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$\mathcal{CP}$ violation from string theory

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ABSTRACT

We identify a natural way to embed $\mathcal{CP}$ symmetry and its violation in string theory. The $\mathcal{CP}$ symmetry of the low energy effective theory is broken by the presence of heavy string modes. $\mathcal{CP}$ violation is the result of an interplay of $\mathcal{CP}$ and flavor symmetry. $\mathcal{CP}$ violating decays of the heavy modes could originate a cosmological matter-antimatter asymmetry.

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1. Introduction

Aspects of $\mathcal{CP}$ symmetry and its violation play a crucial role in several physics phenomena. This includes the question of $\mathcal{CP}$ symmetry in strong interactions (the so-called strong $\mathcal{CP}$ problem), the violation of $\mathcal{CP}$ in the Yukawa sector of the standard model (SM) (with at least 3 families of quarks and leptons) and the desire for a source of $\mathcal{CP}$ violation (CPV) in the process of a dynamical creation of the cosmological matter-antimatter asymmetry. We are thus confronted with the following questions: What is the origin of $\mathcal{CP}$ symmetry and its violation? Is there a relation to the flavor symmetries in the SM of particle physics? Is there a "theory of $\mathcal{CP}$" in the ultraviolet completion of the SM that explains both the origin of $\mathcal{CP}$ symmetry and its breakdown?

In the present letter we try to address these questions about $\mathcal{CP}$ and flavor symmetries in the framework of string theory. Our approach to a "theory of $\mathcal{CP}$" is based on orbifold compactifications of heterotic string theory (the so-called MiniLandscape [1–4]) but should be valid qualitatively for a wide range of string theory constructions. From our exploration of these models the following general picture emerges:

- we find $\mathcal{CP}$ candidates strongly connected to flavor symmetries, specifically $\mathcal{CP}$ as an outer automorphism of the flavor group;
- the light ("massless") string spectrum results in a low-energy effective field theory with a well-defined $\mathcal{CP}$ transformation, which can be conserved only in the absence of couplings to the heavy modes;
- the presence of heavy modes (here the winding modes of string theory) initiates a breakdown of $\mathcal{CP}$ (similar to the picture of "explicit geometrical $\mathcal{CP}$ violation");
- $\mathcal{CP}$ violating decays of the heavy (winding) modes could induce the cosmological matter-antimatter asymmetry. Other possible CPV effects can be induced through couplings of light fields to the heavy modes.

This provides us with a picture where the source of $\mathcal{CP}$ breakdown is already included within the construction of the symmetry itself. It also shows that the breakdown of $\mathcal{CP}$ requires a certain amount of complexity of the theory (reminiscent of the need of three families in the CKM case).

The origin of $\mathcal{CP}$ violation in the context of string theory and extra dimensions has been discussed in many regards, see [5] for a review and references therein. Our approach is new in the following sense: While it has been known that extra dimensions provide an origin of discrete (flavor) symmetries [6–8], a more recent insight, based on the original idea of "explicit geometrical $\mathcal{CP}$ violation" [9], is that a large class of discrete groups is generally incompatible with $\mathcal{CP}$ [10]. This comes about because these groups do not allow for complex conjugation outer automorphisms which, however, correspond to physical $\mathcal{CP}$ transformations in the most general sense [11,12]. In these cases, $\mathcal{CP}$ is explicitly violated by phases which are discrete and calculable because they originate from the complex Clebsch–Gordan coefficients of the respective flavor group. The main progress in this letter is to demonstrate that such a situation arises naturally in string theory.

As a specific example we consider a $\mathbb{Z}_3$ orbifold with flavor group $\Delta(54)$ that appears naturally in the MiniLandscape construc-

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tions [6]. In this case, $\mathcal{CP}$ should be a subgroup of S_4, the group of outer automorphisms of $\Delta(54)$; thus flavor group and $\mathcal{CP}$ are intimately related. The irreducible representations of $\Delta(54)$ include singlets, doublets, triplets and anti-triplets. The massless spectrum of the theory, however, contains only singlets and triplets (as well as anti-triplets) of $\Delta(54)$. This allows for a $\mathcal{CP}$ symmetric low-energy effective field theory of the massless states. The presence of the heavy winding modes that transform as doublets of $\Delta(54)$ leads to an obstruction for the definition of $\mathcal{CP}$ symmetry thereby realizing the mechanism of "explicit geometrical $\mathcal{CP}$ violation". All $\mathcal{CP}$ violating effects originate through couplings of the light states to at least three non-trivial doublets. $\mathcal{CP}$ violating decays of the heavy doublets are a generic property of the scheme. Combined with baryon- and/or lepton-number violation this could lead to a cosmological baryon- and/or lepton asymmetry.

