-10/3}$	1	−2	+2	−6	−8	+1	−13	+432	S_{18}	+192
	$(\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6};\,\frac{1}{3}\,\frac{2}{3}\,0)(\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{-1}{2};\,\frac{-5}{12}\,\frac{1}{4}\,0)'$	$\mathbf{1}_{5/3}$	1	+4	+8	0	−8	+1	−13	+1566	S_{19}	+174
	$(\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6};\,\frac{-2}{3}\,\frac{-1}{3}\,0)(\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{-1}{2};\,\frac{-5}{12}\,\frac{1}{4}\,0)'$	$\mathbf{1}_{5/3}$	1	−8	−4	0	−8	+1	−13	−1206	S_{20}	−134
T_7^-	$(\frac{1}{3}\,\frac{1}{3}\,\frac{1}{3}\,\frac{1}{3}\,\frac{1}{3};\,\frac{-1}{6}\,\frac{-1}{2}\,\frac{1}{6})(\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{1}{2};\,\frac{-1}{12}\,\frac{1}{4}\,0)'$	$\mathbf{1}_{10/3}$	1	−2	−6	+2	−4	−1	+13	−1188	S_{21}	−528
	$(\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6};\,\frac{-2}{3}\,0\,\frac{2}{3})(\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{1}{2};\,\frac{-1}{12}\,\frac{1}{4}\,0)'$	$\mathbf{1}_{-5/3}$	1	−8	0	+8	−4	−1	+13	−1062	S_{22}	−118
	$(\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6};\,\frac{1}{3}\,0\,\frac{-1}{3})(\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{1}{2};\,\frac{-1}{12}\,\frac{1}{4}\,0)'$	$\mathbf{1}_{-5/3}$	1	+4	0	−4	−4	−1	+13	+450	S_{23}	+50
			$\sum_i Q(\mathbf{1}_i)n(\mathbf{1}_i) =$	−16	−28	+8	0	+18	+42	−7632	$\sum_i =$	−460

$$
\begin{aligned}
&\mathrm{Tr}\, Q_{em}^2(\overline{\mathbf{10}}_{-1}) = \mathrm{Tr}\, Q_{em}^2(\mathbf{10}_{+1}) = 2,\\
&\mathrm{Tr}\, Q_{em}^2(\mathbf{5}_{+3}) = \frac{7}{3}, \qquad \mathrm{Tr}\, Q_{em}^2(\mathbf{1}_{-5}) = 1,\\
&\mathrm{Tr}\, Q_{em}^2(\mathbf{5}_{-2}) = \mathrm{Tr}\, Q_{em}^2(\bar{\mathbf{5}}_{+2}) = \mathrm{Tr}\, Q_{em}^2(\bar{\mathbf{5}}_{-2})\\
&\qquad = \mathrm{Tr}\, Q_{em}^2(\mathbf{5}_{+2}) = \frac{4}{3}.
\end{aligned}
\tag{16}
$$

In passing, note that the trace of Q_{em}^2 for an anomaly-free irreducible set, including the fundamental representation of GUT representations, defines $\sin^2\theta_W^0$ of that GUT. Such examples in Eq. (16) are $\overline{\mathbf{10}}_{-1} + \mathbf{5}_{+3} + \mathbf{1}_{-5}$, $\mathbf{5}_{-2} + \bar{\mathbf{5}}_{+2}$, etc. Assuming the universal coupling for all gauge groups in string theory, from $\mathbf{5}_{-2} + \bar{\mathbf{5}}_{+2}$ for example, we obtain

$$
\sin^2\theta_W^0 = \frac{\mathrm{Tr}\, W_3^2}{\mathrm{Tr}\, Q_{em}^2} = \frac{3}{8}. \tag{17}
$$

From the last columns of Tables 1, 2, 3, and 4, we obtain $\mathrm{Tr}\, Q_a^{\gamma\gamma} Q_{em}^2 = -20214$. Thus, we obtain

$$
\bar{c}_{a\gamma\gamma} = \frac{-20214}{-6984} = \frac{1123}{388}. \tag{18}
$$

