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Flowing from a non-commutative (OM) five brane via its supergravity dual

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Abstract: The dual supergravity description of the flow between (2,0) five-brane theory and the non-commutative five-brane (OM) theory is examined at critical five-brane field strength. The self-duality of the field strength is shown to arise as a consequence of the supergravity solution. Open membrane solutions are examined in the background of the five brane giving rise to an M analogue of the non-commutative open string (NCOS) solution.

Keywords: Field Theories in Higher Dimensions, M-Theory, p-branes, AdS/CFT Correspondance.

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1. Introduction

The space/time noncommutativity that arises on D-branes in the presence of a near critical "electric" Neveu-Schwarz potential has produced some interesting surprises. In particular on a D3-brane after taking a certain limit, one is left with a new non-commutative open string theory (NCOS) that is decoupled from closed strings [1, 2]. One natural question is to determine the M-theory origin of these NCOS. The five-brane plays the role of the D-brane and the open membrane plays the role of the string. The background three form C then plays the role of the NS two form. This has motivated the investigation of the five-brane theory in the background of a non-trivial C field [3, 4]. A decoupling limit for the five-brane that is the M-theory origin of the NCOS limit was given in [5, 6]. This theory has near critical field strength and is believed to be associated with an open membrane theory in six dimensions.

Previously, the dual supergravity descriptions of different brane theories have been investigated in several contexts, for a review see [7]. In particular the soliton that interpolates between two different SUSY vacua has been interpreted as providing a description of the the flow between the corresponding decoupled brane theories [8]. This has recently been discussed for the NCOS in [5, 9]. In this paper we will examine some aspects of the supergravity dual of the five-brane theory. In particular we identify the solution to eleven-dimensional supergravity that is dual to the five-brane theory at critical field strength and also describes the flow from the conformal (2,0) theory to the non-commutative five-brane (OM) theory. This solution has been analysed previously in [10]–[14]. We will also describe the appropriate critical decoupling limit for the non-commutative five-brane (OM) theory from the supergravity point of view as an asymptotic flow.

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There is one important consideration that need to be adressed when determing the limits that one may take on the five-brane. The adapted field strength $\mathcal{H} = db + f_5^* C$ must obey the following non-linear self-duality constraint [16],

$$\frac{\sqrt{-\det g}}{6}\epsilon_{\mu\nu\rho\sigma\lambda\tau}\mathcal{H}^{\sigma\lambda\tau} = \frac{1+K}{2}(G^{-1})_\mu{}^\lambda\mathcal{H}_{\nu\rho\lambda}\,, \tag{1.1}$$

where g is the determinant of the induced spacetime metric $g_{\mu\nu}$, $\epsilon^{012345} = 1$, the scalar K and the tensor $G_{\mu\nu}$ are given by

$$K = \sqrt{1 + \frac{\ell_p^6}{24}\mathcal{H}^2}\,, \tag{1.2}$$

$$G_{\mu\nu} = \frac{1+K}{2K}\left(g_{\mu\nu} + \frac{\ell_p^6}{4}\mathcal{H}^2_{\mu\nu}\right). \tag{1.3}$$

This presents a small puzzle; why should the bulk supergravity three form potential obey such a self-duality constraint? Here we will analyse the five-brane supergravity solution described in [12] and demonstrate how this solution leads to the non-linear self-duality of C pulled back to the five-brane and also how one may describe the critical field limit, crucial to the NCOS construction, from the point of view of the five-brane SUGRA solution.

We will also examine the five-brane directly in six dimensions from the open membrane point of view. A solution to the open membrane equations of motion in the background of near critical field strength is presented that is the natural lift of the string solution given in [2]. The properties of this solution are in accordance with the physical picture of the critical field limit where the tension of the membrane cancels the force excerted due to the charged membrane boundary. This solution describes how the membrane becomes absorbed into the five-brane worldvolume which is also in agreement with the dual supergravity solution. Related ideas concerning the non-commutaive five-brane (OM) theory and NCOS can be found in [17].