2. $\Delta(54)$ flavor symmetry from string theory and the light spectrum

In order to understand the origin of $\Delta(54)$ from strings it is sufficient to concentrate on the compactification of two extra dimensions on a $\mathbb{T}^2/\mathbb{Z}_3$ orbifold. For a full string model this $\mathbb{T}^2/\mathbb{Z}_3$ can easily be extended to a six-dimensional orbifold, e.g. $\mathbb{T}^6/\mathbb{Z}_3 \times \mathbb{Z}_3$.

Geometrically, a $\mathbb{T}^2/\mathbb{Z}_3$ orbifold can be defined in two steps: (i) one defines a torus $\mathbb{T}^2$ by specifying a lattice $\Lambda = \{n_1 e_1 + n_2 e_2 \,|\, n_i \in \mathbb{Z}\}$, spanned by the vectors e_1 and e_2. We choose $|e_1| = |e_2|$ and the angle between e_1 and e_2 is set to 120°. (ii) one identifies points on $\mathbb{T}^2$ that differ by a 120° rotation generated by θ. The resulting orbifold has the shape of a triangular pillow, see Fig. 1 and 2.

Closed strings on the $\mathbb{T}^2/\mathbb{Z}_3$ orbifold come in three classes: (i) trivially closed strings, which are closed even in uncompactified space, (ii) winding strings with winding numbers n_1 and n_2 in the torus directions e_1 and e_2, respectively, and (iii) twisted strings, which are closed only up to a θ^k rotation for $k = 1, 2$. For $k = 1$ or $k = 2$ they belong to the so-called first or second twisted sector, respectively. On the other hand, trivially closed strings and winding strings belong to the so-called untwisted sector and live in the bulk of the orbifold. In contrast, twisted strings are localized at the three corners (fixed points) of the $\mathbb{T}^2/\mathbb{Z}_3$ orbifold. For $k = 1, 2$, they are created by twisted vertex operators which we label as

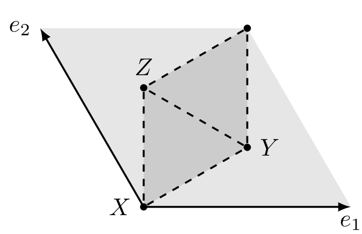

Fig. 1. $\mathbb{T}^2/\mathbb{Z}_3$ orbifold with fixed points X, Y, Z. The fundamental domain is shaded in dark gray.

$$\chi^{(\mathbf{3}_1)} \sim \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}, \quad \text{and} \quad \psi^{(\bar{\mathbf{3}}_1)} \sim \begin{pmatrix} \bar{X} \\ \bar{Y} \\ \bar{Z} \end{pmatrix}, \tag{1}$$

respectively (compared to Ref. [13] we set $X = \sigma_0^+$, $Y = \sigma_1^+$, $Z = \sigma_2^+$ and $\bar{X} = \sigma_0^-$, $\bar{Y} = \sigma_1^-$, $\bar{Z} = \sigma_2^-$).

Interactions of strings on orbifolds are restricted by selection rules. In the case of $\mathbb{T}^2/\mathbb{Z}_3$ the point group (PG) and space group (SG) selection rules result in a $\mathbb{Z}_3^{\mathrm{PG}} \times \mathbb{Z}_3^{\mathrm{SG}}$ symmetry [14]. Massless untwisted strings transform trivially, while twisted strings transform as

$$\chi^{(\mathbf{3}_1)} \xmapsto{\mathbb{Z}_3^{\mathrm{PG}}} \mathrm{diag}(\omega, \omega, \omega)\ \chi^{(\mathbf{3}_1)}\,, \tag{2a}$$

$$\chi^{(\mathbf{3}_1)} \xmapsto{\mathbb{Z}_3^{\mathrm{SG}}} \mathrm{diag}(1, \omega, \omega^2)\ \chi^{(\mathbf{3}_1)}\,, \tag{2b}$$

