Anomalies of the SO(32) five-brane and their cancellation

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Abstract

The anomaly due to the chiral fermions on the world-volume of the $SO(32)$ five-brane is calculated. It is shown that this contribution has the correct structure for it to be cancelled by the variation of the classical world-volume action. The cancellation mechanism requires a Green-Schwarz-like term in the classical action. The result confirms the field content of the $SO(32)$ five-brane proposed by Witten.

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1 Introduction

Anomaly cancellation in ten dimensions greatly restricts the number of consistent string theories. The Green-Schwarz mechanism \cite{1} allows the anomaly cancellation for the $SO(32)$ and $E_8 \times E_8$ string theories. The essential ingredient in the Green-Schwarz mechanism is that the anomaly polynomial of the effective target space action be factorizable as $I_{12} = X_4 X_8$. The $X_4$ part enters then in the modification of the Bianchi identity of the three-form field strength: $dH = X_4$ and the $X_8$ part in the modification of the equations of motion $d^* H = X_8$ \cite{1}. These two modifications ensure that the total effective action is anomaly free. Very interestingly, there exists a way to understand the modification of the Bianchi identity from the heterotic string world-sheet point of view \cite{2}. In fact the pull-back of $X_4$ into the world-sheet is simply the anomaly polynomial of the two-dimensional sigma model. The cancellation of the world-sheet anomalies requires a non-trivial variation of the two-form which gives rise to the modified Bianchi identity and which via the interaction term

$$\int_{\Sigma_2} B,$$  \hfill (1)

compensates the anomaly.

A way to understand the modification of the equations of motion of the three-form was proposed \cite{3, 4, 5, 6, 7} and relies on the existence in string theory of a solitonic extended object of five spatial dimensions that preserves half of the supersymmetries: the heterotic five-brane \cite{8, 9, 10}. In fact the five-brane is expected to couple to the six-form, $B_6$, by the world-volume term

$$\int_{\Sigma_6} B_6,$$  \hfill (2)

where $B_6$ is the dual to $B_2$ that is

$$H_7 = * H,$$  \hfill (3)

$H_7$ being the field strength of $B_6$. Since the five-brane is chiral, world-volume anomalies of the five-brane are expected to appear. Their cancellation would require a non-trivial transformation of $B_6$ which in turn modifies the Bianchi identity of $H_7$ that is the equations of motion of $H$. So the $X_8$ part is expected to be related to the world-volume anomaly of the five-brane. The precise relation will be explained later on. This program has not been fully accomplished \cite{1} because the world-volume fermions of the heterotic five-brane were not all known.

Recently, Witten \cite{11} proposed a field content of the SO(32) five-brane. This field content comprises an $SU(2)$ vector supermultiplet and a pseudo-real hypermultiplet belonging to the fundamental representations of $SU(2)$ and $SO(32)$.

\footnote{The analysis in the Introduction is sketchy, the dependance on the various constants and the dilaton will be explicited in section 4}
The aim of this paper is to re-examine the anomaly issue of the five-brane in the light of this new field content of the $SO(32)$ five-brane. We shall prove that indeed the anomaly of the five-brane has the correct structure. This is due to a number of cancellations and “miracles” which have a tiny chance to happen for a different field content of the five-brane. The result constitutes thus a confirmation of Witten’s proposition.

In Section 2 we briefly review the field content of the $SO(32)$ five-brane proposed by Witten. In Section 3 we calculate the contribution of the various worldvolume chiral fermions to the anomaly. The local symmetries that are potentially anomalous are $i)$ those of a bare six-dimensional theory: Lorentz $SO(1,5)$ rotations and $SU(2)$ gauge transformations and $ii)$ those that are induced from ten-dimensional symmetries: the $SO(4)$ rotations of the normal bundle and $SO(32)$ gauge transformations. We shall express the anomaly eight-form in terms of characteristic classes of the four bundles involved. We find terms that depend on the Euler class of the normal bundle not encountered before. In Section 4 we examine the anomaly cancellation mechanism. Since the $SO(32)$ five-brane has no antisymmetric tensor field, no purely six-dimensional Green-Schwarz-like term is possible in the effective world-volume action. However it is possible to have a term that depends on the restriction to the five-brane of the ten-dimensional antisymmetric tensor field. This renders the anomaly cancellation more constraining than is the case for a six-dimensional theory with a tensor field [12, 13]. We shall find that the anomaly calculated in section 3 is indeed of this constrained form. In section 5 we briefly consider the generalisation to the case of $k$ coincident five-brane and finally in section 6 we collect our conclusions.

