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Semiclassical decay of near-extremal fivebranes

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Abstract: We argue that a near-extremal charge-k type II NS fivebrane can be reliably described in semiclassical string perturbation theory as long as both k and $\frac{\mu}{k}$ are large, where μ is the energy density in string units. For a small value of the asymptotic string coupling g, the dynamics in the throat surrounding the fivebrane reduces to the CGHS model with massive fields. We find that the energy density leaks off the brane in the form of Hawking radiation at a rate of order $\frac{1}{k^{7/2}}$ in string units independently of g to leading order. In the $g \to 0$ limit the radiation persists but never reaches asymptotic infinity because the throat becomes infinitely long.

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One of the most surprising and intriguing results of recent years is the discovery of hitherto-unsuspected quantum field theories without gravity in six [1] and five [2] dimensions. These theories are incompletely understood and have been analyzed by a variety of methods. In this note we shall adopt the method of [3] and deduce some properties of the fivebrane theories [1, 4] from the corresponding near-extremal black fivebrane solution. In particular we shall focus, following [4], on the theory of k nearby fivebranes with finite energy densities in string units in the limit in which the asymptotic value of the string coupling $g \to 0$.

The near-extremal string-frame charge-k fivebrane solution is [5]

$$ds^2 = -(1 - \frac{r_0^2}{r^2})dt^2 + (1 + \frac{k\alpha'}{r^2})(\frac{dr^2}{1 - \frac{r_0^2}{r^2}} + r^2 d\Omega_3^2) + dy_5^2 \, , \tag{1}$$

$$e^{2\phi} = g^2(1 + \frac{k\alpha'}{r^2}) \, . \tag{2}$$

This configuration has string-frame energy per unit five-volume

$$\frac{M}{V_5} = \frac{M_s^6}{(2\pi)^5}(\frac{k}{g^2} + \mu) \, , \tag{3}$$

where

$$\mu = \frac{r_0^2 M_s^2}{g^2} \, . \tag{4}$$

$\mu/(2\pi)^5$ is the dimensionless energy density in string units and $M_s = 1/\sqrt{\alpha'}$. As in [4] we wish to consider the case that μ is order one and so $r_0 \sim g\sqrt{\alpha'}$. To analyze the limit $g \to 0$ it is useful to introduce coordinates

$$r = r_0 cosh\sigma \, . \tag{5}$$

In these coordinates the horizon is at $\sigma = 0$, and as $g \to 0$ the asymptotically flat region moves off to infinity. For $g \to 0$ we are left with the two-dimensional black hole [6]

$$ds^2 = -tanh^2\sigma dt^2 + k\alpha' d\sigma^2 + k\alpha' d\Omega_3^2 + dy_5^2 \, . \tag{6}$$

(6) is independent of μ. The μ-dependent dilaton is

$$e^{2\phi} = \frac{k}{\mu cosh^2\sigma} \, . \tag{7}$$

Notice that the value of ϕ at the horizon (located at $\sigma = 0$) is independent of g when expressed in terms of k and μ. The dynamics of this theory were studied in [7]. In fact the CGHS model was originally derived by considering precisely this limit of near-extremal NS fivebranes.

String loop perturbation theory is good if

$$\frac{k}{\mu} \ll 1 \tag{8}$$

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so that the dilaton at the horizon is small. α' perturbation theory is good if the curvatures are small

$$k \gg 1\,. \tag{9}$$

If both expansions are good then

$$\mu \gg k \gg 1\,. \tag{10}$$

It is evidently possible to have both expansions good for $g \to 0$. In this case one can compute the leakage of energy off the brane as semiclassical Hawking radiation[1]. The Hawking temperature is

$$T_H = \frac{1}{2\pi\sqrt{k\alpha'}\,.} \tag{11}$$

This is of order the mass gap for throat excitations. Hence there will be Hawking radiation of string states, even accounting for greybody factors. Angular momentum produces a contribution to the effective mass proportional to $\frac{\ell}{\sqrt{k\alpha'}}$ along the throat, so higher angular modes can also be emitted at the temperature (11) . The rate of mass loss is

$$\frac{d\mu}{dt} \sim -\frac{M_s}{k^{7/2}}\,. \tag{12}$$

In the context of two dimensional black holes the rate of mass loss was estimated in [8] as

$$\frac{d\mu}{dt} \sim -\frac{M_s}{k}\,. \tag{13}$$

The difference is due to the fact that this last calculation does not take into account the emission of gravitons with momenta along the directions parallel of the fivebrane[2]. So (13) is correct when the fivebrane is compactified on a torus with sizes much smaller than $\sqrt{k\alpha'}$ (and bigger than $\sqrt{\alpha'/k}$). There is also some mass loss due to fivebrane emission which is finite for $g \to 0$ but suppressed in the regime (10).

This suggests that the theory of k NS fivebranes does not decouple from the throat theory for $g \to 0$ for energies of order M_s, although it does decouple from the asymptotically flat region. It may nevertheless decouple in the $k \to \infty$ limit needed for matrix theory [9]. We also note that, for finite k and $g \to 0$, there is no Hawking radiation for excitation energies far below M_s because of the mass gap in the throat. Hence the excitations of the 5+1 conformal field theories at the low energy fixed point [1] should decouple from the throat.

In the matrix description of k type II fivebranes [10, 11, 12, 13] the throat and asymptotically flat regions are the Coulomb branch of a two-dimensional gauge theory, while the branes themselves are described by the Higgs branch. Our results suggest that excitations of the Higgs branch with energy of order M_s can leak on to the Coulomb branch even for $g \to 0$.

It would be of interest to reconcile our observations with those of [4, 12, 13].

[1] One may also reliably compute the Bekenstein-Hawking entropy density as $S = \mu\sqrt{k}/(2\pi)^4$. It is of interest to note in the present context that this formula was microscopically reproduced in [3] as the entropy of a gas of strings on the fivebrane with tensions $1/2\pi k\alpha'$ and central charge 6.

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