From 0-Branes to Torons.

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The moduli space of 0-branes on $T^4$ gives a prediction for the moduli space of torons in $U(n)$ Super Yang Mills theory which preserve 16 supersymmetries. The zero brane number corresponds to the greatest common denominator of the rank $n$, magnetic fluxes and the instanton number. This prediction is derived using U-duality. We explicitly check this prediction by analyzing $U(n)$ bundles with non-zero first as well as second Chern classes. The argument is extended to deduce the moduli space of torons which preserve 8 supersymmetries. Parts of the discussion extend naturally to $T^2$ and $T^3$. Some of the U-dualities involved are related to Lorentz boosts along the eleventh direction in M theory.
1. Introduction

The connection between D-branes \[1,2,3,4\] and torons \[5\] was studied in some detail \[6,7,8,9,10,11\]. Torons also appeared in the context of Matrix theory in \[12,13\]. Torons are related to systems of branes at angles, where the angles involved are mapped to field strengths. In this paper we show how some detailed properties of moduli spaces of torons follow from their connection to D-brane bound states.

Section 2 discusses most of the key points in the simpler case of \(U(N)\) bundles on \(T^2\). For simplicity we will restrict attention to tori which have diagonal metric. We first describe how dualities can be used to map a system of \(N\) 2-branes with \(m\) zero branes to a system of D-strings at an angle. The map to D-strings gives a hint about the moduli space, but a more precise prediction is obtained by mapping to zero branes. The basic strategy is to map via dualities the system of 2-brane and 0-brane related to torons, to a system where the moduli space of supersymmetric solutions is known and has a simple geometrical interpretation. The counting of BPS states is invariant under the dualities. Further, since these are systems with a lot of supersymmetry the bound state spectrum is determined largely by the properties of the moduli space. Hence we can expect the moduli space to stay unchanged. These ideas were used to motivate Nahm duality exchanging instanton number and rank of gauge group for \(T^4\) bundles by H. Verlinde \[14\], and also appeared in \[15\]. After briefly describing the dualities involved, we do the gauge theory calculation which establishes that the moduli space is as expected.

In section 3, we recall the setup of \[6\], where torons (constant field strength solutions on \(T^4\)) were related to systems of 4-branes, 2-branes and zero-branes. The relation to systems of 2-branes at angles described in \[6\] gives a hint about the structure of the moduli space. Again more information is obtained by mapping to zero branes. In terms of these, the moduli space is entirely geometrical, given by the coordinates of \(p\) 0-branes, where \(p\) is related to the rank and fluxes as described in detail in section 3. Therefore the dimension of the moduli space of gauge inequivalent torons with the same field strengths should be \((T^4)^p/S_p\). This is equal to the moduli space of flat connections, since the torons which preserve 16 supersymmetries have non-zero \(Tr F_{\mu \nu}\), but vanishing \(SU(N)\) field strength. We explicitly count the number of flat connections of the gauge potential which survive when such twisted boundary conditions are imposed, and verify that there are \(4p\) independant zero modes. The toron solutions which are dual to 0-branes are particularly simple in the sense that the \(SU(N)\) field strengths vanish and half the supersymmetries are
preserved. However by simple arguments discussed in [6], we extend these results to more
general toron solutions associated with intersecting 2-branes which preserve a quarter of
the supersymmetries.

In section 4, we extend the discussion to class of solutions on $T^3$ as an example of how
facts about moduli spaces on odd dimensional tori can also be obtained from dualities.

2. Torons on $T^2$.

2.1. Prediction from dualities

For simplicity, we begin by considering the moduli space of the torons on $T^2$ in max-
imally supersymmetric $U(N)$ Yang Mills on $T^2 \times \mathbb{R}$. We will predict the moduli space by
mapping to a system of D-strings. We also describe a map to zero branes which makes
the moduli space that of positions of the zero branes. Then we will explicitly determine
the space of flat connections in a twisted sector of the Yang-Mills theory and find that it
matches.