$$\psi^{(\bar{\mathbf{3}}_1)} \xmapsto{\mathbb{Z}_3^{\mathrm{PG}}} \mathrm{diag}(\omega^2, \omega^2, \omega^2)\ \psi^{(\bar{\mathbf{3}}_1)}\,, \tag{2c}$$

$$\psi^{(\bar{\mathbf{3}}_1)} \xmapsto{\mathbb{Z}_3^{\mathrm{SG}}} \mathrm{diag}(1, \omega^2, \omega)\ \psi^{(\bar{\mathbf{3}}_1)}\,, \tag{2d}$$

where $\omega := e^{2\pi i/3}$. In the absence of non-trivial backgrounds on $\mathbb{T}^2/\mathbb{Z}_3$ there is in addition an S_3 symmetry corresponding to all permutations of the three twisted strings. Combining this symmetry with the PG and SG symmetries, one obtains a $\Delta(54)$ flavor symmetry, see Appendix A. Massless untwisted strings transform as trivial singlets $\mathbf{1}_0$, while the twisted strings $\chi^{(\mathbf{3}_1)}$ and $\psi^{(\bar{\mathbf{3}}_1)}$ transform as $\mathbf{3}_1$ and $\bar{\mathbf{3}}_1$ of $\Delta(54)$, respectively [6,8].

3. $\Delta(54)$ and explicit geometrical $\mathcal{CP}$ violation

Let us discuss some details of $\Delta(54)$ and how this group can lead to the phenomenon of explicit geometrical $\mathcal{CP}$ violation. The non-trivial irreps of $\Delta(54)$ are the real $\mathbf{1}_1$, a quadruplet of real doublets $\mathbf{2}_{k=1,2,3,4}$ as well as the faithful complex triplets $\mathbf{3}_1$, $\mathbf{3}_2$ and their respective complex conjugates $\bar{\mathbf{3}}_1$ and $\bar{\mathbf{3}}_2$. Tensor products relevant to this work are

$$\mathbf{3}_i \otimes \bar{\mathbf{3}}_i = \mathbf{1}_0 \oplus \mathbf{2}_1 \oplus \mathbf{2}_2 \oplus \mathbf{2}_3 \oplus \mathbf{2}_4\,, \tag{3a}$$

$$\mathbf{2}_k \otimes \mathbf{2}_k = \mathbf{1}_0 \oplus \mathbf{1}_1 \oplus \mathbf{2}_k\,. \tag{3b}$$

The outer automorphism group (Out) of $\Delta(54)$ is

$$\mathrm{Out}\,[\Delta(54)] \cong S_4\,, \tag{4}$$

the permutation group of four elements. On the four doublets, S_4 acts as all possible permutations. On the triplets, odd permutations in S_4 act as complex conjugation, while even permutations in S_4 map the triplets to themselves [12]. In addition, all these transformations are typically endowed with matrices that act on the representations internally.

A physical $\mathcal{CP}$ transformation maps all fields of a theory in some irreps $\boldsymbol{r}$ to their respective complex conjugate fields, which transform in $\boldsymbol{r}^*$ [12]. Therefore, a physical $\mathcal{CP}$ transformation

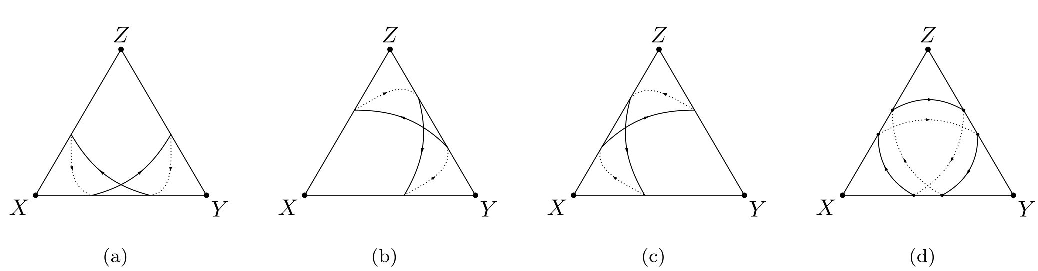

Fig. 2. Illustration of the geometrical winding strings. For example, (a), (b), and (c) depict the winding modes from $X\bar{Y}$, $Y\bar{Z}$, and $Z\bar{X}$ which all have winding number $N = 2$.

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