THE STRONG *CP* PROBLEM IN ORBIFOLD COMPACTIFICATIONS AND AN SU(3)⊗SU(2)⊗U(1)^n MODEL

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We point out that the anomalous U(1)'s arising frequently in nonstandard embeddings of orbifold compactification is the needed Peccei–Quinn symmetry which can be broken at the intermediate scale We show this in an orbifold model with the minimal gauge group SU(3)⊗SU(2)⊗U(1)^n

1. Introduction

Recent four-dimensional string theories [1–4] seem to contain a phenomenologically satisfactory supersymmetric standard model In particular, the orbifold compactification with Wilson lines [5] is simple enough to pursue toward a supersymmetric standard model Indeed, chiral supersymmetric models with gauge group SU(3)⊗SU(2)⊗U(1)^n⊗ (hidden sector nonabelian gauge groups) have been obtained [6] Further study on three-generation models were obtained, but with extra unbroken hidden-sector nonabelian gauge groups [7]

Obviously, there are a few obstacles to overcome in this type of compactification as discussed by Casas et al [18] Among these problems, the most serious one seems to be the Yukawa coupling problem

In this paper, we discuss the strong *CP* problem in these orbifold compactifications [#1] Even though the orbifold models have not produced a realistic model so far, the strong *CP* problem can be attacked now This is because we know how to calculate the U(1) charges of the various U(1)'s arising in these compactifications

Another byproduct of this investigation is the construction of a three-generation SU(3)⊗SU(2)⊗U(1)$_Y$⊗U(1)^{11}⊗U(1)$_X$ model which is by far the simplest one in this category It does not include any extra unbroken nonabelian gauge group so that there would not appear the difficulty of the two-θ problem and any assumption on the condensation of fermions transforming nontrivially under the additional unbroken nonabelian gauge group to understand the strong *CP* problem

The strong *CP* problem in superstring models has been discussed previously [9,11–13] The discussion relies on the antisymmetric tensor field B_{MN} ($M,N=1,2,\ ,10$) In any compactification schemes, $B_{\mu\nu}$ ($\mu,\nu=1,\ ,4$) plays the role of an (model-independent) axion Depending on the compactification schemes, B_{mn} ($m,n=5,\ ,10$) can be an (model-dependent) axion or not However, the world-sheet instantons on some Calabi–Yau space compactifications remove B_{mn} from the light particle spectrum, excluding it from solving the strong *CP* problem [13] Also, the decay constant of the model-independent axion $B_{\mu\nu}$ is greater than 10^{15} GeV, which is not cosmologically favorable Thus the solution of the strong *CP* problem is not found in superstring models in the form originally conceived [9] There may arise approximate and acceptable global symmetries [14] which may solve the strong *CP* problem as studied in ref [15]

There is one important aspect in the whole discussion This is the nonlinearly realized 't Hooft mechanism

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[#1] For the Calabi–Yau space compactifications, it has been studied previously [9] The $D=10$, $N=1$ field theory study can be found in ref [10]

[16] The first example in the literature appeared in the monopole compactification of Witten [17,9] Here, we present the second example It has been known previously [9,17], but the present study of U(1) charges make it possible to figure out to see its realization The essence is the following In some nonstandard orbifold compactifications, one encounters an anomalous U(1) gauge group, which has been noticed before [18,6] This anomalous U(1) gauge boson obtains a mass through the Green–Schwarz term [18,6] Then, there results a global symmetry below the compactification scale which we interpret as the Peccei–Quinn symmetry