2. The supergravity description

A five-brane solution of eleven-dimensional supergravity with a finite deformation of the spacetime three-form potential was found in [10, 11, 12]. Here we will use the notation of [12]. ($\mu = 0, 1, \ldots, 5$; $p = 6, \ldots, 9, 11$):

$$\begin{aligned} ds^2 &= (\Delta^2 - \nu^2)^{-1/6}\left(\left(\frac{\Delta+\nu}{\Delta-\nu}\right)^{1/2} dx_-^2 + \left(\frac{\Delta-\nu}{\Delta+\nu}\right)^{1/2} dx_+^2\right) + \\ &\quad + (\Delta^2 - \nu^2)^{1/3} dy^2\,, \end{aligned} \tag{2.1}$$

$$H_{pqrs} = \ell_p^{-3}\epsilon_{pqrst}\partial_t\Delta\,, \qquad \Delta = k + \frac{R^3}{r^3}\,, \quad R \equiv N^{1/3}\ell_p\,, \tag{2.2}$$

$$H_{\mu\nu\rho p} = \ell_p^{-3} e_\mu{}^i e_\nu{}^j e_\rho{}^k F_{ijk}\partial_p\Delta\,, \tag{2.3}$$

where k and R are integration constants and F_{ijk} $(i = 0, 1, \ldots, 5)$ is the following three-form;

$$F_{ijk} = (\Delta^2 - \nu^2)^{-1/2} \left(\frac{(\delta_i^l + \frac{1}{2\nu} q_i{}^l) h_{ljk}}{2(\Delta + \nu)^{1/2}} + \frac{(\delta_i^l - \frac{1}{2\nu} q_i{}^l) h_{ljk}}{2(\Delta - \nu)^{1/2}} \right), \tag{2.4}$$

$$h_{ijk} = \frac{1}{6} \epsilon_{ijklmn} h^{lmn}, \qquad q_{ij} = h_{ikl} h_j{}^{kl}, \qquad \nu^2 = \frac{1}{24} q^{ij} q_{ij}. \tag{2.5}$$

The spatial line element dx_+^2 and the lorentzian line element dx_-^2 are given by

$$dx_\pm^2 = \frac{1}{2} \delta_\mu^i \delta_\nu^j \left(\delta_{ij} \pm \frac{1}{2\nu} q_{ij} \right) dx^\mu dx^\nu. \tag{2.6}$$

The geometry of the solution was analysed in [12]. To avoid naked singularities the parameter ν must be restricted to $0 \leq \nu \leq k$. There are three distinct cases.

(i) $\nu = 0$ the solution is the usual five-brane metric with $AdS_7 \times S^4$ in the near horizon.

(ii) $0 < \nu < k$, this is a non-critical field strength deformation. The solution interpolates between the near horison $AdS_7 \times S^4$ geometry of N coinciding five-branes and flat spacetime at $r = \infty$.

(iii) $\nu = k$, this is the critical field strength deformation, it interpolates between $AdS_7 \times S^4$ and the geometry of an array of membranes stretched in the x_- direction and "smeared" in the x_+ direction. The line element is given below in (2.7).

The precise justification for relating ν to the field strength on the five-brane is given below when we analyse the properties of C_3. It is the third case we wish to study. In the asymptotic region, $r \to \infty$ one recovers the "smeared" membrane metric:

$$ds^2 = \left(\frac{r}{R} \right)^2 dx_-^2 + \frac{R}{r} (dx_+^2 + dy^2). \tag{2.7}$$

As disussed in [12] the solution has 16 unbroken supersymmetries. As we flow to AdS, $r \to 0$ we have the usual $16 \to 32$ symmetry restoration. This metric (2.7) had also been investigated in the context of seven-dimensional domain wall supergravity with 16 unbroken supersymmetries [18]. The fact it is the smeared membrane metric that appears in the world volume of the five-brane is consistent with the OM interpretation of the critical field limit [5], see the discussion below.

