

Ghost D-brane, supersymmetry and matrix model

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ABSTRACT: In this note we study the world volume theory of pairs of D-brane and ghost D-brane, which is shown to have 16 linear supersymmetries and 16 nonlinear supersymmetries. In particular we study a matrix model based on the pairs of $D(-1)$ -brane and ghost $D(-1)$ -brane. Since such pairs are supposed to be equivalent to the closed string vacuum, we expect all 32 supersymmetries should be unbroken. We show that the world volume theory of the pairs of D-brane and ghost D-brane has unbroken 32 supersymmetries even though a half of them are nonlinearly realized.

KEYWORDS: Extended Supersymmetry, D-branes, M(atrix) Theories, Spontaneous Symmetry Breaking.

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1. Introduction

As non-perturbative formulations of M-theory and string theory, the BFSS matrix model [1] and the IKKT matrix model [2] has been extensively studied. Since the BFSS matrix model is supposed to describe M-theory in an infinitely boosted frame, the action is the same as a low energy effective action on multiple BPS D0-branes in type IIA superstring. From the conservation of the D0-charge, we can not construct D-branes without the D0-charge in this action. This means that the D-branes in the theory always need to have nonzero field strengths and thus non-commutative world-volumes. The IKKT matrix model has same problem if we think it is described by the BPS D(-1)-branes in type IIB superstring.

In order to overcome this, one might consider the matrix model based on non-BPS D0-branes or $D0 - \overline{D0}$ pairs [3] since these branes have no conserved charges and it was shown that we can construct any D-branes from them [4, 3] using the boundary string field theory action [5, 6] or boundary state.¹ Furthermore, such unstable D-branes can decay into the closed string theory then restore 32 supersymmetries. In [10]–[12] such 32 unbroken supersymmetries in the action of unstable D-branes were discussed. On the other hand, the BPS D0-branes actions can have unbroken 16 supersymmetries only. Thus it is interesting to study the matrix models based on the unstable D-branes. However, the presence of the tachyons can not allow us to use a simple effective action for unstable D-branes although the string field theory actions can be used at least in principle.²

Recently, a ghost D-brane in superstring theories was introduced as an object that cancels the effects of a D-brane [17]. Thus a pair of D-brane and ghost D-brane at the same point is physically equivalent to the closed string vacuum. This is similar to the pair of D-brane and anti-D-brane, especially, after the tachyon condensation or VSFT [18].

¹See [7–9] for the tachyon dynamics in open string theory.

²For the two-dimensional string theory, it was proposed that the $c = 1$ matrix model, which had been known to describe the two-dimensional string theory, can be considered as a tachyon action on multiple D0-branes [13–15] and in [16] it was indeed shown that the boundary string field theory action for D0-branes is equivalent to the $c = 1$ matrix model for this case. Maybe we can find some simple action for other cases.

However, for the ghost D-brane case we do not have the tachyon and then we can consider the “low energy effective action” for the D-branes and the ghost D-branes. In particular, for the D0-brane or D(−1)-brane, we can have a simple matrix model action for the pairs. (Here the ghost D-brane has wrong sign for the kinetic term and the spectrum contains fermionic scalars and bosonic spinors. Thus the theory will be non-unitary for separated D-brane and ghost D-brane and we should seriously consider a physical meaning of the low energy effective action or the ghost D-brane itself, although we will not do it in this paper.)

In this note we consider this matrix model based on pairs of D(−1)-brane and ghost D(−1)-brane for type IIB superstring though a physical meaning of this matrix model is not clear by now. Of course, we can consider D0-brane and ghost D0-brane for type IIA superstring, however, we will concentrate on the D(−1) brane action mainly for notational simplicity (Another reason is that a ghost D(−1)-brane action does not have kinetic term and it might be easier to consider the (path-)integral for the action than other ghost Dp-brane.) Our main interest in this paper is supersymmetry on the matrix model. Because pairs of D-brane and ghost D-brane without any nonzero vev will be equivalent to the closed string vacuum unlike the D-brane-anti-D-brane pairs, 32 supersymmetries should be unbroken on it. We will see that 32 supersymmetries of pairs of D-brane and ghost D-brane are actually unbroken despite the fact that a half of them are realized nonlinearly, which usually means the symmetries are broken.

