Received: *August 16, 1999,* Accepted: *November 8, 1999*

Electric black holes in type-0 string theory

Ivo Sachs

Department of Mathematical Sciences, University of Durham
Science Site, Durham DH1 3LE, UK, and
Department of Mathematics, King's College London
The Strand, London WC2R 2LS, UK
E-mail: Ivo.Sachs@durham.ac.uk

Abstract: We discuss AdS_{2+1} (BTZ) black holes arising in type-0 string theory corresponding to D1-D5 and F1-NS5 bound states. In particular we describe a new family of non-dilatonic solutions with only Dp_+, that is "electric" branes. These solutions are distinguished by the absence of fermions in the world volume theory which is an interacting CFT. They can not be obtained as a projection of a type-II BPS-configuration. As for previous type-0 backgrounds linear stability is guaranteed only if the curvature is of the order of the string scale where α' corrections cannot be excluded. Some problems concerning the counting of states are discussed.

Keywords: D-branes, Black Holes in String Theory.

JHEP11(1999)011

Contents

1. Introduction

String theory has lead to important new insights in the microscopic properties of those black holes for which the near horizon geometry consists of an anti-de Sitter (AdS) throat times a sphere which represents the horizon [1]. In the case of AdS_{2+1} the entropy and Hawking radiation can be exactly reproduced within the world volume theory of the corresponding brane configuration of type-II string theory which in this case is a $1+1$-dimensional conformal field theory (CFT). In fact, many of the properties of this CFT, in particular, the central charge can be obtained solely by analysing the generators of the asymptotic symmetries of the near horizon geometry [2] (see [3] for implications for the black hole entropy). These properties are therefore universal and essentially independent of the underlying microscopic theory. In fact AdS_{2+1} gravity itself without any extra fields provides the simplest representation of the conformal algebra on the boundary [2, 4], but there are indications that gravitational degrees of freedom alone cannot account for for all micro states needed to produce the geometric entropy of black holes [5]. Another representation of the algebra is, of course, provided by the superconformal world volume theory of the D1D5-brane system of type-II theory [1, 6]. So far this is essentially the only realisation for which it has been possible to count the micro states explicitly. In that sense string theory passes a non-trivial test for a consistent microscopic theory of gravity. One of the puzzles raised by this is the role of supersymmetry, or the necessity of fermions in any consistent theory of gravity. It is therefore of interest to analyse black holes in theories without space-time supersymmetry from this point of view. As mentioned above pure gravity provides one such theory but does not seem to be able to account for all degrees of freedom.

JHEP11(1999)011

In this paper we consider type-0 string theory which is distinguished by being supersymmetric on the world sheet but has no space-time fermions in the perturbative closed-string sector. As we shall see under suitable assumptions about higher order corrections there are black hole solutions that are indistinguishable from their type-II cousins. The world volume theory, however, is rather different due to the absence of fermions. The main focus of this paper is to find consistent solutions to the type-0 low energy gravitational effective action and to identify the corresponding world volume theory. Previous work on the AdS_{p+1}/CFT correspondence in type-0 theories includes [7, 8]. In particular we use the results of [7] where the low energy effective action has been determined up to second order in the tachyon. In [8] the $\mathrm{D1}_{\pm}\mathrm{D5}_{\pm}$ black hole solution was given and the entropy was reproduced within the corresponding world volume theory which is, in fact, a $\mathbb{Z}_2$ projection of the type-IIB theory. This solution was further analysed in [9]. In this paper we shall describe a new solution which consists of only $\mathrm{D}p_+$ (i.e. 'electric') branes. The fact that such a configuration leads to a non-dilatonic (that is conformal) background may come as a surprise. Indeed generically both electric- and magnetic RR-fields need to be turned on in order to cancel the tachyon tadpole. However, as we shall see, for the D1D5-brane system this is not so. Another important feature that distinguishes the $\mathrm{D1}_+\mathrm{D5}_+$ black hole constructed here is that it cannot be obtained by a projection of a corresponding type-II solution. In particular the world volume theory is purely bosonic. This is interesting, in particular in view of the the above remarks about the role of supersymmetry in black hole physics. On the other hand, as expected, the absence of a simple relation with supersymmetric black holes complicates the analysis of the world volume theory. So, for example is is unclear at present how the entropy can be reproduced within world volume theory. Another important issue concerns the stability of the the background. As for all type-0 solutions constructed so far linear stability is guaranteed only for AdS-radii of the order of the string scale. Hence, α' corrections to the background cannot be excluded on general grounds. However, it has been suggested in (e.g. [7, 8]) that AdS backgrounds are indeed protected due to the vanishing of the Weyl tensor, but further work is clearly needed to decide on the stability. We address some of the issues about the world volume theory which in the infrared is a $1+1$ dimensional CFT. A more in depth analysis, needed for an explicit understanding of the counting of micro states will be referred to future work.