Consider $N$ parallel 2-branes wrapped on $T^2$ bound to $m$ 0-branes. This corresponds
to a $U(N)$ Yang-Mills theory in a twisted sector with magnetic flux $m$. By a T-duality
in the 1 direction, we obtain D-strings with charges $Q_1 = m$ and $Q_2 = N$. When the
greatest common denominator, $g.c.d(N, m) = p$ is one, the D-string wraps once around a
cycle which is a linear combination of $N$ times one generating cycle and $m$ times another
cycle. So we expect a moduli space for the position of the D-string center of mass on
$T^2$. When $p$ is greater than one, we can have a family of flat connections on the D-string
worldvolume, some of which describe winding configurations of the D-strings, but most of
which have no geometrical interpretation [16]. This is illustrated in Fig.1. The various
wrappings are characterized by holonomies of the D-string effective action which form the
Weyl subgroup of $SU(p)$. The rest of the moduli space interpolates between the wrapping
geometries. This suggests that the moduli space should be a $U(p)$ moduli space of flat
connections on $T^2$. This is a $2p$ dimensional space $(T^2)^p / S_p$, $p$ of which is roughly related
to the wrapping geometries, and the other $p$ is roughly related to positions of D-strings.
If we map to zero branes then the moduli space is entirely given by positions of the $p$ zero
branes.

There is an element of the U-duality group which acts on the charges $(N, m)$ of a
system of $N$ two-branes and $m$ zero-branes, by shifting $m$ by a multiple of $N$. One way to
see this is to compactify on a further circle, do a T-duality to convert the (20) system to
a (31) system, then use S-duality to get 3-brane and elementary string. Then do further two T-dualities to get D-string and elementary string. Here we know from \[\text{[17]}\] that we can shift the elementary string charge by a multiple of the D-string charge (or vice versa). We can then transform back to the (02) system with shifted charges. Using these symmetries we can map the \((N, m)\) system to a \((0, p)\) system, i.e a system with zero brane charge only. Another way to see that one can get pure zero branes is to consider the T-duality group \(O(2, 2, \mathbb{Z})\), in which case we do not have to compactify on an extra circle. The theta-shift symmetry \[\text{[18]}\] which changes the combination of \(U(1)\) gauge field strength and NS 2-form, \((F + B)\), by 1, and hence the zero brane charge of \(N\) two-branes by \(N\), can be combined with the usual factorized T-dualities to convert the \((N, m)\) system to a \((0, p)\) system. Since the theta shift is of the form \(T_1 S T_1\) where \(T_1\) is a factorized T-duality and \(S\) is in the geometrical \(SL(2, \mathbb{Z})\), the above element is a product of a transformation that maps the \((N, m)\) system to D-string at an angle with a T-duality at an angle. Note that this generalizes Nahm duality which exchanges \(N\) and \(m\) to an \(SL(2, \mathbb{Z})\) action on the pair \((N, m)\). For \(p\) zero branes on \(T^2\), the moduli space is \((T^2)^p/S_p\). Since in these highly supersymmetric systems we can expect the moduli space to be invariant under the dualities, we have a prediction for the moduli space \(U(N)\) with flux \(m\).

The shift of the zero brane charge of a system of zero and 2-brane charge, by a multiple of the 2-brane charge, has a simple interpretation in terms of the picture of type IIA string theory on \(T^2\) as M theory compactified on \(T^3\). It is due to Lorentz invariance. Consider for example \(N\) two-branes. Adding \(Nk\) units of zero brane charge amounts to boosting by \(Nk\) units of momentum along the eleventh direction. We can partition the momentum equally between the \(N\) two-branes, with each having \(k\) units. This defines a unique map from the system of bound states (including multi-particle states) of charge \((N, 0)\) to those of charge \((N, kN)\). The \((N, 0)\) system is therefore related by eleven dimensional Lorentz symmetry to the \((N, kN)\) system. (This is analogous to how one interprets \(SL(2, \mathbb{Z})\) of type IIB in terms of reparametrizations of the two-torus of M theory \[\text{[19]}\text{[20]}\]. If we start with a single bound state of two-branes we can boost it by any number of units to get another state in the Hilbert space, but when the boost is a multiple of \(N\) we can expect a symmetry of the multi-particle spectrum.
2.2. Gauge theory calculation