The organization of this paper is as follows. In section 2 we study the world volume action of pairs of D9-brane and ghost D9-brane. In section 3 we propose a matrix model based on D(−1)-brane and ghost D(−1)-brane and show the translational symmetry and 32 supersymmetries are unbroken. In section 4 we draw conclusions and discuss future problems.

2. Pairs of D9-brane and ghost D9-brane

In this section we consider the world volume theory on N pairs of D9-brane and ghost D9-brane in type IIB superstring following [17].³

It is well known that the low energy effective action of the N D9-brane is the ten-dimensional $U(N)$ super Yang-Mills action,

$$L = -\frac{1}{4g^2} \text{tr}_{N \times N} (F_{\mu\nu} F^{\mu\nu}) - \frac{i}{2g^2} \text{tr}_{N \times N} (\bar{\lambda} \Gamma^\mu D_\mu \lambda), \quad (2.1)$$

where the gauge field A_μ and the gaugino λ , which is a Majorana-Weyl spinor, are written in matrix notation and the spinor index was not explicitly written. The supersymmetry transformation is given by

$$(\delta + \delta') A_\mu = -i \bar{\zeta} \Gamma_\mu \lambda \quad (2.2)$$

$$(\delta + \delta') \lambda = \frac{1}{2} F_{\mu\nu} \Gamma^{\mu\nu} \zeta + \zeta', \quad (2.3)$$

³The ghost D-brane was considered in [19] and some aspects of the ghost D-brane were considered implicitly in [20].

where ζ corresponds to the unbroken 16 supersymmetries, which is supposed to be linearly realized in the superfield formalism, and ζ' corresponds to the nonlinearly realized 16 supersymmetries which is broken by the presence of the D9-branes.

The world volume theory of N pairs of D9-brane and ghost D9-brane can be described by a gauge theory with $U(N|N)$ Chan-Paton matrices and the low energy action in which massive fields and higher derivative terms are dropped is given by the super Yang-Mills action with the supergroup $U(N|N)$ [17]. The gauge field A_μ is replaced by

$$\hat{A}_\mu = \begin{pmatrix} A_\mu^{(1)} & \chi_\mu \\ \chi_\mu^\dagger & A_\mu^{(2)} \end{pmatrix}, \quad (2.4)$$

where $A^{(i)}$ and χ are bosonic and fermionic $N \times N$ matrices, respectively. $A^{(1)}$ (or $A^{(2)}$) comes from the open string between the N D-branes (or the N ghost D-branes) and χ are from the open string between the D-branes and the ghost D-branes. Similarly, λ is replaced by

$$\hat{\lambda} = \begin{pmatrix} \lambda^{(1)} & \varphi \\ \varphi^\dagger & \lambda^{(2)} \end{pmatrix}, \quad (2.5)$$

where $\lambda^{(i)}$ and φ is a fermionic and bosonic spinor $N \times N$ matrices, respectively. Then the Lagrangian is given by

$$L = -\frac{1}{4g^2} \text{Str}_{2N \times 2N} \left(\hat{F}_{\mu\nu} \hat{F}^{\mu\nu} \right) - \frac{i}{2g^2} \text{Str}_{2N \times 2N} \left(\bar{\lambda} \Gamma^\mu D_\mu \hat{\lambda} \right), \quad (2.6)$$

where Str denotes the supertrace which is defined by

$$\text{Str} \hat{X} = \text{tr} A - \text{tr} D, \quad (2.7)$$

where

$$\hat{X} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}. \quad (2.8)$$

It may be important to note that the gauge group $U(N|N)$ does not have decoupled $U(1)$ part unlike (2.1) and it may be significantly different from the action with gauge group $SU(N|N)$.⁴ This fact can be seen as follows.⁵ The gauge field \hat{A}_μ can be written as

$$\hat{A} = \frac{1}{2N} A^{tr} \mathbb{1}_{2N} + \frac{1}{2N} A^{Str} K + A^a T_a, \quad (2.9)$$