2. Type-0 strings

Type-0 string theory [10] has been discussed in numerous papers. For the analysis presented here [11] and [7] will be most relevant. These papers provide excellent sources for the material used here so that we can limit ourselves to summarise the main points.

JHEP11(1999)011

Spectrum: here we will be concerned with type-0B string theory which is based on a non supersymmetric diagonal GSO projection ($\frac{1}{2}[1+(-1)^{F+\bar{F}}]$), [10]

$$(NS-, NS-) \oplus (NS+, NS+) \oplus (R+, R+) \oplus (R-, R-)\,, \tag{2.1}$$

which projects out the fermions in the bulk. Alternatively it can be obtained by projecting type-IIB by the discrete symmetry generated by $(-1)^{F_s}$, where F_s is the space time fermion number. The massless bosonic degrees of freedom in the NS-sector contain a sector identical with the type-II theories but include the tachyon in addition. Furthermore the RR fields are doubled. Correspondingly there are two sorts of Dp branes for p odd. We denote them by D$p_\pm$. The corresponding boundary states are [11]

$$\mathrm{D}p_\pm : \qquad |Bp,\pm\rangle_{NSNS} + |Bp,\pm\rangle_{RR}\,, \tag{2.2}$$

where $|Bp,\epsilon\rangle_\eta$ satisfies

$$\begin{aligned}(\alpha^\mu_n - \tilde{\alpha}^\mu_{-n})|Bp,\epsilon\rangle_\eta &= 0\,,\\ (\psi^\mu_r - i\epsilon\tilde{\psi}^\mu_{-r})|Bp,\epsilon\rangle_\eta &= 0\,,\end{aligned} \tag{2.3}$$

for $\mu = 0,\ldots,p$ and

$$\begin{aligned}(\alpha^\mu_n + \tilde{\alpha}^\mu_{-n})|Bp,\epsilon\rangle_\eta &= 0\,,\\ (\psi^\mu_r + i\epsilon\tilde{\psi}^\mu_{-r})|Bp,\epsilon\rangle_\eta &= 0\,,\end{aligned} \tag{2.4}$$

for $\mu = p+1,\ldots,9$ and $\eta \in \{NSNS, RR\}$. Further information about the spectrum of type-0B strings comes form the observation [11] that only the combination Dp_+D$p_- \equiv$ D$p_\pm$ which is charged only under the untwisted RR-fields, has the correct number of degrees of freedom to be interpreted as the S-duals of the fundamental string and the NS-five brane respectively (the D$3_\pm$ is self dual [7]). The twisted fields should then be invariant under S-duality.

Effective action: the string frame low energy effective action up to second order in the tachyon has been worked out in [7] (see also [12])

$$\begin{aligned}S = \frac{1}{2\kappa_{10}^2}\Bigg[\int \sqrt{-G}\; e^{-2\phi}R + 4(e^{-2\phi}\mathrm{d}\phi,\mathrm{d}\phi) - \frac{1}{4}(e^{-2\phi}\mathrm{d}T,\mathrm{d}T) - \frac{m^2}{4}(e^{-2\phi}T,T) -\\ -\frac{1}{2}(e^{-2\phi}H,H) - \frac{1}{2}(f_+(T)F_{[3]+},F_{[3]+}) - \frac{1}{2}(f_-(T)F_{[3]-},F_{[3]-})\Bigg]\,,\end{aligned} \tag{2.5}$$

where $f_\pm(T) = 1 \pm T + \frac{1}{2}T^2 + O(T^2)$ and (A,B) denotes the scalar product of differential forms. All the other fields are set to zero. It was argued in [7] that, provided the effective action is S-duality invariant, the exact form of the tachyon potential should be given by $f_\pm = e^{\pm T}$.