With the chiral symmetry breaking effect, −1.98, calculated with $m_u/m_d \simeq 0.5$ [34], we obtain $c_{a\gamma\gamma} \simeq \bar{c}_{a\gamma\gamma} - 1.98$. The cavity detector probes the axion–photon–photon coupling in a strong magnetic field **B**,

$$
\mathcal{L} = c_{a\gamma\gamma}\frac{\alpha_{em}\, a}{8\pi\, f_a}\mathbf{E}\cdot\mathbf{B}. \tag{19}
$$

4. Conclusion

We computed the axion–photon–photon coupling in a phenomenologically viable HKK $SU(5)_{flip} \times SU(5)' \times U(1)_{anom}$ model from the heterotic $E_8 \times E_8'$ string compactified on the $\mathbf{Z}_{12-I}$ orbifold, $\bar{c}_{a\gamma\gamma} = 1123/388$, leading to $c_{a\gamma\gamma}^2 \simeq 0.83$. It is between the KSVZ model value, $c_{a\gamma\gamma}^2 \simeq 0.96$, with the neutral heavy quark and the DFSZ model value, $c_{a\gamma\gamma}^2 \simeq 0.48$, with the (d^c, e) unification condition [35]. There has appeared a $c_{a\gamma\gamma}^2$ calculation with an approximate Peccei–Quinn symmetry before [36], but the present calculation is the first calculation with an exact PQ symmetry. The previous calculation gave a smaller $c_{a\gamma\gamma}^2$ compared to the present value, 0.83, and it is likely that $c_{a\gamma\gamma}^2$ from string takes some range of parameters. In particular, we cannot rule out a possibility that $\bar{c}_{a\gamma\gamma}$ is close to 0.98 in which case it is very difficult to prove the existence of axion by the cavity axion detectors.

Acknowledgements

I thank Bumseok Kyae for checking out the tables. This work is supported in part by the National Research Foundation (NRF) grant funded by the Korean Government (MEST) (No. 2005-0093841) and by the IBS (IBS CA1310).

Appendix A

In this appendix, we list the charges of the E_8' non-abelian group representations, those of $SU(5)'$ in Table 3 and those of $SU(2)'$ in Table 4. As claimed, the anomalous charges are exactly

Table 3
The SU(5)′ representations. Notations are the same as in Table 1.