where

$$K = \begin{pmatrix} \mathbb{1}_N & 0 \\ 0 & -\mathbb{1}_N \end{pmatrix} \quad (2.10)$$

and T_a which is bosonic and satisfies $\text{Str} T_a = \text{tr} T_a = 0$ and $\mathbb{1}_{2N}$ form the generators of the $SU(N|N)$ subgroup of the $U(N|N)$. Then the kinetic term containing A^{tr} and/or A^{Str} is proportional to $(\partial_\mu A_\nu^{tr} - \partial_\nu A_\mu^{tr})(\partial_\mu A_\nu^{Str} - \partial_\nu A_\mu^{Str})$ because of $\text{Str}(\mathbb{1}_{2N} K) = 2N$

⁴Similar phenomena happen in noncommutative and non-anti-commutative gauge theory with $U(N)$ gauge group [21]. For the superalgebra, see [22].

⁵This $U(1)$ part in $U(N|N)$ was discussed in [23] more carefully.

and $\text{Str}(\mathbb{1}_{2N}\mathbb{1}_{2N}) = \text{Str}(KK) = \text{Str}(\mathbb{1}_{2N}T_a) = \text{Str}(KT_a) = 0$. There is no interaction term for A^{tr} since interaction terms are written by commutators, however, it is easy to see there are interaction terms contain A^{Str} and A^a . Therefore both A^{Str} and A^a are not decoupled from others. Note that for the N D-brane and M ghost D-branes with $N \neq M$ the gauge group $U(N|M)$ contains a decoupled $U(1)$ part and we can decompose $U(N|M) = U(1) \times SU(N|M)$.

Supersymmetry transformations for the Lagrangian (2.6) can be easily obtained from (2.3) since only the gauge group was changed. Only a problem is that the fermion ζ does not commute with \hat{A}_μ and such property is need to show the invariance. This is because the supermatrix contain fermions in off-diagonal parts. However, if we introduce

$$\hat{\zeta} = \zeta K, \quad (2.11)$$

we find, for example, $\zeta \hat{A}_\mu = (K \hat{A}_\mu K) \zeta$ and then $[\hat{A}_\mu, \hat{\zeta}] = 0$.⁶ We also find that $\{\hat{\lambda}, \hat{\zeta}\} = 0$. Hence the supersymmetry transformations for (2.6) are given by

$$(\delta + \delta') \hat{A}_\mu = -i \hat{\zeta} \Gamma_\mu \hat{\lambda} \quad (2.12)$$

$$(\delta + \delta') \hat{\lambda} = \frac{1}{2} \hat{F}_{\mu\nu} \Gamma^{\mu\nu} \hat{\zeta} + \hat{\zeta}'. \quad (2.13)$$

Actually, if we formally expand ‘‘bosonic’’ superfield \hat{A} as $\hat{A} = A^a \hat{T}_a$, where A^a is a usual bosonic field and \hat{T}_a is the ‘‘bosonic’’ supermatrix, and ‘‘fermionic’’ superfield $\hat{\lambda}$ as $\hat{\lambda} = (\lambda^a K) \hat{T}_a$, where λ^a is a usual fermionic field, then $\text{Str}_{2N \times 2N} (\hat{\lambda} \Gamma^\mu D_\mu \hat{\lambda})$ in (2.6) contains $\text{Str}_{2N \times 2N} (\hat{T}_a [\hat{T}_b, \hat{T}_c]) = f_{abc}$ where f_{abc} is bosonic constant antisymmetric for a, b, c . Thus, using this basis we can trivially follow the standard computation showing the invariance of (2.1) under the supersymmetry.

Here the supersymmetry transformations associated with $\hat{\zeta}'$ are nonlinear and they seem to be broken. This seems to contradict the fact that the pair of D-brane and ghost D-brane is equivalent to the closed string vacuum. However, in the next section, we will see nonlinearly realized symmetries can be unbroken.