3. Non-dilatonic solutions

All non-dilatonic solutions to the type-0 low energy effective action found so far had non-vanishing electric *and* magnetic RR-flux and correspond to appropriate projections of certain type-II BPS solutions. However, as we shall argue below bound states that are purely electric or magnetic also exist but they cannot be obtained by as projections from the type-II BPS states.

We consider the six dimensional action obtained from (2.5) by parametrising G_{10} in terms of the six dimensional Einstein metric

$$G_{10} = e^{\phi_6} g_6 + e^{2\nu} dx_I dx^I \,. \tag{3.1}$$

That is

$$\begin{aligned} S_6 = \frac{1}{2\kappa_6^2}\Bigg[\int \sqrt{-G}R_6 - \frac{1}{2}(\mathrm{d}\phi_6, \mathrm{d}\phi_6) - \frac{1}{4}(\mathrm{d}T, \mathrm{d}T) - 4(\mathrm{d}\nu, d\nu) - \frac{m^2}{4}(e^{\phi}T, T) - \\ -\frac{1}{2}(e^{-2\phi_6}H, H) - \frac{1}{2}\left(e^{4\nu} f_+(T) F_{[3]+}, F_{[3]+}\right) - \frac{1}{2}\left(e^{4\nu} f_-(T) F_{[3]-}, F_{[3]-}\right)\Bigg] \,, \end{aligned} \tag{3.2}$$

where $\phi_6 = \phi - 2\nu$, $\kappa_6^2 = \kappa_{10}^2/L^4$ and we have performed the consistent truncation $B_{IJ} = F_{I\mu\nu} = H_{I\mu\nu} = 0$. The relevant equations of motion that follow from (3.2) are given by

$$\begin{aligned} \nabla^2\phi_6 &= -\frac{m^2}{4}T^2 e^{\phi_6} + (e^{-2\phi_6}H, H) \\ \frac{1}{2}\nabla^2 T &= -\frac{m^2}{2}T e^{\phi_6} - \frac{1}{2}\left(e^{4\nu} f'_+(T) F_{[3]+}, F_{[3]+}\right) - \frac{1}{2}\left(e^{4\nu} f'_-(T) F_{[3]-}, F_{[3]-}\right) \\ 8\nabla^2\nu &= -2\left(e^{4\nu} f_+(T) F_{[3]+}, F_{[3]+}\right) - 2\left(e^{4\nu} f_-(T) F_{[3]-}, F_{[3]-}\right) \\ 0 &= d*(He^{-2\phi_6}) \\ 0 &= d*(F_{[3]+} e^{4\nu} f_+(T)) \\ 0 &= d*(F_{[3]-} e^{4\nu} f_-(T)) \end{aligned} \tag{3.3}$$

supplemented with the charge quantisation conditions

$$Q_{1\pm} = \frac{1}{4\pi^2 g\alpha'}\int_{S^3} *e^{4\nu}F_{[3]\pm} \qquad \text{and} \qquad Q_{5\pm} = \frac{1}{4\pi^2 g\alpha'}\int_{S^3} F_{[3]\pm} \,, \tag{3.4}$$

and similarly for the NS field H. For radially symmetric configurations the latter can be implemented by writing the RR-3 form as ($r_i^2 = gQ_i\alpha'$)

$$F_{[3]\pm} = 2r_{5\pm}^2\epsilon_3 + 2r_{1\pm}^2 e^{-4\nu} * \epsilon_3 \,, \tag{3.5}$$

where ϵ_3 is the volume form of the unit 3-sphere. The 'effective' potential for the tachyon on field and the size of the internal space ν is then found to be[1]

$$V_{eff}(\nu,T)=\frac{m^2}{2}T^2e^{\phi_6}+\frac{4}{V_3^2}\left(e^{-4\nu}\left(\frac{r_{1+}^4}{f_+(T)}+\frac{r_{1-}^4}{f_-(T)}\right)+e^{4\nu}(r_{5+}^4f_+(T)+r_{5-}^4f_-(T))\right), \tag{3.6}$$

where V_3 is the volume of the 3-sphere. In the NS sector one finds a similar potential with ν replaced by ϕ_6.