Sect.	States	SU(5)′	Multiplicity	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	$Q_{\rm anom}$	Label	$Q_a^{\gamma\gamma}$
T_1^0	$(10000;\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6})(\underline{-1\,0\,0\,0}\,0;\tfrac{1}{4}\,\tfrac{1}{4}\,\tfrac{1}{2})'$ $(10000;\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6})(\underline{\tfrac{1}{2}\,\tfrac{1}{2}\,\tfrac{-1}{2}\,\tfrac{-1}{2}}\,\tfrac{1}{2};\tfrac{-1}{4}\,\tfrac{-1}{4}\,0)'$	$\overline{\mathbf{10}}'_0$	1	−2	−2	−2	0	+3	+9	−648	$3T'_1$	0
T_1^0	$(00000;\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6})(\underline{1\,0\,0\,0}\,0;\tfrac{1}{4}\,\tfrac{1}{4}\,\tfrac{1}{2})'$ $(00000;\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6})(00000;\tfrac{-3}{4}\,\tfrac{-3}{4}\,\tfrac{-1}{2})'$ $(00000;\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6})(\underline{\tfrac{1}{2}\,\tfrac{-1}{2}\,\tfrac{-1}{2}\,\tfrac{-1}{2}}\,\tfrac{-1}{2};\tfrac{-1}{4}\,\tfrac{-1}{4}\,0)'$ $(00000;\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6})(\tfrac{1}{2}\,\tfrac{1}{2}\,\tfrac{1}{2}\,\tfrac{1}{2}\,\tfrac{-1}{2};\tfrac{-1}{4}\,\tfrac{-1}{4}\,0)'$	$(\mathbf{5}',\mathbf{2}')_0$	1	−2	−2	−2	0	+3	−3	−540	$2F'_1$	0
T_1^0	$(00000;\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6})(\underline{\tfrac{-1}{2}\,\tfrac{1}{2}\,\tfrac{1}{2}\,\tfrac{1}{2}}\,\tfrac{-1}{2};\tfrac{-1}{4}\,\tfrac{-1}{4}\,0)'$ $(00000;\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6})(0000{-1};\tfrac{1}{4}\,\tfrac{1}{4}\,\tfrac{1}{2})'$	$\bar{\mathbf{5}}'_0$	1	−2	−2	−2	0	+3	−15	−432	F'_2	0
T_1^+	$(\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6};\tfrac{1}{3}\,\tfrac{-1}{3}\,0)(\underline{\tfrac{-5}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}}\,\tfrac{1}{2};\tfrac{1}{12}\,\tfrac{-1}{4}\,0)'$ $(\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6};\tfrac{1}{3}\,\tfrac{-1}{3}\,0)(\tfrac{-1}{3}\,\tfrac{-1}{3}\,\tfrac{-1}{3}\,\tfrac{-1}{3}\,0;\tfrac{7}{12}\,\tfrac{1}{4}\,\tfrac{1}{2})'$	$\bar{\mathbf{5}}'_{-5/3}$	1	+4	−4	0	+4	+1	+11	−414	F'_3	−230
T_4^+	$(\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6};\tfrac{-1}{6}\,\tfrac{1}{6}\,\tfrac{1}{2})(\underline{\tfrac{2}{3}\,\tfrac{-1}{3}\,\tfrac{-1}{3}\,\tfrac{-1}{3}}\,0;\tfrac{1}{3}\,0\,0)'$ $(\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6};\tfrac{-1}{6}\,\tfrac{1}{6}\,\tfrac{1}{2})(\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{2};\tfrac{-1}{6}\,\tfrac{-1}{2}\,\tfrac{-1}{2})'$	$\mathbf{5}'_{-5/3}$	3	−2	+2	+6	+4	−2	+2	−18	$3F'_4$	−10
T_4^-	$(\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6};\tfrac{-1}{6}\,\tfrac{-1}{2}\,\tfrac{1}{6})(\underline{\tfrac{-2}{3}\,\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{1}{3}}\,0;\tfrac{-1}{3}\,0\,0)'$ $(\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6};\tfrac{-1}{6}\,\tfrac{-1}{2}\,\tfrac{1}{6})(\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{2};\tfrac{1}{6}\,\tfrac{1}{2}\,\tfrac{1}{2})'$	$\bar{\mathbf{5}}'_{5/3}$	3	−2	−6	+2	−4	+2	−2	−1242	$3F'_5$	−690
T_7^-	$(\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6};\tfrac{1}{3}\,0\,\tfrac{-1}{3})(\underline{\tfrac{5}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}}\,\tfrac{-1}{2};\tfrac{-1}{12}\,\tfrac{1}{4}\,0)'$ $(\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6};\tfrac{1}{3}\,0\,\tfrac{-1}{3})(\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{1}{3}\,0;\tfrac{-7}{12}\,\tfrac{-1}{4}\,\tfrac{-1}{2})'$	$\mathbf{5}'_{-5/3}$	1	+4	0	−4	−4	−1	−11	+666	F'_6	+370
			$\sum_i Q(q'_i)n(q'_i) =$	−16	−28	+8	0	+18	+6	−6984	$\sum_i =$	−1960

Table 4
The SU(2)′ representations. Notations are the same as in Table 1. We listed only the upper component of SU(2)′ from which the lower component can be obtained by applying T^- of Eq. (6).