2 The $SO(32)$ five-brane

According to the heterotic-type I duality, the heterotic $SO(32)$ five-brane is mapped to the Dirichlet five-brane of the type I theory [14]. D-branes present the advantage of having an explicit conformal theory description [15]. In fact, the excitations of the D-branes are open strings that have one boundary or two boundaries that end on the D-brane. All that one have to know is the Chan-Paton factors characterizing the open strings that end on the D-five-brane. Motivated by the physics of the instanton of zero size, Witten [11] proposed that the Chan-Paton factors are those of $Sp(1) = SU(2)$. This was confirmed later by Gimon and Polchinsky [16].

The determination of the spectrum of the D-five-brane goes along the same line as the usual open string except that one has to consider two sectors depending on whether there is one (DN sector) or both ends (DD sector) of the string on the D-brane. Furthermore, the operator $\Omega$ that exchanges the two ends of the string acts in an unusual manner. We refer the reader to [11, 14] for the details. The result is that from the DD sector one gets: an $Sp(1)$ gauge field, $G$, its supersym-
metric partner, $\lambda$, which belong to the $4_-$ of $SO(1,5)$ and the $2_-$ of $SO(4)$, and finally four scalars which represent the fluctuations of the five-brane in ten dimensions and their supersymmetric partners, $\theta$ which transform in the $4_+$ of $SO(1,5)$ and the $2_+$ of $SO(4)$. Note the probably a priori unexpected transformation of the gauginos under the $SO(4)$ group. The transformation of $\theta$ under the $SO(4)$ group can be understood as follows: the Green-Schwarz fermionic coordinates of the five-brane are a Weyl-Majorana fermion in ten dimensions whose reduction to six dimensions transforms in the $(4_+, 2_+) + (4_-, 2_-)$ of $SO(1,5) \times SO(4)$, since half of the supersymmetries are broken we are left with the $(4_+, 2_+)$ component.

An important fact for the anomaly cancellation is that $\lambda$ and $\theta$ have opposite chirality, this is due to $N = 1$ six-dimensional supersymmetry.

Since the end of the string on the D-five-brane carries a 2 of $SU(2)$ and the end with Neumann boundary conditions carries a 32 of $SO(32)$ the states from the DN sector must be in the $(32,2)$ of $SO(32) \times SU(2)$. It turns out that from that sector one gets one pseudo-real hypermultiplet belonging to this representation. The scalars of this hypermultiplet transform in the vector representation of $SO(4)$ and the fermions, $\psi$, transform under the $4_+$ of $SO(1,5)$ and are singlets under the $SO(4)$.

### 3 The anomaly calculation

In this section we shall calculate the contributions to the anomaly of the three fermion multiplets described in the preceding section. We shall use the standard anomaly formulas as found for example in [17]. The transformations of interest are: $SO(1,5)$ Lorentz transformations on $T(\Sigma)$, the tangent bundle of the five-brane, $SO(4)$ Lorentz transformations on $N$, the normal bundle of the five-brane, $SO(32)$ gauge transformations and finally the $SU(2)$ gauge transformations. We will denote by $2\pi F$ the $SO(32)$ curvature and by $2\pi G$ the $SU(2)$ curvature. The anomaly in $D$ dimensions is given by a $(D + 2)$-form: $I_{D+2} = 2\pi I_{D+2}$. The $2\pi$ factors are included to simplify the anomaly formulas. We shall also express the anomaly in terms of characteristic classes of the ten dimensional tangent bundle $TQ$, and of the four dimensional normal bundle $N$.