Here we are interested in non-dilatonic solutions. Equating $\frac{\partial}{\partial T}V_{eff}=\frac{\partial}{\partial\nu}V_{eff}=0$ we find

$$\begin{aligned}T&=0\,,\\ e^{8\nu}&=\frac{r_{1+}^4+r_{1-}^4}{r_{5+}^4+r_{5-}^4}\,,\\ 0&=e^{-4\nu}\left(-r_{1+}^4+r_{1-}^4\right)+e^{4\nu}\left(r_{5+}^4-r_{5-}^4\right),\end{aligned} \tag{3.7}$$

where we have used the fact that $f_\pm(0)=\pm f'_\pm(0)=1$. Note that this is satisfied for any RRT coupling $f_\pm(T)$ that agrees with $1\pm T$ up to $O(T)$. A particular solution of the the system (3.7) is given by $r_{i+}=r_{i-}$, $i=1,5$. This is the solution discussed in a paper by Costa [8]. However, (3.7) admits yet another set of solutions for $r_{i-}=0$ ($r_{i+}=0$). This new class of black hole solutions has electric (Dp_+) brane charge but no magnetic charge. More precisely one finds

$$e^{4\nu}=\frac{r_1^2}{r_5^2}\qquad\text{and}\qquad ds_6^2=\frac{r^2}{r_1r_5}(-\mathrm{d}t^2+\mathrm{d}z^2)+\frac{r_1r_5}{r^2}(\mathrm{d}r^2+r^2\mathrm{d}\Omega_3^2)\,. \tag{3.8}$$

Note that we have chosen the solution which is AdS_{2+1} for all r (up to identifications). It corresponds to the near horizon regime of the asymptotically flat solution. The present solution is more suitable for reasons of stability but encodes the essential features of asymptotically flat black holes [14].

The obvious question that arises now is whether the set of all these solutions is connected. This turns out to be the case. Indeed (3.7) admits a family of solutions with

$$r_{1+}=r_{5+}\equiv r_+\qquad\text{and}\qquad r_{1-}=r_{5-}\equiv r_-\,, \tag{3.9}$$

but $r_+\neq r_-$. This family interpolates between the set of D$p_\pm$ black holes discussed by Costa [8] and the the set of electric (Dp_+) solutions described above. The metric for the interpolating solutions (3.9) can be obtained from (3.8) upon substitution

$$r_1^2=r_5^2=\sqrt{r_+^4+r_-^4}\,. \tag{3.10}$$

[1]To obtain the correct potential one proceeds, as in [13], on the level of the equations of motion. Naive substitution of (3.5) into the action leads to the wrong sign for the electric potential.

To summarise: *the low energy effective action for type-0B theory admits a continuous family of solutions interpolating between the* $\mathrm{D}1_\pm\mathrm{D}5_\pm$ *and the* $\mathrm{D}1_+\mathrm{D}5_+$ *configurations. This deformation preserves the non-dilatonic background.*

In the NS sector we parameterise H by

$$H = 2r_5^2\epsilon_3 + 2r_1^2 e^{2\phi} * \epsilon_3 \,. \tag{3.11}$$

The corresponding solution is as in the type-II case

$$\begin{aligned} ds_6^2 &= \frac{r^2}{r_1 r_5}(-\mathrm{d}t^2 + \mathrm{d}z^2) + \frac{r_1 r_5}{r^2}(\mathrm{d}r^2 + r^2\mathrm{d}\Omega_3^2)\,, \\ \nu &= 0\,, \\ e^{2\phi_6} &= \frac{r_5^2}{r_1^2}\,. \end{aligned} \tag{3.12}$$

Hence the metric is identical with the RR-solution. One might take this as an indication that that the configuration (3.12) is the S-dual of the $\mathrm{D}1_+\mathrm{D}5_+$ configuration. This is however misleading. As explained in section 2 and [11] the degrees of freedom of the $\mathrm{D}1_+$ string do not match those of the fundamental string.

