Comments on the Entropy and the Temperature of Non-extremal Black $p$-Brane

Ken-ichi Ohshima

Institute of Physics, University of Tokyo
Komaba, Meguro-ku 153 Tokyo
email: ohshimak@hep1.c.u-tokyo.ac.jp

Abstract

We show that the exact entropy and the temperature (including coefficient) of non-extremal black $p$-brane are calculated by maximizing the entropy under several assumptions. We argue the relation of those assumptions and certain $Dp$-$D(p-2)$ system in compactified space.
1 Introduction

The microscopic origin of black hole entropy have been attached importance for years since it is regarded that its mechanism will be explained in quantum gravity theory. In string theory, Strominger and Vafa [1] showed that the exact entropy of certain class of extremal black holes is actually obtained from string theoretical microscopic model.

For near extremal case, Gubser, Klebanov and Peet [2] showed that D-brane and open string gas model provides the microscopic description of the Bekenstein-Hawking entropy of black 3-brane. The open string degree of freedom is reduced by a factor of 3/4 in their model, and this reduction is regarded as the strong coupling (large quantum correction) effect. Soon [3] showed that the supergravity result of the entropy of the near extremal p-branes in general has simple relation with the temperature and the charge like

$$S \propto q^a T^b.$$ (1.1)

In 2001, Danielsson, Guijosa, Kruczenski [7] showed that D-brane - open string gas model also provide the microscopic description of non-dilatonic Schwarzschild black branes and non-extremal black branes. The innovation they made is that the correct entropy up to coeffecient is obtained by requiring the maximization of the entropy by the number of branes and antibranes. [8] [9] extended it to general neutral p-brane and showed that similar method can be applied to get the correct entropy up to coeffecient. It is also applied to non-extremal p-branes, muti-charged branes, rotating branes [10] [11] [12] [13] [14].

In these models for non-extremal case, the energy of the gas on branes and antibranes must be indentical (to derive the correct entropy). This condition is mysterious in physical point of view especially in the fact that the temperature of the brane and antibrane are different and the Hawking temperature is described by $1/T_H = 1/T_{brane} + 1/T_{antibrane}$.

In this paper, we show that the exact entropy and the temperature (including coeffecient) of non-extremal black p-brane are calculated by maximizing the entropy under several assumptions. For $p = 3$, the exact entropy and the temperature are derived if we assume that the phenomena similar to [15] occur in black 3-brane or there are some correspondence between black 3-brane and D3-D1 system of [15]. There is no “two temperatures” in our procedure so that the Hawking temperature is directly calculated. For gen-
eral $p$, the exact entropy and the temperature are obtained from the similar procedure by requiring its statistical quantities should agree with supergravity result in near extremal limit.

The organization of this paper is as follows. In section 2, we point out some problems lying in this kind of arguments. In section 3, we show that the exact entropy and the temperature of black 3-brane are calculated, and argue its relation to D3-D1 system in [15]. In section 4, we extend the argument to general $p$-branes. Section 5 is the conclusion and discussion.

2 Problems lying in this kind of arguments

Before starting to explain our "prescription", we clarify several fundamental problems lying in this kind of arguments.

The first problem is the non-BPS nature. Even for near extremal case, large quantum correction may exist at large $N$ limit, thus we basically cannot utilize the quantities calculated at finite $N$ region for the quantities at large $N$ region. [25] [26] argued this problem for near extremal case, but for general non-extremal brane, this is open problem. Even if one finds some model which leads to the exact entropy or temperature or energy of non-extremal black $p$-branes, there is no idea to justify it physically unless we have something like "non-renormalisation theorem".