Sect.	States	SU(2)′	Multiplicity	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	$Q_{\rm anom}$	Label	$Q_a^{\gamma\gamma}$
T_1^0	$(00000;\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6})(\underline{1\,0\,0\,0}\,0;\tfrac{1}{4}\,\tfrac{1}{4}\,\tfrac{1}{2})'$ $(00000;\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6})(00000;\tfrac{-3}{4}\,\tfrac{-3}{4}\,\tfrac{-1}{2})'$	$(\mathbf{5}',\mathbf{2}')_0$	1	−2	−2	−2	0	+3	−3	−540	$5D'_1$	Considered in Table 3
T_1^0	$(00000;\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6})(00001;\tfrac{1}{4}\,\tfrac{1}{4}\,\tfrac{1}{2})'$	$\mathbf{2}'_0$	1	−2	−2	−2	0	+3	+21	−756	D_2	0
T_1^+	$(\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6};\tfrac{1}{3}\,\tfrac{-1}{3}\,0)(\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{2};\tfrac{1}{12}\,\tfrac{3}{4}\,0)'$	$\mathbf{2}'_{-5/3}$	1	+4	−4	0	−8	−5	+5	+18	D_3	+4
T_1^-	$(\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6};\tfrac{-2}{3}\,0\,\tfrac{-1}{3})(\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{1}{3}\,0;\tfrac{-1}{12}\,\tfrac{1}{4}\,\tfrac{1}{2})'$	$\mathbf{2}'_{5/3}$	1	−8	0	−4	−4	+5	−5	−774	D_4	−172
T_1^-	$(\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6};\tfrac{1}{3}\,0\,\tfrac{2}{3})(\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{1}{3}\,0;\tfrac{-1}{12}\,\tfrac{1}{4}\,\tfrac{1}{2})'$	$\mathbf{2}'_{5/3}$	1	+4	0	+8	−4	+5	−5	−270	D_5	−20
T_2^+	$(\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6};\tfrac{1}{6}\,\tfrac{-1}{6}\,\tfrac{1}{2})(\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{1}{3}\,0;\tfrac{1}{6}\,\tfrac{1}{2}\,0)'$	$\mathbf{2}'_{5/3}$	1	+2	−2	+6	−4	−4	−8	−54	D_6	−4
T_2^-	$(\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6};\tfrac{1}{6}\,\tfrac{-1}{2}\,\tfrac{-1}{6})(\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{2};\tfrac{1}{3}\,0\,\tfrac{1}{2})'$	$\mathbf{2}'_{-5/3}$	1	+2	−6	−2	+4	+4	+8	−954	D_7	−212
T_4^+	$(\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6};\tfrac{-1}{6}\,\tfrac{1}{6}\,\tfrac{1}{2})(\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{2};\tfrac{-1}{6}\,\tfrac{1}{2}\,\tfrac{1}{2})'$	$\mathbf{2}'_{-5/3}$	2	−2	+2	+6	−8	+4	+8	−450	$2D_8$	−100
T_4^-	$(\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6};\tfrac{-1}{6}\,\tfrac{-1}{2}\,\tfrac{1}{6})(\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{1}{3}\,0;\tfrac{2}{3}\,0\,0)'$	$\mathbf{2}'_{5/3}$	2	−2	−6	+2	+8	−4	−8	−810	$2D_9$	−180
T_7^+	$(\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6};\tfrac{1}{3}\,\tfrac{2}{3}\,0)(\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{2};\tfrac{7}{12}\,\tfrac{1}{4}\,0)'$	$\mathbf{2}'_{5/3}$	1	+4	+8	0	+4	−5	+5	+1782	D_{10}	+396
T_7^+	$(\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6};\tfrac{-2}{3}\,\tfrac{-1}{3}\,0)(\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{6}\,\tfrac{1}{2};\tfrac{7}{12}\,\tfrac{1}{4}\,0)'$	$\mathbf{2}'_{5/3}$	1	−8	−4	0	+4	−5	+5	−990	D_{11}	−220
T_7^-	$(\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6}\,\tfrac{-1}{6};\tfrac{1}{3}\,0\,\tfrac{-1}{3})(\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{1}{3}\,0;\tfrac{5}{12}\,\tfrac{-1}{4}\,\tfrac{1}{2})'$	$\mathbf{2}'_{-5/3}$	1	+4	0	−4	+8	+5	−5	+234	D_{12}	+52
			$\sum_i Q(\mathbf{2}'_i)n(\mathbf{2}'_i) =$	−16	−28	+8	0	+18	+6	−6984	$\sum_i =$	−736