We next determine the three form potential that is induced on the five-brane worldvolume. This essentially means that one must solve the field strength $H_{p\mu\nu\rho}$ for the potential $C_{\mu\nu\rho}$, where

$$H_{\mu\nu\rho p} = -\partial_p C_{\mu\nu\rho} + 3 \partial_{[\mu} C_{\nu\rho]p}. \tag{2.8}$$

First, making use of the algebraic properties of h_{ijk} we determine,

$$H_{\mu\nu\rho p} = \ell_p^{-3} (\Delta^2 - \nu^2)^{-2} \delta_\mu^i \delta_\nu^j \delta_\rho^j \left((\Delta^2 + \nu^2) \delta_i^l - \Delta q_i{}^l \right) h_{ljk} \partial_p \Delta. \tag{2.9}$$

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Then, fixing a gauge so that $C_{\mu\nu p} = 0$ (which preserves the background symmetry) we may solve for $C_{\mu\nu\rho}$ as follows:

$$C_{\mu\nu\rho} = \ell_p^{-3} \delta_\mu^i \delta_\nu^j \delta_\rho^k \left(\frac{(\delta_i^l + \frac{1}{2\nu} q_i{}^l)}{2(\Delta+\nu)} + \frac{(\delta_i^l - \frac{1}{2\nu} q_i{}^l)}{2(\Delta-\nu)} \right) h_{ljk} \,. \tag{2.10}$$

Introducing an $\frac{\mathrm{SO}(5,1)}{\mathrm{SO}(3)\times\mathrm{SO}(2,1)}$ valued sechsbein, $\{v_\mu{}^\alpha, u_\mu{}^a\}$, $\alpha = 0,1,2$, $a = 3,4,5$, of the induced metric, $g_{\mu\nu}$ at $r=\infty$ as follows:

$$g_{\mu\nu} = \partial_\mu X^M \partial_\nu X^N g_{MN}|_{r=\infty} = \eta_{\alpha\beta} v_\mu{}^\alpha v_\nu{}^\beta + \delta_{ab} u_\mu{}^a u_\nu{}^b \,, \tag{2.11}$$

we can write the pull-back of C at infinity

$$C_{\mu\nu\rho}|_{r=\infty} = \ell_p^{-3} \left(\frac{2\nu}{k+\nu}\right)^{1/2} \epsilon_{\alpha\beta\gamma} v_\mu^\alpha v_\nu^\beta v_\rho^\gamma + \ell_p^{-3} \left(\frac{2\nu}{k-\nu}\right)^{1/2} \epsilon_{abc} u_\mu^a u_\nu^b u_\rho^c \tag{2.12}$$

$$= \frac{h}{\sqrt{1+h^2\ell_p^6}} \epsilon_{\alpha\beta\gamma} v_\mu^\alpha v_\nu^\beta v_\rho^\gamma + h \epsilon_{abc} u_\mu^a u_\nu^b u_\rho^c \,, \quad h^2 \ell_p^6 = \frac{2\nu}{k-\nu} \,. \tag{2.13}$$

The purpose of this rewriting is that we can then identify the three-form (2.13) with the solution to the five-brane non-linear self-duality equation (1.1), described in [3]. Thus the vacuum at $r=\infty$ has a non-trivial three-form potential (2.13) in the five-brane directions, and moreover it in fact obeys the five-brane field equation (1.1). Hence we may identify

$$\mathcal{H}_{\mu\nu\rho} = C_{\mu\nu\rho}|_{r=\infty} \,. \tag{2.14}$$

The critical field strength limit described in [5, 6] is when $h^2 \ell_p^6 \to \infty$. From (2.13) we see this occurs in the asymptotic region when $\nu \to k$. Hence this justifies our identification of the $\nu = k$ case with the critical field strength limit. It is important notice that the non-linear nature of the five-brane self-duality is crucial for the critical limit. (Linear self-duality would not allow a critical limit.)

We now wish to describe a decoupling limit, i.e. a limit whereby $\ell_p \to 0$, which has an asymptotic region with five-brane metric and field strength scaling as described in [5, 6]. The decoupling limit must obey the criteria that the line element $\ell_p^{-2} ds^2$ and the four-form field strength H are held fixed (such that the supergravity action is finite for this background; by making N large the curvature becomes small and the supergravity approximation makes sense).