Even if we put aside the "non-renomalisation" problem and go forward to find some corresponding D-brane model, we face second problem. Many recent papers regarding non-extremal black $p$-brane use the "maximizing entropy" procedure (this paper also use it), but actually, for example for Schwarzschild black 3-brane, such calculations lead to (tension of branes) $\sim$ (gas energy) as a result. This means

$$N \tau_3 \sim N^2 T^4,$$

$$\Downarrow$$

$$T^4 \sim O\left(\frac{1}{g_s N l_s^4}\right),$$

The temperature goes infinity at $g_s N << 1$; i.e. we don’t have low energy D-brane picture for Schwarzschild black 3-brane. When $g_s N >> 1$, temperature is low but this time we cannot ignore the existence of horizon, because

$$r_H T = \frac{1}{\pi \cosh \gamma},$$

(2.1)
where $r_H$ is horizon radius, and $\gamma \to 0$ for Schwarzschild limit; i.e. we cannot ignore horizon radius in the energy scale of the Hawking temperature. We must take the curved space and horizon into account, thus it cannot be described by D-brane model in flat space, even if we assume some "non-renormalisation theorem".

Moreover, when the magnitude of the gas energy is comparable to the tension of the branes, massless (free particle) gas model is quite mysterious. Total energy of the statistical model is described as (massless gas) + (brane tension), however it is difficult to consider it as "branes excited by gas", because the excitation is too large to be described in Yang-Mills description.

Taking into consideration the problems above, we start from some limit (but in total, our argument contains imperfect step regarding this problem ). Our model has two parameters: one is the number of (charged) D3-branes $N$, another is the number of (neutral charged) effective 3-brane $n$. Schwarzschild case is $N = 0$, $n \neq 0$, and this limit contains the problem stated above. Thus we start from the case of $g_sN << 1$, $g_sn << 1$, $nN << g_sN$ (means slightly non-extremal ) where low energy D-brane picture is valid. Then we extend it for $g_sN >> 1$, $g_sn >> 1$ to finite non-extremality and Schwarzschild brane. Although we start from low energy D-brane picture we needed to introduce small neutral mass of very high temperature in our argument, and that is the imperfect step.

## 3 The entropy and temperature of black 3-brane

We should point out first that the degree of freedom of open string must be reduced by 3/4 to derive exact near extremal black 3-brane entropy (and temperature) by ordinary D-brane - open string gas model[2]. This 3/4 factor is regarded as strong coupling effect [3] [4], but the detail mechanism has not been clarified yet.

When starting to consider about non-extremal 3-branes, one faces another problem : "How to add stable neutral charged mass to the system?". Brane-antibrane system is one candidate, but at least in flat space and in weak coupling limit and at low temperature, they are unstable and should be decay. In [7], the stabilization of brane-antibrane system at large $N$ limit is argued.
But "3/4 reduced d.o.f. open string gas" and "stable neutral mass" can be simultaneously realized at low temperature and at weak coupling actually. In [15], by compactifying transverse 6 directions, stable neutral mass seems to be realized as "D1-vortices" in D3-brane. RR 2-form field become massive and D1 charges are screened. Simultaneously, gauge field on D3-brane also aquires mass. It can be decoupled when the compactified volume $V_6 \to 0$, thus the open string degree of freedom is reduced by 3/4. Now we have the model of stable neutral mass and 3/4 reduced d.o.f. at low temperature successfully.

Unfortunately the transverse direction of the black 3-brane that we consider is non-compact. Thus the above [15] system seems to have nothing to do with the current problem, but we will show below that the exact entropy and temperature is derived actually not only for near extremal case but for arbitrary non-extremal case if we assume that the similar phenomena occur in the large $N$ limit or there are some correspondences between black 3-brane and D3-D1 system of [15].

### 3.1 Entropy and temperature by statistical model

First, open string gas model on the system [15] describes black 3-brane entropy and temperature at near extremal limit correctly. We have open string gas of 3/4 reduced d.o.f. and $N$ number of D3-branes in some limit of [15], so the total energy is described as

$$E = N\tau_3 V + \frac{6\pi}{16} N^2 VT^4 \quad , \quad (3.1)$$

where the direction along the D3-brane is compactified as a torus, and $V$ is the volume of the torus. Above (3.1) leads to the exact black 3-brane entropy and temperature at near extremal limit, including coefficient $2$.