the same as that of the visible sector group SU(5), −6984. These hidden sector particles can carry the electromagnetic charges and they contribute to the coupling $\bar{c}_{a\gamma\gamma}$.

References

[1] P.A.R. Ade, et al., BICEP2 Collaboration, arXiv:1403.3985 [astro-ph.CO].
[2] J. Preskill, M.B. Wise, F. Wilczek, Phys. Lett. B 120 (1983) 127;
L.F. Abbott, P. Sikivie, Phys. Lett. B 120 (1983) 133;
M. Dine, W. Fischler, Phys. Lett. B 120 (1983) 137.
[3] J.E. Kim, Phys. Rep. 150 (1987) 1;
J.E. Kim, G. Carosi, Rev. Mod. Phys. 82 (2010) 511.
[4] J.E. Kim, Phys. Lett. B 734 (2014) 68, arXiv:1405.0221 [hep-th].
[5] S.-Y. Pi, Phys. Rev. Lett. 52 (1984) 1725;
M.P. Hertzberg, M. Tegmark, F. Wilczek, Phys. Rev. D 78 (2008) 083507, arXiv:0807.1726 [astro-ph].
[6] L. Visinelli, P. Gondolo, arXiv:1403.4594 [hep-ph];
D.J.E. Marsh, D. Grin, R. Hlozek, P.G. Ferreira, arXiv:1403.4216 [astro-ph.CO].
[7] P. Sikivie, Phys. Rev. D 32 (1985) 2988;
L. Krauss, J. Moody, F. Wilczek, D.E. Morris, Phys. Rev. Lett. 55 (1985) 1797;
J. Hong, J.E. Kim, S. Nam, Y. Semertzidis, arXiv:1403.1576 [hep-ph].
[8] D. Lyth, Phys. Rev. Lett. 78 (1997) 1861, arXiv:hep-ph/9606387.
[9] D. Lyth, arXiv:1403.7323 [hep-ph].
[10] K. Freese, J.A. Frieman, A.V. Olinto, Phys. Rev. Lett. 65 (1990) 3233.
[11] J.E. Kim, H.P. Nilles, M. Peloso, J. Cosmol. Astropart. Phys. 0501 (2005) 005, arXiv:hep-ph/0409138;
R. Kappl, S. Krippendorf, H.P. Nilles, arXiv:1404.7127 [hep-th];
K. Choi, H. Kim, S. Yun, arXiv:1404.6209 [hep-th].
[12] J.E. Kim, arXiv:1404.4022 [hep-ph].
[13] J.E. Kim, Phys. Rev. Lett. 111 (2013) 031801, arXiv:1303.1822 [hep-ph];
J.E. Kim, Phys. Lett. B 726 (2013) 450, arXiv:1308.0344 [hep-th];
J.E. Kim, H.P. Nilles, Phys. Lett. B 730 (2014) 53, arXiv:1311.0012 [hep-ph].
[14] A. Ashoorioon, H. Firouzjahi, M.M. Sheikh-Jabbari, J. Cosmol. Astropart. Phys. 0906 (2009) 018, arXiv:0903.1481 [hep-th].
[15] See, for example, D.K. Hazra, A. Shafieloo, G.F. Smoot, A.A. Starobinsky, arXiv:1404.0360 [astro-ph.CO];
K.-Y. Choi, B. Kyae, arXiv:1404.7855 [hep-th].
[16] E. Witten, Phys. Lett. B 149 (1984) 351.
[17] K. Choi, J.E. Kim, Phys. Lett. B 154 (1985) 393.