2. Model building with orbifolds

Model building on orbifold is well known by now [1–8,19,20] Here, we use the notation given in refs [5–8] Our model employs the phenomenologically desirable Z_3 orbifold [3] It needs a shift vector v^I and Wilson lines a_i^I where $i=1,2, \quad 6$ and $I=1,2, \quad ,16$ In fact, there are only three independent Wilson lines

$$a_i^I = a_{i+1}^I , \quad i=1,3,5 , \tag{1}$$

because a rotation by $2\pi/3$ relates two SU(3) lattice vectors The Z_3 orbifold has 27 fixed points These v^I and a_i^I must satisfy the modular invariance condition

$$3(v^I + n_i a_i^I)^2 = 2m, \quad n_i = 0, \pm 1, \quad m \in \mathbb{Z} \tag{2}$$

There are two types of closed strings, untwisted and twisted Untwisted strings are closed on tori Twisted strings propagate around one of the fixed points Thus, there are twenty-seven twisted sectors We denote the twisting in the positive direction as $v^I \pm a_i^I \pm \quad$ and their *CPT* conjugates as $-(v^I \pm a_i^I \pm \quad)$ We have the following constraints for massless modes

gauge multiplet (untwisted sector)

$$p^2 = 2, \quad p^I v^I = \text{integer}, \quad p^I a_i^I = \text{integer}, \quad \text{for all } i , \tag{3a,b,c}$$

matter from untwisted sector

$$p^2 = 2, \quad p^I v^I = \tfrac{1}{3} \text{ mod integer}, \quad p^I a_i^I = \text{integer}, \quad \text{for all } i, \tag{4a,b,c}$$

matter from twisted sector

$$(p^I + v^I + \quad)^2 = \tfrac{4}{3}, \quad \text{for multiplicity} = 1, \quad (p^I + v^I + \quad)^2 = \tfrac{2}{3}, \quad \text{for multiplicity} = 3 \tag{5a,b}$$

Without any nonvanishing a_i, there is only one kind of twisting (v^I) and hence twenty-seven fixed points are identical With one nonvanishing a_i (e g $a_1^I = a_2^I \neq 0$) twisting is grouped into three (v^I, $v^I + a_1^I$, and $v^I - a_1^I$) and hence twenty-seven fixed points are divided into three groups with nine identical copies in each group The model we present here employs three nonvanishing a_i ($a_1^I = a_2^I$, $a_3^I = a_4^I$, $a_5^I = a_6^I$), and hence all twenty-seven fixed points are distinguished

3 The model and U(1) charges

We take the embedding

$$(v^I) = (\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{2}{3}\,0\,\tfrac{1}{3}\,\tfrac{1}{3})\,(\tfrac{1}{3}\,\tfrac{1}{3}\,0\,0\,0\,\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{2}{3}) , \quad (a_1^I) = (\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{2}{3}\,\tfrac{1}{3}\,0\,0\,0)\,(0\,0\,0\,0\,0\,\tfrac{2}{3}\,0\,0) ,$$
$$(a_3^I) = (0\,0\,0\,0\,0\,0\,0\,\tfrac{2}{3})\,(\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{1}{3}\,\tfrac{2}{3}\,0\,0\,0\,\tfrac{1}{3}) , \quad (a_5^I) = (0\,0\,0\,0\,0\,0\,0\,\tfrac{2}{3})\,(0\,\tfrac{1}{3}\,\tfrac{1}{3}\,0\,0\,0\,0\,0) \tag{6}$$

It can be easily checked that the modular invariance condition (2) is satisfied

The untwisted sector gives the gauge bosons and the gauginos

$$p=\pm(\underline{1,-1,0},0,0,0,0,0)(0,0,0,0,0,0,0,0)\,,\quad p=\pm(0,0,0,1,1,0,0,0)(0,0,0,0,0,0,0,0)\,,$$

where the underlining of the numbers means that all permutations are included These roots correspond to

$$SU(3)\otimes SU(2)\otimes U(1)^5\otimes[U(1)^8]' \tag{7}$$

The matter fields from the untwisted sector (UT) are

$$p=(\underline{1,0,0},1,0,0,0,0)(0,0,0,0,0,0,0,0)\,,\quad p=(\underline{1,0,0},0,-1,0,0,0)(0,0,0,0,0,0,0,0)\,, \tag{8a}$$