Next, we consider the situation that "D1-vortices" exists inside D3-branes. According to [15], the total brane mass seems to be described as

$$\sqrt{M_{D3}^2 + M_{D1}^2} \quad . \quad (3.2)$$

(3.2) resembles BPS bound of D3-D1, but note that at this time total D1 charge can be neutral, due to massive RR 2-form field. We assume that total D1 charge is neutral and these D1 vortices form dense string network in
D3-branes so that the network can be described as effectively 3 dimensional
branes.

Low energy approximation of fluctuation of 2-dimensional string network
was argued in [24] and result is that it can be described as massless fields.
In our case, the string network is 3-dimensional and moreover turned into
vortices in D3-branes, thus the situation is quite different. But if we assume
the fluctuation of the string network at low temperature can be described as
massless fields, the total energy is described as

\[ E = \sqrt{N^2 + n^2 \tau_3 V} + f(N, n)VT^4 \]  \hspace{1cm} (3.3)

where \( f(N, n) \) depends on the formation of the string network, and \( n \) is the
number of the ”effective 3-branes” and can be continuous value. The entropy
of this system is

\[ S = \frac{4}{3} f(N, n)VT^3 \]  \hspace{1cm} (3.4)

and we can rewrite it as

\[ S = \frac{4}{3} f(N, n)^{1/4}V^{1/4} (E - \sqrt{N^2 + n^2 \tau_3 V})^{3/4} \]  \hspace{1cm} (3.5)

from (3.3).

If \( f(N, n) \) varies in the process before equilibrium, it varies with regard
to \( n \). Thus we minimize the entropy by \( n \), then it leads to

\[ (E - \sqrt{N^2 + n^2 \tau_3 V}) \frac{\partial f}{\partial n} = 3 \frac{n}{\sqrt{N^2 + n^2 \tau_3 V}} V f . \]  \hspace{1cm} (3.6)

Next we consider how to form the non-extremal black 3-brane. Black
hole can be described by few parameters, charge, mass and so on, as far
as information is lost at the formation of the black hole. In this point of
view, the way of forming black hole is irrelevant, as far as the parameter of
resulting black hole is the same. We suppose the following case: one small
(Schwarzschild) black 3-brane \( m_s \) falls into one extremal black 3-brane (mass
\( M_e \) ) where

\[ M_e >> m_s , \]  \hspace{1cm} (3.7)

so that this collision makes only small influence on the extremal black 3-
brane. (On the contrary, if \( M_e \sim m_s \), it is difficult to predict the final state).
In the D-brane picture, the above situation means that small "neutral charged brane" corresponding to Schwarzschild black brane,

\[ E_s = n\tau_3 V + E_{\text{gas of neutral brane}} , \tag{3.8} \]

gets close to \( N \) number of coincident D-branes,

\[ E_e = N\tau_3 V . \tag{3.9} \]

"Neutral charged brane" is realized by brane-antibrane system if the system has some mechanism of preventing tachyon condensation. In [7], the stabilization of brane-antibrane system by finite temperature is argued. According to [7], the temperature

\[ T >> T_c \sim \frac{1}{(g_s n)^{1/2} t_s} , \tag{3.10} \]

is needed to avoid tachyon condensation. However we are working at \( g_s n << 1 \) region, thus the temperature of this neutral brane exceeds the Hagedorn temperature. For \( n << 1 \), the temperature is high enough to create D-brane so that the metastable state of creation / decay of brane might be realized, but it is difficult to describe what is happening in this small neutral brane and also it is difficult to describe the physics before the equilibrium when this small neutral brane collides with the large number of extremal branes.