The fermions, $\theta$, describing the fermionic coordinates of the five-brane are symplectic-Weyl-Majorana spinors that belong to the $(4_+, 2_+)$ of $SO(1,5) \times SO(4)$. The associated anomaly reads:

$$I_8^\theta = \frac{1}{2} \hat{A}(T\Sigma) chS_+(N),$$

where we keep only, as usual, terms of degree eight; $\hat{A}$ is the Dirac genus, $ch$ is the Chern character and $S_+(N)$ is the spin bundle with positive chirality. The factor $1/2$ is present because the fermions are symplectic-Majorana spinors. The
Dirac genus is given by
\[
\hat{A}(T\Sigma) = 1 - \frac{p_1(\Sigma)}{24} + \frac{7p_1^2(\Sigma) - 4p_2(\Sigma)}{5760} + \ldots,
\] (5)
and the Chern character by
\[
ch(S_{\pm}(N)) = 2 + \frac{p_1(N) \pm 2\chi(N)}{4} + \frac{p_1^2(N) + 4p_2(N) \pm 4p_1(N)\chi(N)}{192}.
\] (6)

In equations (5) and (6) \(p_i\) denotes the \(i^{th}\) Pontryagin class and \(\chi\) the Euler class. They are related to the curvature \(\Omega\) of \(N\) by
\[
p_1(N) = -\frac{1}{2(2\pi)^2} tr(\Omega^2), \quad p_2(N) = \frac{1}{8(2\pi)^4} \left((tr(\Omega^2))^2 - 2tr(\Omega^4)\right),
\]
\[
\chi(N) = \frac{1}{8(2\pi)^2} \epsilon_{abcd} \Omega^{ab} \wedge \Omega^{cd}.
\] (7)

It will be convenient to express the anomaly in terms of ten-dimensional quantities and the curvature of the normal bundle. Let \(TQ\) denotes the restriction of the ten-dimensional tangent space to \(\Sigma\) then since \(T\Sigma + N = TQ\), we have \(p_1(\Sigma) = p_1(Q) - p_1(N)\) and \(p_2(\Sigma) = p_2(Q) - p_2(N) - p_1(N)p_1(Q) + p_1^2(N)\). Keeping only terms of order eight we get
\[
I_8^\lambda = \frac{7p_1^2(Q) - 4p_2(Q)}{5760} - \frac{2p_1(Q)p_1(N) + 3p_1(Q)\chi(N)}{288} + \frac{4p_2(N) + 3p_1^2(N)}{5760} + \frac{p_1(N)\chi(N)}{48}.
\] (8)

The \(SU(2)\) gauginos are symplectic-Weyl-Majorana that belong to the \((1,3,4,2)\) of \(SO(32) \times SU(2) \times SO(1,5) \times SO(4)\). Their contribution to the anomaly reads
\[
I_8^\lambda = -\frac{1}{2} \hat{A}(T\Sigma)chS_{-}(N)Tr(e^{iG}),
\] (9)
where \(Tr\) is the trace in the adjoint representation of \(SU(2)\) and the minus sign reflects the fact that \(\lambda\) has negative chirality. Keeping terms of order eight we obtain
\[
I_8^\lambda = -\frac{3}{48} \frac{7p_1^2(Q) - 4p_2(Q)}{5760} + \frac{3}{48} \frac{2p_1(Q)p_1(N) - 3p_1(Q)\chi(N)}{288} - \frac{p_1(Q)Tr(G^2)}{48} + \frac{p_1(N)Tr(G^2)}{5760} - \frac{\chi(N)Tr(G^2)}{8} - \frac{Tr(G^4)}{24}.
\] (10)