plus $3\times8=24$ singlets The representation (8a) corresponds to

$$3(3^*,2) \tag{8b}$$

under $SU(3)\otimes SU(2)$

Twenty-seven twisted sectors are denoted as

$$\begin{aligned}
&TT=v, && TNT1=v+a_1, && TNT2=v-a_1,\\
&TNT3=v+a_3, && TNT4=v-a_3, && TNT5=v+a_5,\\
&TNT6=v-a_5, && TNT7=v+a_1+a_3, && TNT8=v+a_1-a_3,\\
&TNT9=v-a_1+a_3, && TNT10=v-a_1-a_3, && TNT11=v+a_1+a_5,\\
&TNT12=v+a_1-a_5, && TNT13=v-a_1+a_5, && TNT14=v-a_1-a_5,\\
&TNT15=v+a_3+a_5, && TNT16=v+a_3-a_5, && TNT17=v-a_3+a_5,\\
&TNT18=v-a_3-a_5, && TNT19=v+a_1+a_3+a_5, && TNT20=v+a_1+a_3-a_5,\\
&TNT21=v+a_1-a_3+a_5, && TNT22=v+a_1-a_3-a_5, && TNT23=v-a_1+a_3+a_5,\\
&TNT24=v-a_1+a_3-a_5, && TNT25=v-a_1-a_3+a_5, && TNT26=v-a_1-a_3-a_5
\end{aligned} \tag{9}$$

For example, TNT8 contains the twisting wrapped with Wilson lines

$$(v^I+a_1^I-a_3^I)=(\tfrac{2}{3},\tfrac{2}{3},\tfrac{2}{3},1,1,0,\tfrac{1}{3},-\tfrac{1}{3})(0,0,-\tfrac{1}{3},-\tfrac{2}{3},0,1,\tfrac{1}{3},\tfrac{1}{3}) \tag{10}$$

With (10), the following (p^I) satisfies eq (5a),

$$(p^I)=(\underline{-1,-1,0},-1,-1,0,0,0)(0,0,0,1,0,-1,0,0)\,, \tag{11}$$

which is $(3^*,1)$ representation under $SU(3)\otimes SU(2)$ In this way all the massless matter fields are obtained Putting the contributions from all the sectors, we obtain

$$3\{(3,2)+2(3^*,1)+(1,2)+\mathbf{1}\}+12(1,2)+216\cdot\mathbf{1}=285\,, \tag{12}$$

where we have taken the opposite chiralities of the untwisted and twisted sectors This model contains three chiral fermion generations, 12 Higgs doublets and 216 singlets But there is no extra nonabelian gauge group

Thirteen U(1)'s are labelled by

$$\begin{aligned}
&U_1\ \ (11100000)(0\ \ 0)', && U_2\ \ (0001-1000)(0\ \ 0)', && U_3\ \ (00000100)(0\ \ 0)',\\
&U_4\ \ (00000010)(0\ \ 0)', && U_5\ \ (00000001)(0\ \ 0)', && U_6\ \ (0\ \ 0)(10000000)',\\
&U_7\ \ (0\ \ 0)(01000000)', && U_8\ \ (0\ \ 0)(00100000)', && U_9\ \ (0\ \ 0)(00010000)',\\
&U_{10}\ \ (0\ \ 0)(00001000)', && U_{11}\ \ (0\ \ 0)(00000100)', && U_{12}\ \ (0\ \ 0)(00000010)',\\
&U_{13}\ \ (0\ \ 0)(00000001)'
\end{aligned} \tag{13}$$

Table 1
U(1) charges of the colored matter fields Properly normalized U(1) charges are obtained from $Q_1 \sim Q_{13}$ dividing by $6\sqrt{2}N_i$ where $N_1=\sqrt{3}$, $N_2=\sqrt{2}$, and $N_3=N_4= \; =N_{13}=1$ X is the anomalous global charge which is interpreted as the Peccei–Quinn charge Y is a possible $U(1)_Y$ assignment for the standard model

