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Z_2 Orbifold-Prime Model of $N = 2$ Superconformal Theories with $c = 3$

Sayipjamal Dulat

(Institute of High Energy Physics, The Chinese Academy of Sciences, Beijing 100039, China)

Abstract We consider $N = 2$ superconformal field theories on a two dimensional torus with central charge $c = 3$. In particular, we present the partition function for this theory. Furthermore, to generate new theories, we recall general orbifold prescription. At last, we construct the modular invariant Z_2 orbifold-prime model.

Key words conformal field theory, orbifold, partition function

1 Introduction

The complete understanding of the moduli space of $N = 2$ superconformal field theories with central charge $c = 3$ needs a description of all its orbifold theories. The $N = 2$ superconformal Z_M orbifolds were given in Ref. [7]. When fermions are omitted from the $c = 3$ superconformal theories, one obtains $c = 2$ bosonic theories that are given in Ref. [8].

The $N = 2$ superconformal field theories with $c = 3$[1] are described by a free chiral scalar superfield containing two real bosons or a single complex left (right) boson $\varphi^{\pm}(z) = \varphi^1(z) \pm i\varphi^2(z)(\overline{\varphi}^{\pm}(\overline{z}) = \overline{\varphi}^1(\overline{z}) \pm i\overline{\varphi}^2(z))$ (each of $c = 1$) and two Majorana-Weyl (MW) fermions or a free complex left(right) fermion $\psi^{\pm}(z) = \psi^1(z) \pm i\psi^2(z)(\overline{\psi}^{\pm}(\overline{z}) = \overline{\psi}^1(\overline{z}) \pm i\overline{\psi}^2(\overline{z}))$ $\left(\text{each of } c = \frac{1}{2}\right)$. The action for this system may be written as

$$S = \frac{1}{2\pi}\int d^2 z(G_{ij}\,\partial\varphi^i\,\overline{\partial}\varphi^j + B_{ij}\,\partial\varphi^i\,\overline{\partial}\varphi^j + \psi^-\,\overline{\partial}\,\psi^+ + \psi^+\,\overline{\partial}\,\psi^-). \tag{1}$$

In string theory language, this action corresponds to the superstring compactification on a two dimensional torus $T^2 = R^2/\Lambda$. For the two dimensional lattice Λ, we use a basis $\{e_i\} \in Z(i = 1,2)$. The action (1) depends on four real parameters or moduli, the constant symmetric metric $G_{ij} = \frac{1}{2}e_i e_j$ on T^2, and the antisymmetric tensor field $B_{ij} = -B_{ji}$. It has $N = 2$ superconformal symmetry. Directly from the action, we can determine the generators of the $N = 2$ superconformal algebra, the stress-energy tensor $T(z)$, its super partners $Q^i(z) = Q^1(z) \pm iQ^2(z)$ $(i = 1,2)$, and the $U(1)$ current $J(z)$ with conformal dimensions h equal to 2, 3/2 and 1, respectively,

$$\begin{aligned} T(z) &= -\frac{1}{2}\,\partial\varphi^-(z)\,\partial\varphi^+(z) - \\ &\quad \frac{1}{4}\psi^-\,\partial\psi^+(z) - \frac{1}{4}\psi^+(z)\,\partial\psi\ \ (z), \\ Q^{\pm}(z) &= \psi^{\mp}(z)\,\partial\varphi^{\pm}(z), \\ &\quad (z)\psi^+(z) \end{aligned} \tag{2}$$

$$\sum_{n=-\infty}^{+\infty} L_n z^{-n-2},$$

$$Q^i(z) = \sum_{r=-\infty}^{+\infty} Q_r z^{-r-3/2}$$

$$J(z) = \sum_{n=-\infty}^{+\infty} J_n z^{-n-1},$$

and satisfy $N = 2$ superconformal algebra that can be found

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in Refs. [1,12].