[18] J.E. Kim, Phys. Lett. B 207 (1988) 434.
[19] A. Casas, E.K. Kathehou, C. Munoz, Nucl. Phys. B 317 (1989) 171.
[20] J.E. Kim, Phys. Rev. Lett. 43 (1979) 103;
M.A. Shifman, V.I. Vainshtein, V.I. Zakharov, Nucl. Phys. B 166 (1980) 493.
[21] M. Dine, W. Fischler, M. Srednicki, Phys. Lett. B 104 (1981) 199;
A.P. Zhitnitsky, Sov. J. Nucl. Phys. 31 (1980) 260.
[22] K. Choi, J.E. Kim, Phys. Rev. Lett. 55 (1985) 2637;
S.M. Barr, K. Choi, J.E. Kim, Nucl. Phys. B 283 (1987) 591.
[23] J.-H. Huh, J.E. Kim, B. Kyae, Phys. Rev. D 80 (2009) 115012.
[24] J.-H. Huh, J.E. Kim, B. Kyae, arXiv:0904.1108 [hep-ph].
[25] For orbifold compactification and introduction to $\mathbf{Z}_{12-I}$, see K.-S. Choi, J.E. Kim, Quarks and Leptons from Orbifolded Superstring, Lect. Notes Phys., vol. 696, Springer, Heidelberg, 2006.
[26] J.E. Kim, B. Kyae, Nucl. Phys. B 770 (2007) 47, arXiv:hep-th/0608086.
[27] T. Kobayashi, S. Raby, R.-J. Zhang, Nucl. Phys. B 704 (2005) 3, arXiv:hep-ph/0409098;
For a review, see H.P. Nilles, S. Ramos-Sanchez, M. Ratz, P.K.S. Vaudrevange, Eur. Phys. J. C 59 (2009) 249, arXiv:0806.3905 [hep-th].
[28] G. Veneziano, Phys. Lett. B 128 (1983) 199;
I. Affleck, M. Dine, N. Seiberg, Nucl. Phys. B 256 (1985) 557;
E. Poppitz, S.P. Trivedi, Phys. Lett. B 365 (1996) 125.
[29] S. Ferrara, L. Girardello, H.P. Nilles, Phys. Lett. B 125 (1983) 457;
J.P. Derendinger, L.E. Ibañez, H.P. Nilles, Phys. Lett. B 155 (1985) 65;
M. Dine, R. Rohm, N. Seiberg, E. Witten, Phys. Lett. B 156 (1985) 55.
[30] L.E. Ibañez, J.E. Kim, H.P. Nilles, F. Quevedo, Phys. Lett. B 191 (1987) 282;
J.A. Casas, C. Munoz, Phys. Lett. B 214 (1988) 63.
[31] S.M. Barr, Phys. Lett. B 112 (1982) 219;
J.-P. Derendinger, J.E. Kim, D.V. Nanopoulos, Phys. Lett. B 139 (1984) 170.
[32] I. Antoniadis, J.R. Ellis, J.S. Hagelin, D.V. Nanopoulos, Phys. Lett. B 231 (1989) 65.
[33] P. Sikivie, Phys. Rev. Lett. 48 (1982) 1156.
[34] A.V. Manohar, C.P. Sachrajda, Quark masses, in J. Beringer, et al., Particle Data Group, Phys. Rev. D 86 (2012) 010001.
[35] J.E. Kim, Phys. Rev. D 58 (1998) 055006, arXiv:hep-ph/9802220.
[36] K.-S. Choi, I.-W. Kim, J.E. Kim, J. High Energy Phys. 0703 (2007) 116, arXiv:hep-ph/0612107.