SU(3)⊗SU(2)	Sector	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}	Q_{11}	Q_{12}	Q_{13}	X	Y
3(3,2)	UT	−6	−6	0	0	0	0	0	0	0	0	0	0	0	−15	$\frac{1}{6}$
(3*,1)	TNT1	0	0	0	2	2	2	2	0	0	0	0	2	−2	−5	$\frac{1}{3}$
(3*,1)	TNT8	0	0	0	2	−2	0	0	−2	2	0	0	2	2	−5	$-\frac{2}{3}$
(3*,1)	TNT12	0	0	0	2	−2	2	0	−2	0	0	0	2	−2	−5	$-\frac{2}{3}$
(3*,1)	TNT19	0	0	0	2	−2	−2	0	−2	−2	0	0	2	0	−5	$-\frac{2}{3}$
(3*,1)	TNT20	0	0	0	2	2	−2	2	0	−2	0	0	2	0	−5	$\frac{1}{3}$
(3*,1)	TNT21	0	0	0	2	2	0	2	0	2	0	0	2	2	−5	$\frac{1}{3}$
	sum	−36	−36	0	12	0	0	6	−6	0	0	0	12	0	−120	0

Table 2
U(1) charges of the doublet matter fields which consist of the three lepton doublets and twelve Higgs doublets Notation is the same as table 1

SU(3)⊗SU(2)	Sector	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}	Q_{11}	Q_{12}	Q_{13}	X	Y
3(3,2)	UT	−6	−6	0	0	0	0	0	0	0	0	0	0	0	−15	$\frac{1}{6}$
(1,2)	TNT1	3	0	−3	−1	−1	2	2	0	0	0	0	2	−2	1	$\frac{1}{2}$
(1,2)	TNT8	3	0	3	−1	1	0	0	−2	2	0	0	2	2	1	$-\frac{1}{2}$
(1,2)	TNT9	0	2	0	2	0	−2	−2	2	−2	0	−2	2	0	1	$\frac{1}{2}$
(1,2)	TNT9	0	2	0	2	0	1	1	−1	1	3	1	−1	3	1	$-\frac{1}{2}$
(1,2)	TNT9	0	2	0	2	0	1	1	−1	1	−3	1	−1	−3	1	$-\frac{1}{2}$
(1,2)	TNT12	3	0	3	−1	1	2	0	−2	0	0	0	2	−2	1	$-\frac{1}{2}$
(1,2)	TNT13	0	2	0	2	0	2	−2	2	0	0	−2	2	−2	1	$\frac{1}{2}$
(1,2)	TNT13	0	2	0	2	0	−1	1	−1	3	−3	1	−1	1	1	$-\frac{1}{2}$
(1,2)	TNT13	0	2	0	2	0	−1	1	−1	−3	3	1	−1	1	1	$-\frac{1}{2}$
(1,2)	TNT19	3	0	3	−1	1	−2	0	−2	−2	0	0	2	0	1	$-\frac{1}{2}$
(1,2)	TNT20	3	0	−3	−1	−1	−2	2	0	−2	0	0	2	0	1	$\frac{1}{2}$
(1,2)	TNT21	3	0	−3	−1	−1	0	2	0	2	0	0	2	2	1	$\frac{1}{2}$
(1,2)	TNT26	0	2	0	2	0	0	−2	2	2	0	−2	2	2	1	$\frac{1}{2}$
(1,2)	TNT26	0	2	0	2	0	−3	1	−1	−1	−3	1	−1	−1	1	$-\frac{1}{2}$
(1,2)	TNT26	0	2	0	2	0	3	1	−1	−1	3	1	−1	−1	1	$-\frac{1}{2}$
	sum	−36	−36	0	12	0	0	6	−6	0	0	0	12	0	−120	0