Thus we are drawn to consider the following limit:

$$\nu = k = \frac{\ell_g^{3n}}{2\ell_p^{3n}} \,, \qquad \tilde{x}_\pm = \ell_g^{-n/2} \ell_p^{n/2-1} x_\pm \,, \qquad \tilde{r} = \frac{\ell_g^n r}{\ell_p^{1+n} N^{1/3}} \,, \tag{2.15}$$

where $\tilde{x}_\pm$, $\tilde{r}$ and the length scale ℓ_g are fixed and[1] $n > 0$. After rewriting in terms of

[1] This condition follows from considering the graviton absorption cross section [19]; this was pointed out to us by M. Alishahiha.

Figure 1: The flow as controlled by $\tilde{r}$ to the (2,0) theory from the NC five-brane (OM) theory is given by the interpolation between $AdS_7 \times S^4$ and the smeared membrane metric.

fixed variables one has:

$$\frac{ds^2}{\ell_p^2} = f^{1/3}\tilde{r}^2 d\tilde{x}_-^2 + f^{-2/3}\tilde{r}^{-1}d\tilde{x}_+^2 + N^{2/3}f^{1/3}\tilde{r}^{-1}(d\tilde{r}^2 + \tilde{r}^2 d\Omega^2)\,, \tag{2.16}$$

$$H_4 = N\epsilon_4(S^4) + \frac{1}{2}d\left(\tilde{r}^3 d\tilde{x}_-^3 + f^{-1}d\tilde{x}_+^3\right), \tag{2.17}$$

$$f = 1 + \tilde{r}^{-3}\,. \tag{2.18}$$

This does not describe a field theory limit in the asymptotic region. It would be wrong to expect a field theory description of the non-commutive five-brane, just as one does not have a field theory description for the D3-brane with temporal noncommutativity. The five-brane with non-trivial C in a decoupling limit has also been considered in [14] and indeed the line element (2.16) was found. This predated the discussion of the non-commutative five-brane (OM) theory and the importance of the critical field limit.

One may then check that scaling $\tilde{r} \sim \epsilon^{-1/3}$ exactly reproduces the scaling taken for the non-commutative five-brane (OM) theory [5, 6]:

$$\begin{aligned} &\ell_p \longrightarrow \epsilon^{1/3}\,, \qquad &&\mathcal{H}_{\alpha\beta\gamma} \longrightarrow \epsilon^{-1}\,, \qquad &&\mathcal{H}_{abc} \longrightarrow \epsilon^{0}\,, \\ &g_{\alpha\beta} \longrightarrow \epsilon^{0}\,, &&g_{ab} \longrightarrow \epsilon^{1}\,. \end{aligned} \tag{2.19}$$

One important property of this limit is that the open membrane metric described in [6] is fixed in units of ℓ_p.

In summary, the solution (2.1)–(2.2) interpolates between a stack of five-branes at $r = 0$ with zero field strength and a stack of five-branes at $r = \infty$ with non-vanishing field strength $\mathcal{H}_{\mu\nu\rho}$ given by (2.14). The solution is fixed in the limit given by $\ell_p \to 0$ and (2.15), which flows to a decoupled six-dimensional non-commutative five-brane (OM) theory.

It is worth remarking that such a limit is only possible at critical field strength. In the non-critical case, $0 < \nu < k$, one cannot obtain a brane decoupled from the bulk theory. This is consistent with how the NCOS limit requires critical field strength to decouple the bulk modes.

3. Critical open membrane solution

We may interpret the source of the constant field strength at $r = \infty$ as an array of self-dual strings stretched along the boundary of the space in the x_- direction and smeared homogeneously in the x_+-directions. These self-dual strings are boundaries of open membranes. In the critical limit, given by $\nu = 1$, the open membranes become dissolved into the five-brane. This is exactly analogous to how open strings behave in D3-brane with the critical field strength [1, 2].

We will now illustrate this by analysing the solutions of the membrane field equations in the background provided by a five-brane with critical field strength.