The hypermultiplet contains 128 real scalars and 32 symplectic-Weyl-Majorana fermions transforming in the \((32,2)\) of \(SO(32) \times SU(2)\). They have the opposite
chirality compared to the gaugino and are singlets under the $SO(4)$ group. Their contribution to the anomaly reads:

$$I_8^\psi = \frac{1}{2} \hat{A}(T\Sigma) tr(e^{iF}) tr(e^{iG}), \quad (11)$$

where $tr$ is the trace in the fundamental representation, the factor $1/2$ is due to the reality condition. The evaluation of $\hat{A}(T\Sigma)$ gives

$$I_8^\psi = 32 \frac{7p_1^2(Q) - 4p_2(Q)}{5760} - 16 \frac{p_1(Q)p_1(N)}{288} + 16 \frac{p_1(Q)tr(G^2)}{48} - 16 \frac{p_1(Q)tr(F^2)}{48}$$

$$+ 32 \frac{3p_2^2(N) + 4p_2(N)}{5760} - 16 \frac{p_1(N)tr(G^2)}{48} - 16 \frac{p_1(N)tr(F^2)}{48} + 16 \frac{tr(G^4)}{24} + \frac{tr(F^4)}{24} + \frac{tr(G^2)tr(F^2)}{8}. \quad (12)$$

The traces in the fundamental representations and in the adjoint representations of $SU(2)$ are related by

$$Tr(G^2) = 4tr(G^2), \quad Tr(G^4) = 16tr(G^4). \quad (13)$$

Summing the contributions of $\theta, \lambda$ and $\psi$ and using the relations $\hat{A}(T\Sigma)$ we get for the total anomaly

$$I_8 = I_8^\theta + I_8^\lambda + I_8^\psi = \frac{7p_1^2(Q) - 4p_2(Q)}{192} - \frac{p_1(Q)p_1(N)}{24} - \frac{p_1(Q)p_1(N)}{24} - \frac{p_1(Q)p_1(N)}{24}$$

$$+ \frac{p_1(Q)tr(G^2)}{4} + \frac{p_1(Q)tr(F^2)}{4} + \frac{p_1(N)tr(G^2)}{12} - \frac{p_1(N)tr(F^2)}{48} - \frac{\chi(N)tr(G^2)}{2} + \frac{\chi(N)tr(F^2)}{24} + \frac{tr(G^2)tr(F^2)}{8}. \quad (14)$$

Note that the terms in $tr(G^4), p_1(N)tr(G^2), p_2(N)$ and $p_1^2(N)$ cancelled. This allows the partial factorization

$$I_8 = \left[ \chi(N) - \frac{tr(F^2)}{4} - \frac{p_1(Q)}{2} \right] \left[ \frac{p_1(N)}{12} - \frac{p_1(Q)}{24} - \frac{tr(G^2)}{2} \right]$$

$$+ \frac{3p_2^2(Q) - 4p_2(Q)}{192} + \frac{p_1(Q)tr(F^2)}{96} + \frac{tr(F^4)}{24}. \quad (15)$$

We shall see in the next section that this partial factorization is of the required form for the anomalies to cancel.
4 Anomaly cancellation

Since anomaly cancellation in ten dimensions requires a non-trivial transformation of $B$ and $B_6$ and since the world-volume action of the five-brane depends on these forms, the classical action of the five-brane is not expected to be invariant. So classical anomalies of the world-volume action may compensate the quantum anomalies computed in the preceding section. Here, we shall first determine, from the known ten-dimensional transformations of $B$ and $B_6$, the structure of the expected classical anomaly and then prove that total anomaly cancellation is possible.

Recall that the ten dimensional space-time anomalies are given by a twelve form, $I_{12}$, which factorizes as

$$I_{12} = X_4 X_8,$$

with

$$X_4 = -\frac{tr(F^2)}{4} - \frac{p_1(Q)}{2},$$

and

$$X_8 = \frac{3p_2^2(Q) - 4p_2(Q)}{192} + \frac{p_1(Q)tr(F^2)}{96} + \frac{tr(F^2)}{24}.$$