We assume that the temperature of the gas gets lower in sufficiently short time at the collision of this small neutral brane and large number of extremal branes (of zero temperature). When the temperature gets lower than \( T_c \), the neutral brane has to decay to lower dimensional branes such as D1-brane, and then it forms bound state with the extremal 3-brane. If this lowering occur in sufficiently short time, most of the gas energy cannot turn into the tension of the neutral brane, thus the gas energy will be almost conserved after equilibrium:

\[ E_{\text{gas of non-extremal}} \simeq E_{\text{gas of neutral brane}} . \tag{3.11} \]

\( E_{\text{gas of neutral brane}} \) can be written as

\[ E_{\text{gas of neutral brane}} = \beta n\tau_3 V , \tag{3.12} \]

of some \( \beta \), then we can write as

\[ E - \sqrt{N^2 + n^2\tau_3 V} = \beta n\tau_3 V , \tag{3.13} \]
and plugging this into (3.6), we get the equation
\[
\frac{\partial f}{\partial n} = \frac{3/\beta}{\sqrt{N^2 + n^2}} f .
\] (3.14)
The solution is
\[
f(N, n) = C(\sqrt{N^2 + n^2} + n)^{3/\beta} ,
\] (3.15)
where \(C\) is a constant. We have the following statistical model for non-extremal 3-brane now:
\[
E = \sqrt{N^2 + n^2} \tau_3 V + C(\sqrt{N^2 + n^2} + n)^{3/\beta} VT^4 ,
\] (3.16)
\[
S = \frac{4}{3} C(\sqrt{N^2 + n^2} + n)^{3/\beta} VT^3 .
\] (3.17)
We can take the near extremal limit \((n/N \to 0)\) of this model smoothly. The near extremal limit of (3.16) (3.17) is
\[
E = N\tau_3 V + CN^{3/\beta} VT^4 ,
\] (3.18)
\[
S = \frac{4}{3} CN^{3/\beta} VT^3 .
\] (3.19)
We already know the near extremal limit as (3.1). By comparing (3.18) and (3.1) we get
\[
C = \frac{6\pi^2}{16} ,
\] (3.20)
\[
\beta = \frac{3}{2} .
\] (3.21)
Then the statistical model of the non-extremal 3-brane is decided as
\[
E = \sqrt{N^2 + n^2} \tau_3 V + \frac{6\pi^2}{16}(\sqrt{N^2 + n^2} + n)^2 VT^4
\] (3.22)
\[
S = \frac{\pi^2}{2}(\sqrt{N^2 + n^2} + n)^3 VT^3 .
\] (3.23)
The entropy and the temperature are written as
\[
S = 2^{1/2}\pi^{1/2}(\sqrt{N^2 + n^2} + n)^{1/2}n^{3/4}\tau_3^{3/4}V ,
\] (3.24)
\[
T = \frac{2^{1/2}\tau_3^{1/4}n^{1/4}}{\pi^{1/2}(\sqrt{N^2 + n^2} + n)^{1/2}} .
\] (3.25)
3.2 Comparing with supergravity result

The mass (total energy), charge per unit volume, entropy and temperature of black 3-brane by supergravity is \cite{17} \cite{18} \cite{16},

\[ E = \frac{\pi^3}{2\kappa^2} V \mu^4 (5 + 4 \sinh^2 \gamma) , \]  
\[ q = \frac{2\pi^3}{\sqrt{2}\kappa} \mu^4 \sinh 2\gamma , \]  
\[ S = \frac{2\pi^4}{\kappa^2} \mu^5 V \cosh \gamma , \]  
\[ T = \frac{1}{\pi \mu \cosh \gamma} , \]

where \( \mu \) and \( \gamma \) are parameters.

The above mass, entropy and temperature can be written by the number of D3-branes as

\[ E = \sqrt{N^2 + n^2 \tau_3} V + \frac{3}{2} n \tau_3 V , \]  
\[ S = 2^{1/2} \pi^{1/2} (\sqrt{N^2 + n^2 + n})^{1/2} n^{3/4} \tau_3^{3/4} V , \]  
\[ T = \frac{2^{1/2} \tau_3^{1/4} n^{1/4}}{\pi^{1/2} (\sqrt{N^2 + n^2 + n})^{1/2}} , \]

and those exactly agree with \cite{21} \cite{25} \cite{21} derived from the statistical model, at all the point from near extremal limit to Schwarzschild case.