The membrane is described by the following equations of motion, constraints and boundary conditions [20].

$$
\begin{aligned}
\ddot{X}^\mu + \frac{1}{\ell_p^2}\{X^\nu, \{X^\mu, X_\nu\}\} &= 0\,,\\
\dot{X}^2 &= -\frac{1}{2\ell_p^2}\{X^\mu, X^\nu\}\{X_\mu, X_\nu\}\,,\\
\dot{X}^\mu \partial_i X_\mu &= 0\,, \qquad i = \rho, \sigma\,,\\
\frac{1}{\ell_p^2}\sqrt{-\det\gamma}\, n^\alpha \partial_\alpha X_\mu + \epsilon^{\alpha\beta\gamma}\mathcal{H}_{\mu\nu\rho} n_\alpha \partial_\alpha X^\nu \partial_\gamma X^\rho &= 0\,,
\end{aligned}
\tag{3.1}
$$

where $\dot{X}^\mu$ and $\partial_i X^\mu$ denote differentiation with respect to the worldvolume time τ and spatial coordinates ρ, σ, respectively,

$$
\{A, B\} = \epsilon^{ij}\partial_i A \partial_j B\,, \tag{3.2}
$$

and the determinant of the worldvolume metric is given by

$$
\sqrt{-\det\gamma} = \frac{1}{2\ell_p^4}\{X^\mu, X^\nu\}\{X_\mu, X_\nu\}\,. \tag{3.3}
$$

In what follows we shall choose the normal derivative at the boundary to be given by $n^\alpha \partial_\alpha = \partial_\rho$.

In order to find a solution we make an ansatz where the open membrane is infinitely stretched in the X^2 direction as follows:

$$
X^0 = X^0(\tau, \rho)\,, \qquad X^1 = X^1(\tau, \rho)\,, \qquad X^2 = \ell_p \sigma\,, \tag{3.4}
$$

$$
X^\mu = \text{constant}\,, \qquad \mu = 3, \ldots, 9, 11\,. \tag{3.5}
$$

This results in the equations:

$$
\begin{aligned}
\ddot{X}^\mu - X''^\mu &= 0\,,\\
(\dot{X}^0)^2 + (X'^0)^2 &= (\dot{X}^1)^2 + (X'^1)^2\,,\\
\dot{X}^0 X'^0 &= \dot{X}^1 X'^1\,,\\
X'^\mu &= H\dot{X}^\mu\,, \quad H \equiv \frac{h\ell_p^3}{\sqrt{1 + h^2\ell_p^6}}\,.
\end{aligned}
\tag{3.6}
$$

These equations are equivalent to the equations of an open string in an electric field $H = \alpha' \mathcal{F}^0{}_1 = \alpha' g^{00} \mathcal{F}_{01}$.

In case $0 \leq H < 1$ the general solution is given by

$$X^0 = \pm X^1 = a\ell_g(\tau \pm H\rho)\,, \tag{3.7}$$

where ℓ_g is a fixed length and a a real constant. In the case $H = 1$, however, there are new critical solutions appearing. The solution for $H = 1$ is given by

$$X^0 = \ell_g(a\tau + b\rho)\,, \qquad X^1 = \ell_g(b\tau + a\rho)\,. \tag{3.8}$$

Thus we have a static, non-degenerate open membrane solution given by

$$\begin{aligned} &X^0 = \ell_g\tau, \qquad X^1 = \ell_g\rho\,, \qquad X^2 = \ell_g\sigma\,, \\ &X^\mu = \text{constant}\,, \qquad \mu = 3, \ldots, 9, 11\,. \end{aligned} \tag{3.9}$$

Notice that in the limit $\ell_p \to 0$ we have carried out a reparametrisation of $\sigma \to \frac{\ell_g}{\ell_p}\sigma$. Clearly this does not affect the geometry of the solution.

The length scale ℓ_g for this solution is the scale introduced in [5, 6]. This is the effective tension of the open membrane inside the five-brane and is related to the five-brane field strength by $\ell_g = (h^2\ell_p^9)^{1/3}$.

Thus the solution describes a membrane stretched out inside the five-brane in the $0, 1, 2$ directions. This is what one expects from the dissolved membrane interpretation of the five-brane supergravity solution given by (2.7).

Physically, one sees that the membrane tension (which is scaled to ∞) is cancelled by the scaling of the electric field so that the membrane retains a finite length scale. This is reminiscent of the zero force condition experienced by BPS solutions. It would be interesting to see whether the cancellation properties persist (as they do for BPS solutions) beyond the classical level.

An obvious application would be to investigate the thermal properties of the non-commutative (OM) theory by analysing the non-extremal version of the smeared membrane metric (2.7).

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