Now let us return to the original system of \( N \) parallel 2-branes described by a \( U(N) \) Yang Mills theory. This system will also have a zero brane charge if \( Tr(F_{12} + B_{12}) \) is non-vanishing. The gauge potentials of the \( U(N) \) theory on a torus satisfy boundary conditions

\[
A(x + a_\mu) = U_\mu(x)(i\partial + A(x))U_\mu^\dagger(x)
\]

where \( a_\mu \) are cycles around the torus. For a well defined bundle,

\[
U_\mu(x)U_\nu(x + a_\mu)U_\mu^\dagger(x + a_\nu)U_\nu^\dagger(x) = 1,
\]

in the presence of zero \( B \). \( U_\mu \) may be written as a product of a \( U(1) \) part and an \( SU(N) \) part with the \( SU(N) \) part satisfying

\[
U_\mu(x)U_\nu(x + a_\mu)U_\mu^\dagger(x + a_\nu)U_\nu^\dagger(x) = e^{2\pi i n_{\mu\nu}/N}
\]

with antisymmetric integer \( n_{\mu\nu} \). In 2 dimensions the supersymmetric solutions have vanishing \( SU(N) \) field strengths, but the twist \( n_{12} \) may be nontrivial, and is canceled by \( U(1) \) twist arising from a non vanishing \( Tr F_{12} \).

\[
m = \frac{1}{2\pi} \int d^2 x tr F_{12} = n_{12}.
\]

In a gauge in which the \( SU(N) \) potentials are constant, one can find constant matrices \( U_\mu \) satisfying (2.3) by writing

\[
U_\mu = Q^{s_\mu} P^{t_\mu},
\]

where

\[
s_\mu t_\nu - s_\nu t_\mu = n_{\mu\nu} mod N
\]

and

\[
PQ = QPe^{\frac{2\pi i}{N}}
\]

We shall choose the convenient representation

\[
Q = \begin{pmatrix}
1 & e^{\frac{2\pi i}{N}} & \cdots \\
& e^{\frac{2\pi i}{N}} & \cdots \\
& & \ddots & e^{\frac{2\pi i(N-1)}{N}} \\
& & & e^{\frac{2\pi i(N-1)}{N}}
\end{pmatrix}, \quad P = \begin{pmatrix}
1 & 1 & \cdots \\
& 1 & \cdots \\
& & \ddots & 1
\end{pmatrix}
\]

1 If \( B \neq 0 \), the right hand side is modified to \( e^{i\int B} \).
A solution of (2.7) for flux $m$ is given by $U_1 = Q$ and $U_2 = P^m$. The $SU(N)$ gauge potentials then satisfy the conditions

$$A_\mu = QA_\mu Q^{-1}$$
$$A_\mu = P^m A_\mu P^{-m}$$

The first condition restricts $A_\mu$ to be diagonal. The second condition constrains this diagonal matrix to be invariant under cyclic permutations of length $m$. The number of independent diagonal elements of $A_\mu$ is therefore $p$ where $p = \gcd(N, m)$. Since there are two dimensions, a $2p$ dimensional moduli space of flat connections survives, which is consistent with the zero brane description.

Two D-string configurations on $T^2$. (a) has $N = 3$ and $m = 2$ so that $p = \gcd(N, m) = 1$, and there is only one way to wind the string. (b) has $N = 4$ and $m = 2$ so that $p = 2$.

\footnote{The elimination of $SU(N)$ torons in the case $m = 1$, $p = 1$ was used in \cite{[21]}, where the removal of zero modes facilitates the computation of $\text{tr}(-1)^F$.}
and there may be two copies of a singly wound string, or one copy of a doubly wound string.

