Type 0 Strings and Gauge Theories

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Abstract

We briefly review some recent work on extending the ideas of gauge theory – gravity correspondence to type 0 string theory context. The main hope is understanding non-perturbative aspects of non-supersymmetric gauge theories.

In the papers [1-3] non-supersymmetric large N gauge theories dual to certain backgrounds of the type 0 string theory were studied. This work was inspired by the recently discovered relations between type II strings and superconformal gauge theories on N coincident D3-branes, and, in particular, by Polyakov's suggestion [4] that the type 0 string theory in dimensions $D \leq 10$ is a natural setting for extending this duality to non-supersymmetric gauge theories.

The type 0 string has world sheet supersymmetry but no space-time supersymmetry. In both type 0A and type 0B theory the fermions are completely projected out of the spectrum. The massless bosonic fields are as in the corresponding type II theory (A or B), but with the doubled set of Ramond-Ramond (R-R) fields. The spectrum of type 0 theory also contains a tachyon, but, as suggested in [1,4], its presence does not spoil the application to large N gauge theories. In fact, the tachyon background provides a natural mechanism for breaking the conformal invariance and introducing the renormalization group flow [1,2,5].

In [1] the $3+1$ dimensional $SU(N)$ theory coupled to 6 adjoint massless scalars was constructed as the low-energy description of N coincident electric D3-branes. The conjectured dual type 0B background thus carries N units of electric 5-form flux. The set of equations for a background with a 5-form flux follows from the following action:

$$S_0 = -\frac{1}{2\kappa_{10}^2}\int d^{10}x\sqrt{-g}\Big[R - \frac{1}{2}\partial_n\Phi\partial^n\Phi$$

$$- \frac{1}{4}(\partial_n T\partial^n T + m^2 e^{\frac{1}{2}\Phi}T^2) - \frac{1}{4\cdot 5!}f(T)F_{n_1\ldots n_5}F^{n_1\ldots n_5} + \ldots\Big] , \qquad (1)$$

where g_{mn} is the Einstein-frame metric, $m^2 = -\frac{2}{\alpha'}$, and

$$f(T) = 1 + T + O(T^2) \ .$$

In [1,2,5] it was shown that, if the tachyon–R-R field coupling function $f(T)$ has a minimum, then there exists an asymptotically free type 0 background with the tachyon approximately localized near the minimum. The tachyon background induces a radial variation of the dilaton Φ which has the physical interpretation of renormalization group flow. The Einstein metric is approximately $AdS_5 \times S^5$, while the effective gauge coupling evolves logarithmically with the scale. In [5,2] the infrared behavior of the background was also considered. It turns out that there is a fixed point at infinite coupling which, just like the fixed point at zero coupling, is characterized by the $AdS_5 \times S^5$ Einstein frame metric [2]. We argued that there is a renormalization group trajectory extending all the way from the zero coupling fixed point in the UV to the infinite coupling fixed point in the IR.

In [3] we considered a background of type 0 theory which has exact conformal invariance (a line of fixed points). The existence of such a background was pointed out already in [1]: it is the near-horizon region of the self-dual 3-brane of type 0B theory which, just as in the type IIB case, turns out to be $AdS_5 \times S^5$. In the type IIB case the dual gauge theory is $\mathcal{N}=4$ SYM but in the type 0B case it is different. The self-dual 3-brane is constructed by stacking equal numbers N of coincident electric and magnetic 3-branes. One can show [3] that the non-supersymmetric theory on this stack is the $SU(N) \times SU(N)$ gauge theory coupled to 6 adjoint scalars of the first $SU(N)$, 6 adjoint scalars of the second $SU(N)$, and fermions in the bifundamental representations – 4 Weyl fermions in the $(\mathbf{N}, \overline{\mathbf{N}})$ and 4 Weyl fermions in the $(\overline{\mathbf{N}}, \mathbf{N})$. One can argue [3,6] argue that this theory is conformal in the large N limit. Since it has the maximal global $SO(6)$ invariance, this theory is not of the kind that occurs on the D3-branes of type IIB theory placed at the orbifold singularity of R^6/Γ (the latter theories are dual to the $AdS_5 \times S^5/\Gamma$ backgrounds of type IIB theory [7,8]).