Anomaly cancellation in ten dimensions requires that the Bianchi identity of the three form field strenght be modified to read

$$dH = \alpha' X_4,$$

where $\alpha'$ is the string slope, and that the action be supplemented with the Green-Schwarz term

$$S_{GS} = T_2 \int Q B \wedge X_8,$$

where $T_2$ is the string tension: $T_2 \alpha' = 2\pi$. The modification of the Bianchi identity implies that the two-form transforms as

$$\delta B = -\alpha' X_2^1,$$

where $X_2^1$ is related to $X_4$ by the descent equations

$$X_4 = dX_3, \quad \delta X_3 = dX_2^1.$$

It is easy then to see that the variation of the term (20) compensates the anomaly (15). Due to the Green-Schwarz term, the modified equations of motion of the two-form become

$$d(e^{-\phi} * H) = 2T_2 \kappa^2 X_8,$$

where $\phi$ is the dilaton, $*$ denotes the Hodge dual in the string metric and $\kappa$ is the ten-dimensional gravitational constant.
The five-brane couples to the dual, $B_6$, of the two-form $B$. This coupling is realised by the term

$$T_6 \int_\Sigma B_6,$$

(24)

$T_6$ being the five-brane tension. The forms $B_6$ and $B$ are related, via their field strength, by $H_7 = e^{-\phi} * H$, which implies that

$$dH_7 = 2T_2\kappa^2 X_8.$$

(25)

The Bianchi identity of $H_7$ gives the transformation of $B_6$ as

$$\delta B_6 = -2T_2\kappa^2 X_6^1.$$

(26)

On the other hand the Dirac quantization condition gives:

$$T_6 T_2\kappa^2 = n\pi,$$

(27)

where $n$ is an arbitrary integer. From equations (26) and (27) we deduce that the interaction term (24) varies as

$$-2\pi n \int_\Sigma X_6^1.$$

(28)

Another term which may exist in the world-volume action is a Green-Schwarz-like term

$$\Delta S = T_2 \int_\Sigma B \wedge Y_4,$$

(29)

where $Y_4$ is a polynomial of degree four. In the presence of the five-brane the Bianchi identity of the three form $H$ is modified and reads

$$dH = X_4 + 2T_6\kappa^2 \delta(\Sigma),$$

(30)

where $\delta(\Sigma)$ is a four-form defined by

$$\intQ \omega = \intQ \omega \wedge \delta(\Sigma),$$

(31)

for all six-forms $\omega$. An important property noticed in [18] is that the restriction of $\delta(\Sigma)$ to $\Sigma$ has a finite part given by the Euler class of the normal bundle, that is

$$\delta(\Sigma)|_\Sigma = \chi(N).$$

(32)

The variation of the restriction to $\Sigma$ of the two-form is then easily seen to be given by

$$\delta B|_\Sigma = -\alpha' X_2^1|_\Sigma - 2T_6\kappa^2 \chi_2^1(N).$$

(33)

The corresponding variation of the Green-Schwarz-like term (29) is then

$$\delta \Delta S = -2\pi \int_\Sigma \left(X_2^1 + n\chi_2^1(N)\right) \wedge Y_4.$$

(34)
The two terms (28) and (34) contribute to the anomaly polynomial with

\[ -nX_8 - \left( X_4 + n\chi(N) \right) \wedge Y_4. \tag{35} \]

We deduce that the total variation of the effective action vanishes if the quantum anomaly eight form \( I_8 \) is of the form

\[ I_8 = nX_8 + \left( X_4 + n\chi(N) \right) \wedge Y_4, \tag{36} \]

for some integer \( n \) and some polynomial \( Y_4 \). This is the condition of anomaly cancellation on the five-brane. Note that anomaly cancellation in a six-dimensional theory with an antisymmetric six-dimensional tensor field \([12, 13]\) requires the anomaly to be factorizable as \( Y_4 \wedge Y_4 \). The form (36) is much more constraining because it involves only one polynomial.

The partial factorization of the anomaly given in (15) is precisely of the form (36). The integer \( n \) must be set to unity and the polynomial \( Y_4 \) is given by

\[ Y_4 = -\frac{p_1(Q)}{24} + \frac{p_1(N)}{12} - \frac{\text{tr}(G^2)}{2}. \tag{37} \]

The effective world-volume action of the five-brane must thus contain the Green-Schwarz-like term (29) with \( Y_4 \) given by (37).