3. Torons on $T^4$

Let us recall the set-up from [6]. We have maximally supersymmetric $U(N)$ Yang Mills theory in $4 + 1$ dimensions, on $T^4 \times R$, as the world volume theory of $N$ 4-branes. First restrict attention to configurations where the field strengths are proportional to the identity in the $U(N)$ Lie algebra. They leave unbroken 16 supersymmetries. These were discussed under the heading (4220) type solutions in [6]. The discussion of supersymmetry there was based on an equation in [22]. More detailed discussions can be found for example in [23, 24]. These constant field strength solutions of Yang-Mills theory on $T^4$ correspond to BPS bound states of 4-branes, 2-branes and 0-branes. The 0-brane charge is given by the instanton number $\nu$, 2-brane charge by the t’Hooft twists $n_{\mu\nu}$, and 4-brane charge by the rank of the gauge group $N$. Using an $SL(4, Z)$ isomorphism of the toron solutions [25], one can set all twists but $n_{12}, n_{34}$ and $n_{14}$ equal to zero without effecting the rank or the instanton number. Then T-dualities in the 1 and 3 directions yield systems of flat 2-branes at angles, with 2-brane charges

\[
\begin{align*}
Q_{24} &= N, \\
Q_{12} &= n_{14}, \\
Q_{34} &= n_{32}, \\
Q_{13} &= \nu, \\
Q_{14} &= n_{12}, \\
Q_{14} &= Q_{23} = 0. 
\end{align*}
\]  

(3.1)

If we generalize to solutions which break the $U(N)$ symmetry, (and preserve only eight supersymmetries), these charges may be written as the sums of contributions coming from 2-branes at different angular orientations, $Q_{\mu\nu} = \sum_i Q_{\mu\nu}^{(i)}$ where $\epsilon_{\mu\nu\alpha\beta}Q_{\mu\nu}^{(i)}Q_{\alpha\beta}^{(j)} = 0$. Initially we will only concern ourselves with solutions preserving 16 supersymmetries. All 2-branes are parallel in this case and we will drop the index $i$. The generalization to the
case where \( i \) runs over a set of branes, involves solutions where the field strengths take the form of diagonal matrices breaking the gauge group to \( U(k) \times U(N - k) \) say in the case where \( i \) runs from 1 to 2. Here the moduli space takes the form \( (T^4)^p_1/S_p_1 \times (T^4)^p_2/S_p_2 \), and the proof consists in trivially extending the proof we give below for the unbroken symmetry case to each unbroken group \( U(k) \) and \( U(N - k) \).

3.1. Mapping the toron to zero brane

We can use U-duality to map a system of 4-branes and 2-branes preserving 16 supersymmetries to a system of pure zero-branes. For simplicity take the (4220) system which is obtained from Yang Mills with fluxes \( n_{12}, n_{34} \). This is T-dual to a system with 2-brane charges along (24), (13), (14) and (32). After another T duality along the 2 axis, we get three brane charge along (123), (124) and 1-brane charge (4) and (3). An S-duality gives a three brane and elementary string. Finally a T-duality along (1) and (2) gives a D-string parallel to a an NS-string in the (34) plane. The fact that the D-string and NS-string are parallel follows from the zero self-intersection number of the original 2-brane system. Now we know from \([17]\) that, in this system, we can shift the NS charge of the D-string by a multiple of the D-string charge. Undoing the T and S dualities we can get again a system with 3-brane charges (123) and (124) only. This is T-dual to a (02) system, which we have shown before to be U-dual to pure zero branes. As in the \( T^2 \) discussion, we can map to zero branes using only the \( O(4,4,Z) \) T-duality group by using theta-shifts and factorized T-dualities.

3.2. Gauge theory calculation

For the maximally supersymmetric solutions, \( n \land n = 0 \text{mod}(N) \). We want to show that if \( \gcd(n_{\mu\nu}, N) = p \) then the surviving zero modes are \( U(p) \) flat connections. We review Van Baal’s construction \([25]\) of the \( \Omega_\mu \) for arbitrary \( N \), and \( n_{\mu\nu} \) satisfying \( n \land n = 0 \text{mod}(N) \). We use the \( SL(4,Z) \) symmetry to set all the \( n_{ij} = 0 \) except for \( n_{12}, n_{34}, n_{14} \). The case where \( n \land n = 0 \) is simple, since \( n_{12} \) or \( n_{34} \) is zero. For these fluxes we can easily solve for the \( s_\mu, t_\mu \) as defined in \([25]\). The important property of the resulting \( s_\mu, t_\mu \) is that only one \( t_\mu \) is 1 and the other \( t_\mu \) are zero, while the \( s \)'s satisfy \( \gcd(s_\mu, N) = \gcd(n_{\mu\nu}, N) \).