The partition function for the $N=2$ superconformal theories with $c=3$ is constructed by tensoring the theory of a complex free boson defined on a 2-dimentional torus T^2 in the presence of constant background fields, with the theory of a single complex Dirac fermion, namely

$$Z(\tau,\rho,z):=Z(\tau,\rho,\sigma)Z_{\text{Dirac}}(\sigma,z).$$

In the following we briefly discuss how the explicit expression of $Z(\tau,\rho,z)$ can be formulated. The $Z(\tau,\rho,\sigma)$ is the modular invariant partition function for two real boson compactified on the two dimensional torus[9],

$$Z(\tau,\rho):=Z(\tau,\rho,\sigma)=\operatorname{tr} q^{L_0^b-\frac{1}{12}}\bar{q}^{\bar{L}_0^b-\frac{1}{12}}=\frac{1}{|\eta^2(\sigma)|^2}\sum_{\substack{n_1,m_1\\n_2,m_2}}q^{\frac{p^2}{2}}\bar{q}^{\frac{\bar{p}^2}{2}}, \tag{3}$$

where $q=e^{2\pi i\sigma}$, $\sigma=\sigma_1+i\sigma_2$ parametrizes the world sheet torus, and $\eta(\sigma)$ is the Dedekind eta function defined as

$$\eta(\sigma)=q^{\frac{1}{24}}\prod_{n=1}^{\infty}(1-q^n).$$

The Virasoro zero mode operators for the bosons in Eq. (3) are given by

$$L_0^b=\sum_{n>0}\alpha_{-n}^i\alpha_n^i+\frac{1}{2}p^2,\qquad \bar{L}_0^b=\sum_{n>0}\bar{\alpha}_{-n}^i\bar{\alpha}_n^i+\frac{1}{2}\bar{p}^2. \tag{4}$$

The left-right moving zero mode momentum p and $\bar{p}$ in Eq. (3) are defined as

$$(p,\bar{p}):=\left(n_ie^{*i}+e^{*i}B_{ji}m^j+\frac{1}{2}e_jm^j,\ n_ie^{*i}+e^{*i}B_{ji}m^j-\frac{1}{2}e_jm^j\right), \tag{5}$$

where $\{e_i^*\}$ are basis vectors for the dual lattice Λ^* of Λ, which satisfies $e_ie_j^*=\delta_{ij}$ such that $e^{*i}e^{*j}=\frac{1}{2}G^{ij}$; the integers n_i and m_i are the momentum and winding numbers. The action of L_0^b and $\bar{L}_0^b$ in Eq. (4) on the ground state $|m_1,m_2,n_1,n_2\rangle$, which is labeled by the momentum and winding numbers, is given by

$$L_0^b|m_1,m_2,n_1,n_2\rangle=\frac{1}{2}p^2|m_1,m_2,n_1,n_2\rangle,$$

$$\bar{L}_0^b|m_1,m_2,n_1,n_2\rangle=\frac{1}{2}\bar{p}^2|m_1,m_2,n_1,n_2\rangle,$$

where we have used $\alpha_n^i|m_1,m_2,n_1,n_2\rangle=0$ and $\bar{\alpha}_m^j|m_1,m_2,n_1,n_2\rangle=0$ for $n>0$, $m>0$. It is well known[11] that the momenta in Eq. (5) form four dimensional Lorentzian lattice with scalar product $(p,\bar{p})\cdot(p',\bar{p}')=(p\cdot p'-\bar{p}\cdot\bar{p}')$, which is even (because $p^2-\bar{p}^2=2m^in_i\in 2\mathbb{Z}$) and self-dual (because $\Lambda=\Lambda^*$). From Eq. (5), we easily write

$$p^2(\bar{p}^2)=\frac{1}{2}n_in_jG^{ij}+n_im_jB_{jl}G^{il}\pm n_im_i+\frac{1}{2}m_im_j(G_{ij}+B_{jk}B_{il}G^{kl}). \tag{6}$$