We have started from the region \( g_s N << 1, g_s n << 1, \frac{n}{N} << g_s N \) in the D-brane model of previous subsection, but above shows the entropy and the temperature match exactly in the region \( g_s N >> 1, g_s n >> 1, \frac{n}{N} : \) arbitrary. It looks like the correspondence of the region \( g_s N << 1, g_s n << 1, \frac{n}{N} << g_s N \) and the region of \( g_s N >> 1, g_s n >> 1, \frac{n}{N} >> 1 \), where \( N \) and \( n \) can be made large independently.

3.3 Neutral mass as string network

We have assumed that neutral charged mass forms dense string network inside D3-branes. But so far the neutral charged mass are dealt like \( n \tau_3 V \) as if it were "neutral charged 3-brane". If the D3-D1 system of \cite{15} with
D1-vortices are related to black 3-brane and our assumption is correct, there must be some evidences of string network.

Actually the energy of the gas has the following relation with the Hawking temperature:

\[
E_{\text{gas}} = \frac{6\pi^2}{16}N^2VT_H^4 + \frac{3\pi}{2}n^{3/2}\tau_3^{1/2}VT_H^2. \tag{3.33}
\]

The first term is for the gas on the (charged) \(N\) number of D3-branes. The second term implies the excitation of one dimensional object, and moreover, depends only neutral mass \(n\) and does not depend on \(N\). This implies that after the equilibrium, the gas on the neutral mass moves along some 1 dimensional objects.

### 4 The entropy and temperature of black p-brane

We can easily extend the argument in the previous section to general \(p\)-brane. However, we have no near extremal statistical model (like D-brane and open string gas model as the previous section), because \(p\)-brane(except \(p = 3\)) in 10 dimension is dilatonic in general. Thus we present the procedure to derive the exact entropy and temperature of non-extremal black \(p\)-brane from its near extremal result of supergravity.

#### 4.1 Supergravity result

The mass(total energy), charge per unit volume, entropy and temperature of the single charged black \(p\)-brane of 1/2 BPS is \([3][17][18][16]\),

\[
E = \frac{\omega_{d+1}}{2\kappa^2}\mu^dV(d + 1 + d\sinh^2\gamma), \tag{4.1}
\]

\[
q = \frac{\omega_{d+1}}{2\sqrt{2}\kappa}d\mu^d\sinh 2\gamma, \tag{4.2}
\]

\[
S = \frac{2\pi\omega_{d+1}}{\kappa^2}\mu^{d+1}V\cosh\gamma, \tag{4.3}
\]

\[
T = \frac{d}{4\pi\mu\cosh\gamma}, \tag{4.4}
\]
where \( d = 7 - p \), \( \omega_{d+1} \) is the volume of a \( d + 1 \)-dimensional unit sphere, \( V \) is the volume of the torus which the brane wrapped, \( \mu \) and \( \gamma \) are parameters.

We rewrite the mass and the entropy in terms of the number of (charged) branes \( N \)

\[
E = \sqrt{N^2 + n^2} \tau_p V + 2\lambda n \tau_p V, \quad (4.5)
\]

\[
S = BV (\sqrt{N^2 + n^2} + n)^{1/2} n^\lambda, \quad (4.6)
\]

where

\[
n = \frac{\omega_{d+1} \ d \ \mu^d}{4 \kappa^2 \tau_p}, \quad (4.7)
\]

\[
B = 2^{2\lambda+3/2} \pi \ \omega_{d+1}^{1/2-\lambda} d^{-(\lambda+1/2)} \kappa^{2\lambda-1} \tau_p^{\lambda+1/2}. \quad (4.8)
\]

As in [3], the entropy and the temperature have simple relation as \([4.11]\) at near extremal limit (\( n/N \ll 1 \)). The total energy in near extremal limit is

\[
E = N \tau_p V + (2\tau_p)^{1/\lambda} B^{1/\lambda} \lambda N^{1/1-\lambda} V T^{1/\lambda}. \quad (4.9)
\]

The first term corresponds to the tension of the branes and the second term corresponds to ”gas”.