In the general case one decomposes

\[
N = p_1^{e_1} p_2^{e_2} ... p_l^{e_l},
\] (3.2)
where \( p_i \) are distinct primes. Correspondingly we decompose the fluxes as

\[
n_{\mu\nu} = \sum_{i=1}^{l} \frac{N}{N_i} n_{\mu\nu}^{(i)} \tag{3.3}
\]

And we decompose \( \Omega_\mu = \Omega_\mu^{(1)} \otimes \Omega_\mu^{(2)} \cdots \otimes \Omega_\mu^{(l)} \). Each \( \Omega^{(i)} \) is of the form \( Q_{(i)} \) or \( P_{(i)} \). Decomposing the gauge field according to the same tensor product structure, the surviving gauge connection in each sector is a diagonal \( U(p_i) \) connection where \( p_i \) is the gcd \( (n_{\mu\nu}^{(i)}, N_i) \). The surviving flat connections are therefore given by diagonal \( U(\prod p_i) \) matrices. But by the Lemma below, this is just \( U(p) \) flat connections where \( p = \prod p_i \).

**Lemma**

\[
\prod_i \text{gcd}(n_{\mu\nu}^{(i)}, N_i) = \text{gcd}(n_{\mu\nu}, N) \tag{3.4}
\]

We first prove that if \( \lambda_1 \cdots \lambda_l \) divide the pairs \( (n_{\mu\nu}^{(1)}, N_1), \cdots (n_{\mu\nu}^{(l)}, N_l) \) then they divide \( (n_{\mu\nu}, N) \). This follows immediately from the decompositions (3.2) and (3.3). Suppose \( \lambda_i = \text{gcd}(N_i, n_{\mu\nu}^{(i)}) \), then \( \prod \lambda_i \) is a sum of terms, each of which is an integer. For example, the first term is

\[
\frac{n_{\mu\nu}^{(1)} N_2 \cdots N_l}{\lambda_1 \lambda_2 \cdots \lambda_l} \tag{3.5}
\]

which is clearly an integer.

The converse can be established as follows. Let \( \lambda = \text{gcd}(n_{\mu\nu}, N) \), and \( \frac{n_{\mu\nu}}{\lambda} = q_{\mu\nu} \), where \( q_{\mu\nu} \) is an integer. Given the decomposition of \( N \) into distinct primes, there must be a corresponding decomposition of \( \lambda \) into \( \lambda_1 \cdots \lambda_l \), where \( \lambda_i \) is a power of \( p_i \). Now let \( \frac{N_i}{\lambda_i} = p_i^{k_i} \). Then,

\[
q_{\mu\nu} = \frac{n_{\mu\nu}^{(1)} N_2 \cdots N_l}{\lambda_1 \lambda_2 \cdots \lambda_l} + \frac{N_1 n_{\mu\nu}^{(2)} \cdots N_l}{\lambda_1 \lambda_2 \cdots \lambda_l} + \cdots + \frac{N_1 N_2 \cdots n_{\mu\nu}^{(l)}}{\lambda_1 \lambda_2 \cdots \lambda_l} \tag{3.6}
\]

We want to show that each term is separately an integer, i.e for each \( i \), \( \frac{n_{\mu\nu}^{(i)}}{\lambda_i} \) is an integer. Suppose the contrary, e.g that \( n_{\mu\nu}^{(1)} \) is not divisible by \( \lambda_1 \). Then the ratio \( \frac{n_{\mu\nu}^{(1)}}{\lambda_1} \) is of the form \( \frac{r_1}{p_1^{m_1}} \) for some integer \( r_1 \) satisfying \( \text{gcd}(r_1, p_1) = 1 \), and some integer \( m_1 \). Starting from (3.6) multiply both sides by \( \prod p_i^{m_i} \). The LHS is now divisible by \( p_1 \cdots p_l \). The first term on the RHS is of the form \( r_1 p_2^{m_2} \cdots p_l^{m_l} \), where the exponents are all integers. The remaining terms are all divisible by \( p_1 \). The first term on the RHS is not, so the RHS is not divisible by \( p_1 \). This is a contradiction. This establishes Lemma 1.
4. Moduli spaces of torons on $T^3$