In the two dimensional case, it is convenient to group the four real parameteres (G_{11}, G_{12}, G_{22}, and B_{12}) in terms of two parameters τ and ρ in the upper complex half plane as follows,

$$\tau=\tau_1+i\tau_2=\frac{G_{12}}{G_{22}}+i\frac{\sqrt{G}}{G_{22}},$$

$$\rho=\rho_1+i\rho_2=B_{12}+i\sqrt{G}.$$

Here τ represents the complex structure of the target space torus T^2, and ρ is its complexified Kähler structure; both take values on the complex upper half plane; $G=\det(G_{ij})$. Now we write Eq. (6) in terms of τ and ρ in the following form,

$$p^2=\frac{1}{2\tau_2\rho_2}|n_1-\tau n_2-\rho(m_2+\tau m_1)|^2,$$

$$\bar{p}^2=\frac{1}{2\tau_2\rho_2}|n_1-\tau n_2-\bar{\rho}(m_2+\tau m_1)|^2.$$

Finally, torus partition function (3) takes the form

$$Z(\tau,\rho)=\frac{1}{|\eta^2(\sigma)|^2}\sum_{\substack{n_1,m_1\\n_2,m_2}}q^{\frac{1}{4\tau_2\rho_2}|n_1-\tau n_2-\rho(m_2+\tau m_1)|^2}\cdot\bar{q}^{\frac{1}{4\tau_2\rho_2}|n_1-\tau n_2-\bar{\rho}(m_2+\tau m_1)|^2} \tag{7}$$

The partition function for the Dirac fermion can be constructed by taking equal spin structures for the left and right fermions[10],

$$Z_{\text{Dirac}}(\sigma,z)=\operatorname{tr} q^{L_0^f-\frac{1}{24}}\bar{q}^{\bar{L}_0^f-\frac{1}{24}}y^{J_0}\bar{y}^{\bar{J}_0}=\frac{1}{2}\left(\left|\frac{\vartheta_1(z,\sigma)}{\eta(\sigma)}\right|^2+\left|\frac{\vartheta_2(z,\sigma)}{\eta(\sigma)}\right|^2+\left|\frac{\vartheta_3(z,\sigma)}{\eta(\sigma)}\right|^2+\left|\frac{\vartheta_4(z,\sigma)}{\eta(\sigma)}\right|^2\right), \tag{8}$$

where $y=e^{2\pi iz}$. Since the fermionic theory split into Neveu-Schwarz and Ramond sector the Virasoro zero mode generator for the Dirac fermions in Eq. (8) is given by

$$L_0^f=\sum_{n>0}nd_{-n}^id_n^i,\quad n\in\mathbb{Z}+\frac{1}{2}(NS);$$

$$L_0^f=\sum_{n>0}nd_{-n}^id_n^i+\frac{1}{8},\quad n\in\mathbb{Z}\ (R).$$

Similar relation is true for the right moving component.

The classical Jacobi theta functions $\vartheta_i(z,\sigma)$, $i \in \{1,2,3,4\}$ in Eq. (8) are defined in terms of sums and products as

$$\theta_1(z,\sigma) = -\mathrm{i}\sum_{n=-\infty}^{\infty}(-1)^n q^{\frac{1}{2}(n-\frac{1}{2})^2} y^{n-\frac{1}{2}} = -\mathrm{i}y^{\frac{1}{2}} q^{\frac{1}{8}} \prod_{n=1}^{\infty}(1-q^n)(1-yq^n)(1-y^{-1}q^{n-1}),$$

$$\theta_2(z,\sigma) = \sum_{n=-\infty}^{\infty} q^{\frac{1}{2}(n-\frac{1}{2})^2} y^{n-\frac{1}{2}} = y^{\frac{1}{2}} q^{\frac{1}{8}} \prod_{n=1}^{\infty}(1-q^n)(1+yq^n)(1+y^{-1}q^{n-1}),$$

$$\theta_3(z,\sigma) = \sum_{n=-\infty}^{\infty} q^{\frac{n^2}{2}} y^n = \prod_{n=1}^{\infty}(1-q^n)(1+yq^{n-\frac{1}{2}})(1+y^{-1}q^{n-\frac{1}{2}}),$$

$$\theta_4(z,\sigma) = \sum_{n=-\infty}^{\infty}(-1)^n q^{\frac{n^2}{2}} y^n = \prod_{n=1}^{\infty}(1-q^n)(1-yq^{n-\frac{1}{2}})(1-y^{-1}q^{n-\frac{1}{2}}).$$