### 4.2 Entropy and temperature from statistical model

As in 3-brane case, we assume \( D_p - D(p - 2) \) bound state model like

\[
E = \sqrt{N^2 + n^2} \tau_p V + f(N, n) V T^\alpha. \quad (4.10)
\]

This time we left the power of \( T \) as unknown parameter \( \alpha \). Comparing \([4.10]\) at near extremal limit with \([4.9]\), the parameter \( \alpha \) is decided as

\[
\alpha = \frac{1}{1 - \lambda}. \quad (4.11)
\]

The entropy of this system is

\[
S = \frac{1}{\lambda} f(N, n) V T^{1/\lambda}, \quad (4.12)
\]

\[
= \frac{1}{\lambda} f^{1-\lambda} V^{1-\lambda} (E - \sqrt{N^2 + n^2} \tau_p V)^\lambda. \quad (4.13)
\]
We maximize the entropy by \( n \) as in previous section,
\[
(1 - \lambda)(E - \sqrt{N^2 + n^2 \tau_p V}) \frac{\partial f}{\partial n} = \frac{\lambda n \tau_p V}{\sqrt{N^2 + n^2}} f .
\] (4.14)

As in previous section, we can write the gas energy as
\[
E - \sqrt{N^2 + n^2 \tau_p V} = \beta n \tau_p V .
\] (4.15)

Plugging this into (4.14), we get
\[
\frac{\partial f}{\partial n} = \frac{\lambda}{\beta (1 - \lambda)} \frac{1}{\sqrt{N^2 + n^2}} f .
\] (4.16)

The solution is
\[
f = C(\sqrt{N^2 + n^2} + n)^{\frac{\lambda}{\alpha(1 - \lambda)}},
\] (4.17)

then the total energy is
\[
E = \sqrt{N^2 + n^2 \tau_p V} + C(\sqrt{N^2 + n^2} + n)^{\frac{\lambda}{\alpha(1 - \lambda)}} V T^{\frac{1}{1 - \lambda}} .
\] (4.18)

In the near extremal limit,
\[
E = N \tau_p V + C N^{\frac{\lambda}{\alpha(1 - \lambda)}} V T^{\frac{1}{1 - \lambda}} .
\] (4.19)

Comparing above with (4.9), unknown constant \( C \) and \( \beta \) are decided as
\[
\beta = 2 \lambda ,
\] (4.20)
\[
C = (2 \tau_p)^{\frac{1}{\alpha - 1}} B^{\frac{1}{\alpha - 1}} \lambda .
\] (4.21)

Substitute this to (4.13), we get entropy
\[
S = BV(\sqrt{N^2 + n^2} + n)^{1/2} n^\lambda ,
\] (4.22)

and this agrees perfectly with supergravity result (4.6). Also, temperature exactly agrees with (4.4).
5 Conclusion and discussion

In this paper, we showed that exact entropy and temperature of non-extremal black 3-brane are calculated by maximizing entropy under several assumptions. These assumptions imply the correspondence of black 3-brane statistical mechanics and certain D3-D1 system. We extend this argument to general p-branes and presented a procedure to derive exact entropy and temperature of non-extremal black p-brane by requiring its statistical quantities to agree with supergravity result at near extremal limit.

As written in section 2, even if we confirm that the entropy or other thermodynamical quantities are derived from some model in perturbative regime, still it is mysterious unless we have something like non-renormalization theorem.

But the perfect agreement of entropy, temperature, degree of freedom of gas and the total tension of the brane may be nontrivial. Moreover, the system becomes unstable when RR charge = 0, because the screening of D(p − 2) charge breaks when Dp branes do not exist( the screening caused by the coupling of the RR field and the gauge field on Dp branes \[15\]). This may be related to Gregory-Laflamme instability of black p-branes \[19\] \[20\]. We will further investigate on the correspondence between the Dp - D(p−2) model and black p-brane.

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