To obtain the (extremal) black hole one proceeds as usual [15] by adding momentum in the z direction, that is

$$\begin{aligned} ds_6^2 &= \frac{r^2}{r_1 r_5}\left(-\mathrm{d}t^2 + \mathrm{d}z^2 + K(\mathrm{d}t + \mathrm{d}z)^2\right) + \frac{r_1 r_5}{r^2}(\mathrm{d}r^2 + r^2\mathrm{d}\Omega_3^2)\,, \\ K &= \frac{r_K^2}{r^2}\,. \end{aligned} \tag{3.13}$$

The corresponding five-dimensional black hole is obtained by comparing (3.13) to the form

$$ds_6^2 = e^{\frac{2}{3}\lambda} ds_5^2 + e^{2\lambda}(\mathrm{d}z + A_\mu^K)^2\,. \tag{3.14}$$

The resulting (near horizon) five dimensional black hole metric is as in the type-IIB case

$$\begin{aligned} ds_5^2 &= -\frac{1}{f^{2/3}}\mathrm{d}t^2 + f^{1/3}\left(\mathrm{d}r^2 + r^2\mathrm{d}\Omega_3^2\right)\,, \\ f &= \frac{r_1^2 r_5^2}{r^4}\left(1 + \frac{r_K^2}{r^2}\right)\,. \end{aligned} \tag{3.15}$$

Stability: an important issue in all type-0 configurations is their stability. For the configuration with unequal electric and magnetic charge the new issue arising is the mixing tachyonic- and ν-modes[2] (recall ν describes the internal volume). More precisely the mass matrix becomes

$$M = 8\begin{pmatrix} \frac{m^2}{8} + \frac{1}{r_1 r_5} & \frac{4q^2}{(r_1 r_5)^3} \\ \frac{4q^2}{(r_1 r_5)^3} & \frac{16}{r_1 r_5} \end{pmatrix}\,, \tag{3.16}$$

[2]See also [9] for an extensive discussion of stability for equal charges.

where $q = r_{1+}^2 r_{5+}^2 - r_{1-}^2 r_{5-}^2$ is the deformation parameter. On the other hand, in the 6-dimensional Einstein metric the radius of the AdS_3-factor is given by $l^2 = r_1 r_5$. Linear stability for the scalar perturbations T and ν then requires

$$r_1 r_5 \leq -\frac{1}{\lambda_-}\,, \tag{3.17}$$

where λ_- is the smaller eigenvalue of M. For M as in (3.16) one then obtains

$$-\frac{1}{4r_1r_5} \leq \left(\frac{17}{r_1r_5} - \frac{1}{4\alpha'}\right) - \sqrt{\left(\frac{15}{r_1r_5} + \frac{1}{4\alpha'}\right)^2 + 4\frac{16q^2}{(r_1r_5)^6}}\,, \tag{3.18}$$

where we have used that $m^2 = -2/\alpha'$. In the case of equal charges this leads to[3]

$$r_1 r_5 \leq \left(4 + \frac{1}{2}\right)\alpha'\,. \tag{3.19}$$

In the opposite limit, that is for $Q_{i-} = 0$ one finds

$$r_1 r_5 \leq \frac{1}{2}\left(\frac{137}{129}\right)\alpha'\,. \tag{3.20}$$

In either case the curvature is of order of α' and hence corrections to the metric are to be expected unless the backgrounds is protected. It was observed before (e.g. [7, 8]) that this applies to $AdS_{2+1} \times S^3$ backgrounds provided these corrections can be written in terms of the Weyl tensor only.

For the F1NS5 configuration there is no mixing between the tachyon and ν and consequently linear stability requires

$$\frac{\alpha'}{2} \geq e^{\phi_6} r_1 r_5 = g Q_5 \alpha', \tag{3.21}$$

where g is the string coupling.

4. World volume theory

The metric of the $D1_+D5_+$ black hole described in the last section is identical with that of the type IIB black hole solution. The geometric entropy and the Hawking decay rate are therefore also identical. If the black hole background described in the last section is a consistent ground state of string theory then it should be possible to reproduce these features form the world volume theory of the $D1_+D5_+$ system. This task is, however, complicated by the absence of supersymmetry or equivalently, by the presence of the tachyon which prevents us from interpolating the background to curvature much smaller than $1/\alpha'$. As a result the predictions for the world volume theory can be trusted only up to α'- corrections.

[3]The extra 1/2 compared to [8] comes when one takes into account that for a scalar field in AdS_{2+1} stability is compatible with $m^2 = -1/l^2$.