3. Matrix model based on D-brane and ghost D-brane

Now we consider N pairs of D(-1)-brane and ghost D(-1)-brane and the low energy effective action of those. The action is given by the dimensional reduction of (2.6) to 0 dimension which replace $\hat{A}_\mu(x)$ (and $\hat{\lambda}(x)$) to $\hat{\Phi}_\mu$ (and $\hat{\psi}$):

$$S = -\frac{1}{4g^2} \text{Str}_{2N \times 2N} \left([\hat{\Phi}_\mu, \hat{\Phi}_\nu] [\hat{\Phi}^\mu, \hat{\Phi}^\nu] \right) - \frac{1}{2g^2} \text{Str}_{2N \times 2N} \left(\hat{\psi} \Gamma^\mu [\hat{\Phi}_\mu, \hat{\psi}] \right), \quad (3.1)$$

where

$$\hat{\Phi}_\mu = \begin{pmatrix} \Phi_\mu^{(1)} & \chi_\mu \\ \chi_\mu^\dagger & \Phi_\mu^{(2)} \end{pmatrix} \quad (3.2)$$

⁶The constant grassman variable was considered in [24] in a different context.

and

$$\hat{\psi} = \begin{pmatrix} \psi^{(1)} & \varphi \\ \varphi^\dagger & \psi^{(2)} \end{pmatrix}. \quad (3.3)$$

The supersymmetry transformations are

$$(\delta + \delta')\hat{\Phi}_\mu = i\bar{\zeta}\Gamma_\mu\hat{\phi} \quad (3.4)$$

$$(\delta + \delta')\hat{\psi}_\mu = \frac{i}{2} [\hat{\Phi}_\mu, \hat{\Phi}_\nu] \Gamma^{\mu\nu} \hat{\zeta} + \hat{\zeta}'. \quad (3.5)$$

Of course, this matrix model is also obtained from the IKKT matrix model action, which is the 0 dimensional reduction of the 10 dimensional $U(N)$ super Yang-Mills theory, by replacing $U(N)$ by supergroup $U(N|N)$.⁷ Note that a $U(1)$ factor is decoupled from other generators of $U(N|N)$ for this matrix model because there is no kinetic term, though $U(N|N)/U(1)$ is not the $SU(N|N)$ subgroup.

As the IKKT matrix model has been proposed as a nonperturbative formulation of type IIB superstring, this matrix model could give a nonperturbative formulation of type IIB superstring in some large N limit. It is very interesting to investigate this possibility, however, we will only consider symmetry of it here.

There is a constant shift symmetry,

$$\delta\hat{\Phi}^\mu = a^\mu, \quad \delta\hat{\psi} = 0, \quad (3.6)$$

which can be understood as the space-time translation of the D(-1)-brane and the ghost D(-1)-brane. This symmetry is realized nonlinearly and if we separate the D-brane and ghost D-brane it will be broken by the presence of the D-brane. However, for $\hat{\Phi} = \hat{\psi} = 0$ it should be unbroken since both the D-brane and the ghost D-brane disappear.⁸

To resolve this puzzle, we first consider vev of a possible order parameter classically. It should be gauge invariant and then $\langle \text{Str}(\delta\hat{\Phi}_\mu) \rangle$ or the supertrace of polynomials of $\hat{\Phi}, \hat{\psi}$ can be considered. It is easy to see that

$$\langle \text{Str}(\delta\hat{\Phi}_\mu) \rangle = \text{Str}(a_\mu) = 0, \quad (3.7)$$

and the transformation of other gauge invariant operators also vanish for $\hat{\Phi} = \hat{\psi} = 0$ classically. In this way, the nonlinear transformation can be regarded as unbroken. Furthermore, we expect it is unbroken quantum mechanically. Actually for $U(N|N)$ all correlation functions of gauge invariants will vanish at $\hat{\Phi} = \hat{\psi} = 0$ [25] [17]. This is consistent with the interpretation as a closed string vacuum. The transformation of the correlation functions also vanish because the δ transformed $\hat{\Phi}$ to just a constant. Therefore it is unbroken quantum mechanically.

⁷For other supermatrix models, see [25]-[28]. Note that the action (3.5) is not only a supermatrix model, i.e. supergauge symmetric, but also supersymmetric. Thus this is a supersymmetrized supermatrix model.