The type 0 theories have twice as many massless R-R fields as their type IIB ones and thus they also possess twice as many D-branes. For example, there are two types of D3-branes: those that couple electrically to this gauge potential, and those that couple magnetically. Very importantly, the weakly coupled spectrum of open strings on type 0 D-branes does not contain tachyons after the GSO projection $(-1)^{F_{open}} = 1$ is implemented. Thus, gauge theories living on such D-branes do not have obvious instabilities at weak coupling. This suggests via the gauge field/string duality that the bulk tachyon instability of type 0 theory may be cured as well. The argument for tachyon stabilization in the simplest example – the stack of N electric and N magnetic D3-branes – goes as follows [3]. For such a stack the net tachyon tadpole cancels so that there exists a classical solution with $T = 0$. In fact, since the stack couples to the selfdual part of the 5-form field strength, the type 0B 3-brane classical solution is identical to the type IIB one. Taking the throat limit suggests that the low-energy field theory on N electric and N magnetic D3-branes is dual to the $AdS_5 \times S^5$ background of type 0B theory and is therefore conformal in the planar limit. The fact that this non-supersymmetric AdS/CFT duality is a Z_2 quotient of the $\mathcal{N} = 4$ duality lends additional credence to its validity. In particular, general arguments presented in [9] guarantee that the field theory is conformal in the planar limit and that planar correlators of untwisted vertex operators coincide with those of the $\mathcal{N} = 4$ theory. Since this CFT does not appear to have any instabilities at weak coupling, it was argued in [3] that type 0B string theory on $AdS_5 \times S^5$ is stable for sufficiently small radius. This provides a simple AdS/CFT argument in favor of tachyon stabilization; it is also an example of how gauge theory may be used to make predictions about the string theory dual to it.

Lets us parametrize the 10-d string-frame and Einstein-frame metric as ($\mu = 0, 1, 2, 3$ are the 4-d indices)

$$ds^2 = e^{\frac{1}{2}\Phi} ds_E^2 \ , \qquad ds_E^2 = e^{\frac{1}{2}\xi - 5\eta} d\rho^2 + e^{-\frac{1}{2}\xi} dx^\mu dx^\mu + e^{\frac{1}{2}\xi - \eta} d\Omega_5^2 \ . \tag{2}$$

In terms of these variables the effective action describing radial evolution of the fields corresponding to (1)

$$S = \int d\rho \left[\frac{1}{2}\Phi'^2 + \frac{1}{2}\xi'^2 - 5\eta'^2 + \frac{1}{4}T'^2 + U(\Phi, \xi, \eta, T) \right] \ , \tag{3}$$

$$U = -\frac{1}{2}T^2 e^{\frac{1}{2}\Phi + \frac{1}{2}\xi - 5\eta} - 20 e^{-4\eta} \ + \ h(T) \ e^{-2\xi} \ . \tag{4}$$

For the case of the electric 5-form background, it was shown in [1] that $h(T) = Q^2 f^{-1}(T)$, where $f(T)$ is the tachyon–5-form coupling function and Q is the electric charge. Generalizing to the presence of magnetic 5-form charge P we find that

$$h(T) = P^2 f(T) + Q^2 f^{-1}(T) \ . \tag{5}$$

As in the familiar dilaton-vector coupling case, the potential that originates from the $f(T) F_5 F_5$ term in the full $D = 10$ action is invariant under the electro-magnetic duality $P \leftrightarrow Q, \ f \leftrightarrow f^{-1}$.

The function $h(T)$ has an extremum at $T = T_0$ such that $f(T_0) = Q/P$. For $Q = P$ ($\sim N$) we thus get $f(T_0) = 1$ which has a solution $T_0 = 0$. Then the tachyon equation is solved by $T = 0$, the dilaton equation is solved by $\Phi = \Phi_0$, and the equations for ξ, η are solved by the usual $AdS_5 \times S^5$ background

$$\xi = \ln(2Q) + \ln \rho \ , \qquad \eta = \ln 2 + \frac{1}{2} \ln \rho \ . \tag{6}$$

This is the near-horizon limit of the full 3-brane metric. After the change of variables $\rho = u^{-4}$, the $AdS_5 \times S^5$ metric is

$$ds_E^2 = R_0^2 \left(\frac{du^2}{u^2} + \frac{u^2}{2R_0^4} dx^\mu dx^\mu + d\Omega_5^2 \right) \ , \qquad R_0^2 = \frac{1}{2}(2Q)^{1/2} \ . \tag{7}$$

The 4-th power of the radius R of the corresponding string-frame metric, i.e. $\frac{1}{2}e^{\Phi_0}Q$, is proportional to the 't Hooft coupling $N g_{\rm YM}^2$ of the gauge theory on the stack of N electric D3-branes and N magnetic D3-branes.

An important issue is that of stability of the background. Considering small perturbations of the $AdS_5 \times S^5$ background in the T-direction we learn that they are no longer tachyonic for sufficiently small Qe^{Φ_0}. Indeed, the leading quadratic terms in the fluctuation of T near $T_0 = 0$ in the potential U become:

$$U_2 = \frac{1}{4\rho^2}\Big[-\frac{1}{16}(2Qe^{\Phi_0})^{1/2} + f'^2(0)\Big]T^2 + O(T^3) \ . \qquad (8)$$