It is easy to calculate the U(1) charges For example, the representation (11) has $(p+v+a_1-a_3)=(-\frac{1}{3}-\frac{1}{3}\frac{2}{3}000\frac{1}{3}-\frac{1}{3})(00-\frac{1}{3}\frac{1}{3}00\frac{1}{3}\frac{1}{3})$, and hence has $Q_1=0$, $Q_2=0$, $Q_3=0$, $Q_4=2$, $Q_5=-2$, etc , which is shown in table 1 We have calculated all thirteen U(1) charges for 285 chiral fields Among these, we present U(1) charges for quarks and SU(2) doublet representations in table 1 and table 2, respectively

4. The anomalous $U(1)_X$ and the electroweak $U(1)_Y$

In addition to tables 1 and 2, we also have

$$\mathrm{Tr}\,Q_1=-432,\quad \mathrm{Tr}\,Q_2=-432,\quad \mathrm{Tr}\,Q_4=144,\quad \mathrm{Tr}\,Q_7=72,\quad \mathrm{Tr}\,Q_8=-72,\quad \mathrm{Tr}\,Q_{12}=144 \tag{14}$$

The other seven U(1)'s are anomaly-free Out of the anomalous U(1)'s given in (14), we can construct five anomaly-free combinations

$$P_1=(1/\sqrt{10})(Q_1-Q_2),\quad P_2=\tfrac{1}{2}(Q_7+Q_8),\quad P_3=\tfrac{1}{2}(Q_4-Q_{12}), \tag{15a,b,c}$$

$$P_4=(1/\sqrt{5})(\tfrac{1}{2}Q_4-Q_7+Q_8+\tfrac{1}{2}Q_{12}),\quad P_5=(1/\sqrt{60})(Q_1+\tfrac{3}{2}Q_2+3Q_4+\tfrac{3}{2}Q_7-\tfrac{3}{2}Q_8+3Q_{12}) \tag{15d,e}$$

The other seven anomaly-free U(1)'s with proper normalization are called $\tilde{Q}_3$, $\tilde{Q}_5$, $\tilde{Q}_6$, $\tilde{Q}_9$, $\tilde{Q}_{10}$, $\tilde{Q}_{11}$, and $\tilde{Q}_{13}$, i e , $\tilde{Q}_3=Q_3/\sqrt{2}$, etc The remaining U(1) which is orthogonal to the above twelve anomaly-free U(1)'s is called $U(1)_X$,

$$X=Q_1+\tfrac{3}{2}Q_2-Q_4-\tfrac{1}{2}Q_7+\tfrac{1}{2}Q_8-Q_{12} \tag{16}$$

This U(1) gauge boson obtains a mass through the Green–Schwarz term, eating the model-independent axion from, e g

$$\epsilon^{\mu\nu\rho\sigma mnpqrs}B_{\mu\nu}\,\mathrm{Tr}\,F^X_{\rho\sigma}\langle F_{mn}\rangle\,\mathrm{Tr}\,\langle F_{pq}\rangle\langle F_{rs}\rangle \tag{17}$$

Thus the anomalous X symmetry becomes the global symmetry and the theory is renormalizable below the compactification scale This is the so-called 't Hooft mechanism [16] Except the gauge boson mass term (17), the Yukawa couplings respect the X symmetry Thus the X symmetry in the form of global one must exist below the scale defined by eq (17) Because the matter fields are singlets under the shift of the model independent axion, the global X charge is the same as the original anomalous gauge charge These X quantum numbers of the model are also shown in tables 1 and 2 From table 1, we note that it is the Peccei–Quinn symmetry, and when the X symmetry is broken at the intermediate scale, the strong CP problem can be solved