JHEP11(1999)011

As a first step towards a detailed understanding of the world volume theory we discuss the existence an the nature of the $D1_+D5_+$ bound state.[4] For this we compute the open string loop amplitude in terms of the corresponding boundary states [11]. For the NS-NS sector we have

$$\langle Bp, \epsilon | e^{-lH_c^{osc}} | Bs, \epsilon' \rangle_{NSNS} = \mathrm{Tr}_{NS} \left(e^{-2lL_0} (\epsilon\epsilon')^F \prod_{\mu=p+3}^{s+2} (-1)^{B_\mu} \right), \tag{4.1}$$

where

$$(-1)^{B_\mu} \alpha_m^\nu (-1)^{B_\mu} = \begin{cases} \alpha_m^\nu & \mu \neq \nu \\ -\alpha_m^\nu & \mu = \nu \end{cases} \tag{4.2}$$

and the same relation for the fermionic modes ψ_m^ν. Here H_c^{osc} is the oscillator part of the closed string hamiltonian. The RR sector works analogously. The relevant amplitudes are then given by

$$\langle Bp, + | e^{-tH_c^{osc}} | Bp, + \rangle = \frac{f_3^8(\tilde{q})}{f_1^8(\tilde{q})} - \frac{f_2^8(\tilde{q})}{f_1^8(\tilde{q})}$$

and

$$\langle Bp, + | e^{-tH_c^{osc}} | Bs, + \rangle = \frac{f_3^{8-\nu}(\tilde{q})}{f_1^{8-\nu}(\tilde{q})} \frac{f_4^\nu(\tilde{q})}{f_2^\nu(\tilde{q})}, \qquad p < s\,, \tag{4.3}$$

where $\nu = s - p$, $\tilde{q} = e^{-2\pi l}$ and the functions $f_i(\tilde{q})$ can be found in [16]. In order to obtain the potential between two branes separated by a distance r, we perform the remaining integral over the momenta leading to

$$V_{p,p}(r) = -\int \frac{\mathrm{d}t}{2t} (8\pi^2\alpha' t)^{-\frac{p+1}{2}} e^{-t\tilde{r}^2} \left(\frac{f_3^8(q)}{f_1^8(q)} - \frac{f_4^8(q)}{f_1^8(q)} \right) \tag{4.4}$$

and

$$V_{p,s}(r) = -\int \frac{\mathrm{d}t}{2t} (8\pi^2\alpha' t)^{-\frac{p+1}{2}} e^{-t\tilde{r}^2} \left(\frac{f_3^{8-\nu}(q)}{f_1^{8-\nu}(q)} \frac{f_2^\nu(q)}{f_4^\nu(q)} \right), \tag{4.5}$$

where $\tilde{r}^2 = r^2/(2\pi\alpha')$, $q = e^{-\pi t}$ and we have expressed the result in terms of the more familiar open string one loop amplitude via the substitution $l = 1/(2t)$. At short distances which corresponds to $t \to \infty$, the potential between $D1_+$ and $D5_+$ branes is then obtained by expanding the integrand i.e.

$$\frac{f_3^8(q)}{f_1^8(q)} - \frac{f_4^8(q)}{f_1^8(q)} = 16 + O(q) \qquad \text{and} \qquad \frac{f_3^{8-\nu}(q)}{f_1^{8-\nu}(q)} \frac{f_2^\nu(q)}{f_4^\nu(q)} = 2^{\nu/2} + O(q)\,. \tag{4.6}$$

As they stand the t-integrals are, however, not well defined due to the divergence at $t \to 0$. Of course, the full string theory result should be finite. As explained in [17] the divergences in (4.6) are related to the presence of a tachyonic mode in the closed string sector and the coefficients of the counter terms needed to cancel the small t

[4]We refer the reader to [8] for the analogous analysis of the $Dp_\pm$ bound states.

divergences will depend on the details of the tachyon condensation. Fortunately for $V_{1,1}$ and $V_{1,5}$ it turns out that the counter term is r independent and can therefore be discarded. For $r^2 \ll \alpha'$ and $\Lambda = \sqrt{\alpha'}$ the resulting potentials read

$$V_{1,1}(r) = -\frac{\tilde{r}^2}{\pi^2\alpha'}\log(\tilde{r}^2) \qquad \text{and} \qquad V_{1,5}(r) = \frac{1}{4}V_{1,1}(r)\,. \tag{4.7}$$