Partition function for the $N=2$ superconformal theories with $c=3$ is thus given as

$$Z(\tau,\rho,z) := Z(\tau,\rho) Z_{\mathrm{Dirac}}(\sigma,z) = \frac{1}{|\eta^2(\sigma)|^2} q^{\frac{1}{4\tau_2\rho_2}|n_1-\tau n_2-\rho(m_2+\tau m_1)|^2} \times \bar{q}^{\frac{1}{4\tau_2\rho_2}|n_1-\tau n_2-\bar{\rho}(m_2+\tau m_1)|^2} \times \frac{1}{2}\left(\left|\frac{\vartheta_1(z,\sigma)}{\eta(\sigma)}\right|^2 + \left|\frac{\vartheta_2(z,\sigma)}{\eta(\sigma)}\right|^2 + \left|\frac{\vartheta_3(z,\sigma)}{\eta(\sigma)}\right|^2 + \left|\frac{\vartheta_4(z,\sigma)}{\eta(\sigma)}\right|^2\right). \quad (9)$$

2 General prescription for the orbifold construction

Our aim is to construct modular invariant 2-dimensional Z_2 orbifold-prime partition function from a given modular invariant theory (9). To do that we now give a brief introduction to the general procedure for the construction of orbifold theories by modding out a symmetry group G of a conformal field theory with central charge c by following the articles [3—6].

Let $\mathscr{H}$ be the Hilbert space of an orbifold theory. It has two sectors, namely untwisted and twisted sector, i.e., $\mathscr{H} = \mathscr{H}_u \oplus \mathscr{H}_t$. Let us consider first the untwisted sector of the orbifold theory. The untwisted Hilbert space will be a subspace of the Hilbert space for the $N=2$ theories with $c=3$. In the path integral for the partition function this means that the bosonic fields obey periodic boundary conditions along the space direction of the torus and twisted periodic boundary conditions in time. So on an orbifold, the untwisted sector boundary conditions on the bosonic field are given as

$$\varphi^+(1) = \varphi^+(0) + 2\pi\Lambda,$$
$$\varphi^+(\sigma) = g\varphi^+(0) + 2\pi\Lambda,$$

where $g \in G$. For Ramond or Neveu-Schwarz fermion one has

$$\psi^+(1) = \pm\psi^+(0),$$
$$\psi^+(\sigma) = \pm g\psi^+(0).$$

The untwisted Hilbert space $\mathscr{H}_u$ decomposes into G invariant and noninvariant space of states. In oder to construct consistent models, we must project out the group noninvariant space of states. In the path integral formalism, projection on the group invariant states in the untwisted sector is represented as

$$Z_u = \frac{1}{|G|}\sum_{g\in G} g\underset{1}{\square}, \quad (9')$$

where we sum over all possible twistings in the time direction of the torus. $g\underset{1}{\square}$ represents boundary conditions on any generic fields in the theory twisted by g in the time direction of the torus. The partition function of the original model is simply given by $Z = {}_1\underset{1}{\square}$.

The untwisted sector partition function is not modular invariant. To gain modular invariant partition function, we therefore need to consider the contributions of twisted sector Hilbert space of states. For G abelian, the twisted Hilbert space decomposes into a set of twisted sectors labeled by $h \in G$, and in each twisted sector there is a projection onto G invariant states. If G is not abelian, the twisted Hilbert space decomposes into a set of twisted sectors labeled by conjugacy classes $\{h\}$ of G. In the path integral description the bosonic field obey the following twisted boundary conditions,

$$\varphi^+(1) = h\varphi^+(0) + 2\pi\Lambda,$$
$$\varphi^+(\sigma) = g\varphi^+(0) + 2\pi\Lambda.$$

For Ramond or Neveu-Schwarz fermions one has

$$\psi^+(1) = \pm h\psi^+(0),$$
$$\psi^+(\sigma) = \pm g\psi^+(0),$$

where h and g are twists on the fields in the space and time direction of the torus. The twisted Hilbert space $\mathscr{H}_t$ decomposes into G invariant and noninvariant space of states. To construct consistent models, we again have to project onto group invariant states. In the path integral formalism, projection onto group invariant states in the twisted sector is representes as

$$Z_t = \frac{1}{|G|}\sum_{\substack{g,h\in G,\\ h\neq 1,[g,h]=0}} g\,\square_h .$$