⁸Strictly speaking, there are no symmetry breaking in 0 or 1 dimensional theories. We could rigorously define broken or unbroken symmetry by considering higher dimensional analogues, compactified theory or a large N limit.

On the other hand, for a generic classical background

$$\hat{\Phi} = \text{diag}(b_1, b_2, \dots, b_N, c_1, c_2, \dots, c_N), \quad \hat{\psi} = 0, \quad (3.8)$$

it will be broken. Let us consider a gauge invariant $\text{Str}(f_1(\hat{\Phi}, \hat{\psi}))$ and the transformation of it, $\delta \text{Str}(f_1(\hat{\Phi}, \hat{\psi}))$, where f_i is some polynomial. Taking $f_1 = \hat{\Phi}^{\mu_1} \dots \hat{\Phi}^{\mu_M}$, we have

$$\delta \text{Str}(f_1(\hat{\Phi}, \hat{\psi})) = a^{\mu_1} \sum_{i=2}^N \left(\prod_{a=1}^M (b_i^{\mu_a})^2 - \prod_{a=2}^M (c_i^{\mu_a})^2 \right) + (\text{permutation of } \mu_1 \text{ and } \mu_i). \quad (3.9)$$

Therefore if

$$b_i^\mu = c_i^\mu, \quad (i = 1, \dots, N, \quad \mu = 0, \dots, 9) \quad (3.10)$$

(or that with a permutation of N vectors c_i) is satisfied, $\delta \text{Str}(f_1(\hat{\Phi}, \hat{\psi})) = 0$. Considering the transformation of $\langle \text{Str}(f_1(\hat{\Phi}, \hat{\psi})) \text{Str}(f_2(\hat{\Phi}, \hat{\psi})) \dots \rangle$, we see that the translational symmetry is unbroken if (3.10) is satisfied otherwise it is broken. This is consistent with the interpretation that a D-brane and a ghost D-brane in any pair are at same position for (3.10) and are physically equivalent to the closed string vacuum.

We expect the nonlinear supersymmetries generated by $\hat{\zeta}'$ is also unbroken for (3.10) in the same way. Here we note that $\text{Str} \hat{\psi}$ is not gauge invariant because $\text{Str}(\hat{X} \hat{\psi}) \neq \text{Str}(\hat{\psi} \hat{X})$ where \hat{X} is a usual supermatrix and $\hat{\psi}$ is a “fermionic” supermatrix, i.e. a supermatrix with fermions in its diagonal part. Instead, $\text{Str}(K \hat{\psi}) = \text{tr}(\hat{\psi})$ is gauge invariant because $\text{Str}(K \hat{X} \hat{\psi}) = \text{Str}(K \hat{\psi} \hat{X})$ and consistent with the fact that a “fermion” bilinear $\text{Str}(\hat{\zeta}' \hat{\psi})$ is gauge invariant.⁹ Then, it is easy to see that

$$\langle \text{Str}(K \delta \hat{\psi}) \rangle = \text{Str}(K \hat{\zeta}') = \zeta' \text{Str}(K^2) = 0, \quad (3.11)$$

and the supersymmetric transformation of other gauge invariant operators also vanish for $\hat{\Phi} = \hat{\psi} = 0$ classically. For the generic classical background (3.8) we can easily show that (3.10) is the condition for the nonlinear supersymmetries being unbroken by taking $f_1 = \hat{\Phi}^{\mu_1} \dots \hat{\Phi}^{\mu_M} \hat{\psi}$. Therefore the matrix model (3.1) has the 32 unbroken supersymmetries and 10 dimensional translation symmetry (and the Lorentz symmetry linearly realized). It is very interesting to investigate this highly symmetric matrix model further.