In contrast to the D3_+ system [7], the potential for D1_+D1_+ and for D1_+D5_+ is attractive for small distances. This is consistent with the existence of a conformal (non-dilatonic) gravitational background. For a D5_+D5_+-pair the potential takes the form

$$V_{5,5}(r) = c_0 + c_1\tilde{r}^2 + c_2\tilde{r}^4 + \frac{\tilde{r}^6}{3!64\pi^6(\alpha')^3}\log(\tilde{r}^2)\,. \tag{4.8}$$

As mentioned above the constants c_i depend on the details of the tachyon condensation which is not understood in detail so far. We are therefore unable to fix them at present. The configuration with $\tilde{r} = 0$ (i.e. all D5_+ on top of each other) is an extremum of $V_{5,5}(r)$ for all values of the c_i. However, the sign of c_1 determines whether this configuration is stable. If the stable configuration is at $r > 0$ then, unless $Q_5 \ll Q_1$ most of the $(1,1)$ and the $(1,5)$ strings will be massive and will not contribute significantly to the entropy. If, on the other hand all of the D5_+ branes are on top of each other then the $(1,1)$ and the $(1,5)$ strings will be massless. However, a naive counting of the massless degrees of freedom still only accounts for 2/3 of the Beckenstein-Hawking entropy. Indeed the $4Q_1Q_5$ bosonic degrees of freedom lead to a central charge [15]

$$c = 4Q_1Q_5\,, \tag{4.9}$$

which is to be compared with $c = 6Q_1Q_5$ in the type-IIB case. The difference is, of course, due to the absence of fermions in the world volume theory. However, because the world volume theory is interacting even in the infrared the arguments presented above are probably too naive and a more quantitative analysis of the world volume theory will be needed.

5. Discussion

In this paper we have described a new class of non-dilatonic type-0 backgrounds distinguished by the fact that only one of the two RR-fluxes ($F_{[n]\pm}$) is active. Unlike previous non-dilatonic backgrounds the solutions described here cannot be obtained by a projection of some type-II BPS state. In particular we constructed an AdS_{2+1} (BTZ) black hole from 'electric' D1_+D5_+ branes. A novel feature of this configuration is the absence of fermions in the world volume theory. The existence of a non-dilatonic gravity dual suggests, however, that in the IR the world volume theory should nevertheless flow to a conformal field theory. In this paper we presented but a qualitative analysis the world volume theory. From a more detailed analysis of the

JHEP11(1999)011

interactions we may hope to gain valuable insight into the role of fermions in the microscopic theory of black holes. For that purpose the observation that the system can be continuously deformed form the $D1_{\pm}D5_{\pm}$ to the $D1_{+}D5_{+}$ configuration may prove useful. As for all type-0 configurations a tachyonic instability develops when the curvature decreases below the string scale. It seems reasonable to believe that this instability should have an analogue in the world volume theory, for example, in form of a large N phase transition. A similar proposal has been made recently in [18] for the world volume theory of the non-supersymmetric D3-brane system of type-0 theory. It would be interesting to analyse the D1D5-brane system from this point of view.

Acknowledgments

The author would like to thank the Department of Mathematics at Kings College London for hospitality during the final stages of this work. This work was supported by a Swiss Government TMR Grant, BBW Nr. 970557.

References

[1] A. Strominger and C. Vafa, *Microscopic origin of the Bekenstein-Hawking entropy*, *Phys. Lett.* **B 379** (1996) 99 [hep-th/9601029];
A. Sen,*Extremal black holes and elementary string states, Mod. Phys. Lett.* **A 10** (1995) 2081 [hep-th/9504147];
M. Cvetič and A.A. Tseytlin, *Solitonic strings and BPS saturated dyonic black holes, Phys. Rev.* **D 53** (1996) 5619 [hep-th/9512031], erratum *ibid.* **D55** (1997) 3907;
G. Horowitz and A, Strominger, *Counting states of near-extremal black holes*, *Phys. Rev. Lett.* **77** (1996) 2368 [hep-th/9602051].

[2] D. Brown and M. Henneaux, *Central charges in the canonical realization of asymptotic symmetries: an example from three-dimensional gravity, Comm. Math. Phys.* **104** (1986) 207.