Thus, the background is stable if $16f'^2(0) \geq (2Qe^{\Phi_0})^{1/2}$, which is satisfied for small enough $Qe^{\Phi_0} \sim Ng_s$ since $f'(0) = 1$. More precisely, the stability condition for a scalar field with mass M^2 in AdS_5 space-time with radius R is the usual AdS space one: $M^2 \geq -4R^{-2}$, i.e. in the present case $M^2 \geq -8(2Qe^{\Phi_0})^{-1/2}$. Here the effective mass parameter (measured in the string frame, $\alpha' = 1$) is $M^2 = -2 + 32f'^2(0)(2Qe^{\Phi_0})^{-1/2}$, so the stability condition is actually $4 + 16f'^2(0) \geq (2Qe^{\Phi_0})^{1/2}$. Once one is allowed to consider the AdS_5 radius to be of order of $\sqrt{\alpha'}$, one in principle does not need the $f(T)$ coupling to achieve the stability of the string tachyon in the $AdS_5 \times S^5$ background. However, the coupling function $f(T)$ is non-trivial in type 0B theory, and since $f'(0) = 1$, its contribution to the above condition is considerable. Explicitly, we get $\frac{1}{2}Qe^{\Phi_0} = 4\pi g_s N\alpha'^2 = g^2_{\rm YM}N$, and thus the following stability condition on the 't Hooft coupling: $g^2_{\rm YM}N < 100$.

The stability is related to the fact that the $T = 0$ solution is an attractor: a generic solution with $T = T^{(0)}$ at $\rho = 0$ evolves to the $T = 0$ solution at large ρ. This is easy to see explicitly, e.g., by approximating $f(T)$ by e^T which is equal to $f_2(T) = 1 + T + \frac{1}{2}T^2$ at small T. Then $h(T) = 2Q^2 \cosh T$ which indeed gives a positive shift of the coefficient of the T^2 term in the potential. The above stability criterion [1,3] is opposite to the condition of validity of the gravity (leading order in α') approximation. Indeed, one may hope that the theory is stable for $Qe^{\Phi_0} < O(1)$, but here the curvature of the background is of order 1 in string units and it is not clear a priori whether the effective gravity approximation can be trusted in the first place. We would like to argue, though, that it indeed can be trusted due to the special nature of the $AdS_5 \times S^5$ solution.

The tree-level effective action of the type 0B theory coincides with that of the type IIB theory on the subsector of bosonic fields of the type IIB theory. Since the present self-dual solution has $T = 0$ and $F_5 = \tilde{F}_5$ (i.e. the non-vanishing fields belong to the spectrum of type IIB theory), we are in a position to argue that our solution is exact to all orders in α' just as it is in type IIB theory. The stability condition is also expected to hold (at least qualitatively) since the higher-order in α' corrections to the T^2 term in the effective action are likely to involve powers of the Weyl tensor, F_5^2 and the Ricci scalar which all vanish in the $AdS_5 \times S^5$ background. [While for a generic 2-d CFT, e.g., a WZW model, one certainly does not expect the anomalous dimension of the tachyon operator not to receive α' (or $1/k$) corrections, this may happen in the special cases of 'balanced' combinations, like equal-level $SL(2) \times SU(2)$ or $AdS_3 \times S^3$, which also has zero total Ricci scalar and Weyl tensor.] Then one is led to the conclusion that the dual field theory which lives on the stack of D3-branes is a stable large N CFT as long as the 't Hooft coupling $Ng^2_{\rm YM}$ is not very large: less than a number of order 10^2. The weak-coupling analysis of [3] provides some support for this conclusion. Then the conclusion is that while the flat space vacuum is unstable in type 0 string theory, the $AdS_5 \times S^5$ with self-dual 5-form flux should be a stable background for sufficiently small radius. The R-R charge works to stabilize the tachyon. This conclusion is independent of the details of the tachyon – R-R coupling function $f(T)$: any function such that $f(0) = 1$ and $f'(0) = 1$ leads to the stable $AdS_5 \times S^5$ background. These properties of $f(T)$ are obviously satisfied.

Let us finish with few remarks and comments on some open problems. The tachyon interactions in type 0 string effective action are rather peculiar – T couples to the R-R field strengths but not to the NS-NS one; in particular, it is possible to show by direct computation based on the 4-point $TTBB$ amplitudes that there is no $H^2_{mnk}T^2$ term in the effective action (1). This is in contrast with naive expectations based on type IIB "S-duality" which is not, of course, a symmetry of type 0 theory. In general, it would be important to clarify further the structure of tachyon interactions in the effective action. The issue of the tachyon potential is one of the main one. A non-trivial tachyon potential is needed for confinement according to Wilson loop criterion [5]. The problem is that we know only the on-shell S-matrix, and off-shell continuation of the effective action is ambiguous. Also, to address the issue of tachyon stabilization we need to consider radii of string order and thus to include terms of all orders in α' expansion. In principle, the tachyon problem may be cured already on a curved NS-NS background (as was suggested long ago for the case of AdS_3 or $SU(2)$ WZW model in [10]), but R-R case presents a novel mechanism for such stabilization. Another open problem is corrections to large N expansion. It would be interesting to determine the tachyonic terms in the 1-loop (torus) effective action in type 0 string (where the 1-loop dilaton tadpole is non-vanishing).

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