In fact, one may obtain the twisted sector partition function from (9′) by modular transformations $\sigma\to\sigma+1$ and $\sigma\to -1/\sigma$. Thus, the total modular invariant orbifold partition function is

$$Z_{G\text{-orb}} = \frac{1}{|G|}\sum_{\substack{g,h\in G,\\ [g,h]=0}} g\,\square_h . \tag{10}$$

3 The $\mathbb{Z}_2$ orbifold-prime model

The two dimensional $N=2$ superconformal $\mathbb{Z}_2$ orbifold-prime model can be constructed from Eq. (9) for arbitrary τ and ρ. Thus we may now produce another family of theories, i.e. $\mathbb{Z}_2$ orbifold-prime superconformal field theories with the same set of moduli as the $N=2$ theories with $c=3$ by following the general orbifold prescription introduced in section two. The generic symmetry generators for the thoeries of interest is

$$(-1)^{F_s}\mathbb{Z}_2,$$

where the symmetry $\mathbb{Z}_2$ generated by

$$g\varphi^\pm(z) = -\varphi^\pm(z),\quad g\psi^\pm(z) = -\psi^\pm(z).$$

The $\mathbb{Z}_2$ rotations are the symmetries both the action (1) and $N=2$ world sheet supersymmetry generators (2). Here $(-1)^{F_s}$ is a order two $\mathbb{Z}_2$ symmetry of any superconformal field theory, defined to act as $+1$ on states in the antiperiodic (NS, NS) sector of the world sheet supersymmetry generator, and act as -1 on states in the periodic (R,R) sector. The description of modding out a general superconformal theory by $(-1)^{F_s}$ was given in Ref. [2]. Here we calculate the $\mathbb{Z}_2$ orbifold-prime partition function by twisting the super torus model (9) by the symmetry $(-1)^{F_s}\mathbb{Z}_2$ or by twisting the $\mathbb{Z}_2$ orbifold model (see Eq. (11)) by $(-1)^{F_s}$,

$$Z_{\mathbb{Z}_2\text{-orb}'}(\tau,\rho,z) = (-1)^{F_s}\mathbb{Z}_2 Z(\tau,\rho,z) = (-1)^{F_s} Z_{\mathbb{Z}_2\text{-orb}}(\tau,\rho,z),$$

where the complete modular invariant $\mathbb{Z}_2$ orbifold partition function[7] has the form

$$Z_{\mathbb{Z}_2\text{-orb}} = \frac{1}{2}\left(Z(\tau,\rho) + \left|\frac{\vartheta_3\vartheta_4}{\eta^2}\right|^2 \left|\frac{\vartheta_3\vartheta_2}{\eta^2}\right|^2 + \left|\frac{\vartheta_4\vartheta_2}{\eta^2}\right|^2\right) Z_{\text{Dirac}}(\sigma,z), \tag{11}$$

where the $Z_{\text{Dirac}}(\sigma,z)$ is given in Eq. (8). The $\mathbb{Z}_2$ orbifold partition function (11) may be written as the sum of periodic (R,R) sector and antiperiodic (NS,NS) sector partition functions:

$$Z_{\mathbb{Z}_2\text{-orb}} = Z^{\text{R}}_{\mathbb{Z}_2\text{-orb}} + Z^{\text{NS}}_{\mathbb{Z}_2\text{-orb}},$$

where

$$\begin{aligned} Z^{\text{R}}_{\mathbb{Z}_2\text{-orb}} = {} & \frac{1}{2}\left(Z(\tau,\rho,z) + \left|\frac{\vartheta_3\vartheta_4}{\eta^2}\right|^2\right)\times \frac{1}{2}\left(\left|\frac{\vartheta_1(z,\sigma)}{\eta(\sigma)}\right|^2 + \left|\frac{\vartheta_2(z,\sigma)}{\eta(\sigma)}\right|^2\right) + \\ & \frac{1}{2}\left(\left|\frac{\vartheta_3\vartheta_2}{\eta^2}\right|^2 + \left|\frac{\vartheta_4\vartheta_2}{\eta^2}\right|^2\right)\times \frac{1}{2}\left(\left|\frac{\vartheta_3(z,\sigma)}{\eta(\sigma)}\right|^2 + \left|\frac{\vartheta_4(z,\sigma)}{\eta(\sigma)}\right|^2\right), \end{aligned}$$