Supersymmetric constant field strength solutions exist on odd-dimensional tori, which are proportional to the identity in the Lie algebra of $U(N)$. The moduli spaces of flat connections associated with such configurations can also be deduced from dualities. For concreteness we will describe $d = 3$. Take $U(N)$ Yang Mills on $T^3 \times R$, which can be thought as worldvolume theory of $N$ 3-branes wrapping the $T^3$. Consider the sector with fluxes $n_{12}, n_{23}, n_{13}$. This corresponds to moduli spaces which are relevant to bound states of 3-branes with D-strings. Applying a T-duality along the 1 direction, we get $N$ units of 2-brane charge along (23) plane, $n_{13}$ units of two-brane charge along (12) plane, $n_{12}$ units of two-brane charge along the (13) plane, and $n_{23}$ units of zero brane charge. We can apply an $SL(3, \mathbb{Z})$ transformation to get the two-brane charge to lie entirely along the (12) plane. The magnitude of the two-brane charge will be the gcd of $N$, $n_{12}$ and $n_{13}$. Now by the dualities discussed before we can shift the charges of this system until it is purely 0-brane, and the number of zero branes is the gcd of the two-brane and the zero brane charge we start with. This means that the moduli space of supersymmetric solutions in the sector of $U(N)$ gauge theory with fluxes $n_{12}, n_{23}, n_{13}$ is the symmetric product $(T^3)^p / S_p$ where $p$ is the gcd of the rank and fluxes. This can be checked directly in gauge theory using the methods described before. Similar systems have been discussed in [26] where the symmetric dependence of the moduli space on the ranks and fluxes finds an interpretation in the context of Matrix theory at finite $N$ [27].

5. Conclusion and Comments.

We have shown that the moduli space of torons in $U(N)$ Yang Mills theory with 16 supersymmetries is equal to the moduli space of $p$ zero branes, where $p$ is the greatest common denominator of the Chern classes and rank $N$. This has been motivated by using U-duality. In the zero brane description the moduli space, which is a symmetric product, acquires the interpretation of positions of $p$ identical particles. We considered several dimensions, namely 2, 3 and 4. It seems likely that the dependence of the moduli space on the common factor of ranks and fluxes should be true for higher dimensions, since the combinatorics leading to it does not seem too dimension dependent (but we have not studied the problem in detail for arbitrary dimensions). Up to 10 dimensions one can imagine embedding in some appropriate brane theory and interpreting along the lines above. For higher dimensions an intriguing possibility is that there might be a
physical interpretation analogous to that discussed here, perhaps in relation to [28] or to
the speculations regarding higher dimensions in [29].

The moduli space is important in determining the spectrum of bound states [30] [22].
The counting of one-particle states does not depend on the the common factor $p$. However
when $p$ is greater than one, there can be multi-particle states, whose multiplicity is related
to the number of partitions of $p$.

In the course of describing the dualities that map systems related to torons to systems
of zero branes we found, in section 2, that some U-duality symmetries of M theory on $T^3$
have an interpretation in terms of boosts in eleven dimensions. The duality group in
question has the form $SL(2, Z) \times SL(3, Z)$. The $SL(3, Z)$ is interpreted geometrically in
terms of reparametrizations of the torus. Some of the $SL(2, Z)$ can also be interpreted
gometrically by using the eleventh dimension of M theory. We saw, in this discussion,
a simple example where boosts in M theory gave a bigger symmetry for the one-particle
spectrum than for the multi-particle spectrum. It would be interesting to see if this is
related to the analogous facts in Matrix theory [31] discussed in [26].

We end by mentioning an interesting connection between what we studied here and
[32] [33]. In [32] [33] one found a gauge theory whose vacua were in one-one correspondence
with the moduli space of instantons on $R^4$, by studying the action of a $D$-brane probe in
the presence of a $(D + 4)$-brane. Here a similar effect is achieved for the case of the torons
preserving 16 supersymmetries. They get related to vacua of a $U(p)$ gauge theory on the
torus. The intriguing fact is that in this case the physics allowing the relation between
instantons and vacua of gauge theories is T-duality, whereas in the case of [32] [33], it is
the very different physics of probe-source interaction.

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