Finally, we will discuss the supersymmetry algebra. In [2] it was shown that the IKKT matrix model has the 32 supersymmetries which form the super symmetry algebra. We can trivially extend it to our case. Indeed, if we define $\delta_{\hat{\zeta}}^{(1)} = \delta_{\hat{\zeta}} + \delta'_{\hat{\zeta}}$ and $\delta_{\hat{\zeta}}^{(2)} = i(\delta_{\hat{\zeta}} - \delta'_{\hat{\zeta}})$, then we have the algebra of 32 supersymmetries

$$[\delta_{\hat{\zeta}}^{(i)}, \delta_{\hat{\zeta}}^{(j)}] = \epsilon^\mu P_\mu \delta_{ij}, \quad (3.12)$$

where $\epsilon = -2i\hat{\zeta} \Gamma^\mu \hat{\zeta}$ and P_μ is the constant shift of $\hat{\Phi}$.

⁹We also note that $\text{Str}(\hat{\psi} \hat{\psi}') = -\text{Str}(\hat{\psi}' \hat{\psi})$ which is same property as the trace for usual matrices.

4. Conclusions and discussion

We have studied the world volume theory of the pairs of D-brane and ghost D-brane, especially D(-1)-brane and ghost D(-1)-brane and have seen that the nonlinear symmetries, the supersymmetries and the translation symmetry, are unbroken in the model. This is consistent with the interpretation of the system as the closed string vacuum. We can extend our study in this paper to BFSS matrix model, and other dimensional branes. We can also consider the type I superstring and supergroup OSp . Of course, our discussion in this paper is rather naive and need further study. In particular the problem of the unitarity may be important.

The nonlinear supersymmetries in pairs of D9-brane and ghost D9-brane will be also unbroken in the same way as D(-1)-branes. In this case, we can consider the instanton only on the D9-branes and in the small instanton limit what we have is physically equivalent to a D5-brane with nothing [29]. (If we put the same instanton also on the ghost D9-branes, we have closed string vacuum and if we put the anti-instanton on the ghost D9-branes, we have D5-anti-D5-brane pair.) Then the half of the nonlinear supersymmetries generated by $\hat{\zeta}'$ which satisfies $\hat{F}_{\mu\nu}\Gamma^{\mu\nu}\hat{\zeta}' = 0$ are expected to be unbroken, but others are broken from $\langle\delta(\hat{F}_{\mu\nu}\Gamma^{\mu\nu}\hat{\psi})\rangle = 0$. Of course, the half of the linear supersymmetries generated by $\hat{\zeta}$ which satisfies $\hat{F}_{\mu\nu}\Gamma^{\mu\nu}\hat{\zeta} = 0$ are also unbroken. Thus we have different unbroken 16 supersymmetries from what D9-brane has and if we consider the anti-instanton instead of the instanton we will have the other half of unbroken supersymmetries. This is interesting [11] since we discussed the 32 supersymmetries even though for gauge theories without gravity 16 supersymmetries are maximal in a usual sense. However, there is a problem for this picture. For the D9-brane-ghost D9-brane case, the superalgebra is

$$[\delta_{\hat{\zeta}}, \delta_{\hat{\xi}}] = \delta_{\epsilon} + \text{gauge transformation}, \quad [\delta_{\hat{\zeta}}, \delta'_{\hat{\xi}'}] = \delta_{\epsilon'}, \quad [\delta'_{\hat{\zeta}'}, \delta'_{\hat{\xi}'}] = 0, \quad (4.1)$$

where δ_{ϵ} is the translation by $\epsilon^{\mu} = 2\hat{\zeta}\Gamma^{\mu}\hat{\xi}$. In the compactified space-time, $\delta_{\epsilon'}$ is the constant shift of \hat{A}_{μ} , i.e. Wilson line, by $\epsilon^{\mu} = 2\hat{\zeta}\Gamma^{\mu}\hat{\xi}'$ and corresponds to the space-time translation in the T-dual picture. Thus for the uncompactified space-time, $\delta_{\hat{\zeta}}$ form the 16 supersymmetries, but $\delta'_{\hat{\zeta}'}$ is trivial. What we expect is that the $\delta'_{\hat{\zeta}'}$ also form the superalgebra. To make this clear is an interesting question.

Another question is how to realize the Lorentz symmetry of pairs of Dp -brane and ghost Dp -brane. Since it mixes the coordinate and the fields in general, to find the unbroken symmetry will be interesting.

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Note added: as this article was being completed, we became aware of the preprint [30] in which the matrix model proposed in this paper is also proposed.

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