[3] A. Strominger, *Black hole entropy from near horizon microstates*, *J. High Energy Phys.* **02** (1998) 009 [hep-th/9712251];
D. Birmingham, I. Sachs and S. Sen, *Entropy of three-dimensional black holes in string theory, Phys. Lett.* **B 424** (1998) 275 [hep-th/9801019];
M. Banados, T. Brotz, M. Ortiz, *Boundary dynamics and the statistical mechanics of the (2+1)-dimensional black hole, Nucl. Phys.* **B 545** (1999) 340 [hep-th/9802076].

[4] O. Coussaert, M. Henneaux, and P. van Driel, *The asymptotic dynamics of three-dimensional Einstein gravity with a negative cosmological constant*, *Class. and Quant. Grav.* **12** (1995) 2961 [gr-qc/9506019].

[5] S. Carlip, *What we don't know about BTZ black hole entropy*, *Class. and Quant. Grav.* **15** (1998) 3609 [hep-th/9806026].

[6] N. Seiberg and E. Witten, *The D1/D5 system and singular CFT*, *J. High Energy Phys.* **04** (1999) 017 [hep-th/9903224].

[7] I.R. Klebanov and A.A. Tseytlin, *D-branes and dual gauge theories in type-0 strings*, *Nucl. Phys.* **B 546** (1999) 155 [hep-th/9811035]; *Asymptotic freedom and infrared behavior in the type-0 string approach to gauge theory*, *Nucl. Phys.* **B 547** (1999) 143 [hep-th/9812089]; *A nonsupersymmetric large-N CFT from type-0 string theory*, *J. High Energy Phys.* **03** (1999) 015 [hep-th/9901101].

[8] M.S. Costa, *Intersecting D-branes and black holes in type-0 string theory*, *J. High Energy Phys.* **04** (1999) 016 [hep-th/9903128].

[9] H.W. Lee, Y.S. Myung, and J.Y. Kim, *Tachyon and fixed scalars of* $D5_{\pm}$-$D1_{\pm}$ *black hole in type-0B string theory*, *J. High Energy Phys.* **10** (1999) 014 [hep-th/9907024].

[10] L.J. Dixon and J.A. Harvey, *String theories in ten-dimensions without space-time supersymmetry*, *Nucl. Phys.* **B 274** (1986) 93;
N. Seiberg and E. Witten, *Spin structures in string theory, Nucl. Phys.* **B 276** (1986) 272.

[11] O. Bergman and M.R. Gaberdiel, *A nonsupersymmetric open string theory and S-duality*, *Nucl. Phys.* **B 499** (1997) 183 [hep-th/9701137]; *Dualities of type-0 strings*, *J. High Energy Phys.* **07** (1999) 022 [hep-th/9906055].

[12] M.R. Garousi, *String scattering from D-branes in type-0 theories*, *Nucl. Phys.* **B 550** (1999) 225 [hep-th/9901085].

[13] M. Cvetic and A.A. Tseytlin, *Charged string solutions with dilaton and modulus fields*, *Nucl. Phys.* **B 416** (1994) 137 [hep-th/9307123].

[14] K. Sfetsos and K. Skenderis, *Microscopic derivation of the Bekenstein-Hawking entropy formula for nonextremal black holes*, *Nucl. Phys.* **B 517** (1998) 179 [hep-th/9711138];
I. Sachs, *On universality in black hole thermodynamics,* proceedings, PASCOS98, hep-th/9804173.

[15] C.G. Callan and J.M. Maldacena, *D-brane approach to black hole quantum mechanics*, *Nucl. Phys.* **B 472** (1996) 591 [hep-th/9602043].

[16] J. Polchinski and Y. Cai, *Consistency of open superstring theories*, *Nucl. Phys.* **B 296** (1988) 91.

[17] A.A. Tseytlin and K. Zarembo, *Effective potential in nonsupersymmetric* $\mathrm{SU}(N) \times \mathrm{SU}(N)$ *gauge theory and interactions of type-0 D3-branes*, *Phys. Lett.* **B 457** (1999) 77 [hep-th/9902095].

[18] I.R. Klebanov, *Tachyon stabilization in the AdS/CFT correspondence*, hep-th/9906220.