$$\begin{aligned} Z^{\text{NS}}_{\mathbb{Z}_2\text{-orb}} = {} & \frac{1}{2}\left(Z(\tau,\rho,z) + \left|\frac{\vartheta_3\vartheta_4}{\eta^2}\right|^2\right)\times \frac{1}{2}\left(\left|\frac{\vartheta_3(z,\sigma)}{\eta(\sigma)}\right|^2 + \left|\frac{\vartheta_4(z,\sigma)}{\eta(\sigma)}\right|^2\right) + \\ & \frac{1}{2}\left(\left|\frac{\vartheta_3\vartheta_2}{\eta^2}\right|^2 + \left|\frac{\vartheta_4\vartheta_2}{\eta^2}\right|^2\right)\times \frac{1}{2}\left(\left|\frac{\vartheta_2(z,\sigma)}{\eta(\sigma)}\right|^2 + \left|\frac{\vartheta_1(z,\sigma)}{\eta(\sigma)}\right|^2\right). \end{aligned}$$

Eq. (10) the general $\mathbb{Z}_2$ orbifold-prime partition function can be written as

$$Z_{\mathbb{Z}_2\text{-orb}'}(\tau,\rho,z) = (-1)^{F_s} Z_{\mathbb{Z}_2\text{-orb}} = \frac{1}{2}\left(1\,\square_1 + (-1)^{F_s}\,\square_1 + 1\,\square_{(-1)^{F_s}} + (-1)^{F_s}\,\square_{(-1)^{F_s}} \right).$$

The first term is simply given by the Eq. (11). Note that the symmetry operator $(-1)^{F_s}$ defined to act as $+1$ on the states in the antiperiodic (NS,NS) sector and as -1 on the states in the periodic (R,R) sector. Therefore one obtains the following result for the second term,

$$(-1)^{F_s}\,\square_1 = \frac{1}{2}\left(Z(\tau,\rho) + \left|\frac{\vartheta_3\vartheta_4}{\eta^2}\right|^2 - \left|\frac{\vartheta_3\vartheta_2}{\eta^2}\right|^2 - \left|\frac{\vartheta_4\vartheta_2}{\eta^2}\right|^2\right)\times \frac{1}{2}\left(\left|\frac{\vartheta_4(z,\sigma)}{\eta(\sigma)}\right|^2 + \left|\frac{\vartheta_3(z,\sigma)}{\eta(\sigma)}\right|^2\right.$$

$$\left|\frac{\vartheta_2(z,\sigma)}{\eta(\sigma)}\right|^2 \quad \left|\frac{\vartheta_1(z,\sigma)}{\eta(\sigma)}\right|^2\Bigg).$$

By applying modular transformation to $(-1)^{F_s} \square_1$, we find the following modular invariant superconformal $\mathbb{Z}_2$ orbifold-prime partition function:

$$Z_{\mathbb{Z}_2-\mathrm{orb}'} = Z_{\mathbb{Z}_2-\mathrm{orb}} - \frac{1}{2}\left(Z(\tau,\rho,z) \left|\frac{\vartheta_1(z,\sigma)}{\eta(\sigma)}\right|^2 4\sum_{j=2}^{4} \left|\frac{\vartheta_j(z,\sigma)}{\vartheta_j}\right|^2\right). \qquad (12)$$

One can see that twisting by $(-1)^{F_s}$ has a nontrivial action on the $\mathbb{Z}_2$ orbifold model.

4 Conclusion

The classification of $N=2$ superconformal field theories with $c=3$ needs a description of all its orbifold theories. The orbifolds by cyclic groups were given in Ref. [7]. In this article we calculated one of the orbifold-prime partition functions. Further more new models are under study.

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$c=3$, $N=2$ 超共形场论的 $\mathbb{Z}_2$ Orbifold-Prime 模型

沙依甫加马力·达吾来提

(中国科学院高能物理研究所 北京 100039)

摘要 讨论了二维环面上中心荷 $c=3$, $N=2$ 的超共形场论. 特别给出该理论的配分函数. 进一步,为了产生新的模型,回顾了一般的 orbifold 方法. 然后构造了模不变的 $\mathbb{Z}_2$ Orbifold-Prime 模型.

关键词 共形场论 orbifold 配分函数

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