We also note

$$\mathrm{Tr}\,X\tilde{Q}_i=\mathrm{Tr}\,XP_j=-2160,\quad \mathrm{Tr}\,X=-1440, \tag{18,19}$$

where $i=3, 5, 6, 9, 10, 11$ and 13, and $j=1$–5 To compare with $\mathrm{Tr}\,X\,\mathrm{SU}(3)^2=\mathrm{Tr}\,X\,\mathrm{SU}(2)^2=-60$ obtained from tables 1 and 2, eq (18) should be divided by $(6)^2$ because U(1) charges in these tables are multiplied by $6\sqrt{2}$ Thus we agree with the observations of refs [8,18],

$$\partial^\mu J^X_\mu=-(60/32\pi^2)(G^a_{\mu\nu}\tilde{G}^{a\mu\nu}+W^i_{\mu\nu}\tilde{W}^{i\mu\nu}+F^p_{\mu\nu}\tilde{F}^{p\mu\nu}-R\tilde{R}), \tag{20}$$

where $G^a_{\mu\nu}$, $W^i_{\mu\nu}$, and $F^p_{\mu\nu}$ are gluon, the SU(2) and twelve properly normalized U(1) field strengths

One possible electroweak hypercharge is

$$Y=-\tfrac{16}{225}Q_1+\tfrac{13}{300}Q_2-\tfrac{19}{150}Q_4-\tfrac{23}{150}Q_7+\tfrac{26}{75}Q_8+\tfrac{7}{50}Q_{12} \tag{21}$$

For quarks and SU(2) doublets, it is shown in tables 1 and 2 However, this hypercharge assignment is not successful, because it leads to weird charges for singlet fields Nevertheless, (21) gives nine $Y=+1$ singlets, three $Y=-1$ singlets, nine $Y=0$ singlets from the untwisted sector, and eighteen $Y=0$ singlets from the twisted sectors $Y=+1$ singlets contain the charged leptons All the $Y=0$ singlets carry nonvanishing X charges and hence when these singlets obtain nonvanishing VEV's at an intermediate scale the Peccei–Quinn symmetry can be broken and the invisible axion can result [#2] However, the problem is whether these $Y=0$ singlets repeat the 't Hooft mechanism or not In our model, there are enough $Y=0$ singlets (more than eleven corresponding to U(1) gauge groups which must be broken above the electroweak scale), and the breaking of the Peccei–Quinn symmetry at an intermediate scale is a possibility The remaining 180 singlets carry funny hypercharges Thus this model cannot be realistic However, we found that there are many more choices for Y in which all the quarks have the desired hypercharges Then in this case, the SU(2) doublets have so many possibilities for acceptable Y for which we did not exhaust all the alternatives One of these may not allow weird singlet charges

Naively, one would expect the vacuum degeneracy of 120 (see table 1) because the minimum $|X|$ quantum number for the 285 chiral fields is 1 However, the invisible axion model presented here has the domain-wall number $N_{DW}=1$ because the model-independent axion connects the degenerate vacua as discussed in refs [22,12] Here, we have an example in which a "naive" domain-wall problem in gauge theories may not be a problem in the full theory The axion decay constant problem, $F_a \lesssim 2\times 10^{11}$ GeV, is equivalent to $\mathrm{VEV}=120F_a \lesssim 2.4\times 10^{13}$ GeV (if one Higgs field breaks the X symmetry) which is closer to the GUT scale

5. Conclusion

We have shown explicitly by constructing and $SU(3)\otimes SU(2)\otimes U(1)_Y\otimes U(1)^{11}\otimes U(1)_X$ orbifold model that the nonstandard embedding with anomalous U(1)'s leads to the global symmetry below the compactification scale This global symmetry is the much needed Peccei–Quinn symmetry for the strong CP solution in string models There are enough $SU(3)\otimes SU(2)\otimes U(1)_Y$ singlets to assign nonvanishing VEV at an intermediate scale This solution is the type encountered in gauge theory models and any string effects will not remove the resulting invisible axion from the low energy spectrum

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[#2] For a review, see refs [11,21]

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