The fact that \( I_8 \) is of the correct form is due to a number of remarkable cancellation which seem miraculous. In fact, the anomaly \( I_8 \) is \textit{a priori} a sum of more than ten terms, requiring that it be of the form (36) with \( Y_4 \) arbitrary leads to a “fine tuning” of more than five coefficients.

5 \( k \) coincident \( SO(32) \) five-branes

In this section we briefly consider the generalisation to the case of \( k \) coincident five-branes. In this case, the Chan-Paton of the open strings ending on the D-five-branes are those of \( Sp(k) \). The \( Sp(1) \) gauge group of the single five-brane is replaced by \( Sp(k) \). The six dimensional zero modes living on the five-brane transform in the same representations as before under \( SO(1, 5) \times SO(4) \times SO(32) \). The transformations under the gauge group \( Sp(k) \) of the fermionic modes are as follows: \( \theta \) is in the antisymmetric tensor product of two fundamental representations \( (k(2k - 1) - 1) + 1 \); \( \lambda \) in the adjoint representation of dimension \( k(2k + 1) \) and finally \( \psi \) is in the fundamental representation of dimension \( 2k \).

The contribution of each fermion multiplet can be calculated as in section 3. We shall not write down the detailed contribution of each but give the final result of the total quantum anomaly:

\[ I_8 = k\left( \frac{7p_2^2(Q)}{192} - 4p_2(Q) + \frac{p_1(Q)p_1(N)}{24} - \frac{k^2p_1(Q)\chi(N)}{24} \right). \]
\[
\begin{align*}
&+ \frac{p_1(Q) \text{tr}(G^2)}{4} + k \frac{p_1(Q) \text{tr}(F^2)}{48} + k^2 \frac{p_1(N) \chi(N)}{12} - k \frac{p_1(N) \text{tr}(F^2)}{48} \\
&- k \frac{\chi(N) \text{tr}(G^2)}{2} + k \frac{\text{tr}(F^4)}{24} + \frac{\text{tr}(G^2) \text{tr}(F^2)}{8}.
\end{align*}
\]

(38)

In obtaining this result, an essential use was made of the following trace identities of \( \text{Sp}(k) \):

\[
\begin{align*}
\text{Tr}(G^2) &= (2k + 2) \text{tr}(G^2), \\
\text{Tr}(G^4) &= (2k + 8) \text{tr}(G^4) + 3(\text{tr}(G^2))^2, \\
\text{tr}_A(G^2) &= (2k - 2) \text{tr}(G^2), \\
\text{tr}_A(G^4) &= (2k - 8) \text{tr}(G^4) + 3(\text{tr}(G^2))^2,
\end{align*}
\]

(39)

where \( \text{tr}, \text{Tr} \) and \( \text{tr}_A \) are respectively the trace in the fundamental \((2k)\), adjoint \((k(2k+1))\) and antisymmetric \((k(2k-1)-1)\) representations of \( \text{Sp}(k) \). Similarly to the case of a single five-brane, several terms cancelled and the anomaly (38) can be written in the partially factorized form:

\[
I_8 = \left[ k \chi(N) - \frac{\text{tr}(F^2)}{4} - \frac{p_1(Q)}{2} \right] \left[ k \frac{p_1(N)}{12} - k \frac{p_1(Q)}{24} - \frac{\text{tr}(G^2)}{2} \right] \\
+ k \frac{3p_2^2(Q) - 4p_2(Q)}{192} + k \frac{p_1(Q) \text{tr}(F^2)}{96} + k \frac{\text{tr}(F^4)}{24}.
\]

(40)

The anomaly is again of the required form (36) but this time with \( n = k \) and

\[
Y_4 = -k \frac{p_1(Q)}{24} + k \frac{p_1(N)}{12} - \frac{\text{tr}(G^2)}{2}.
\]

(41)

As expected, the tension of \( k \) five-branes must be \( k \) times the tension of a single five-brane.

6 Conclusion

We have proved that Witten’s \( SO(32) \) five-brane is anomaly free, this is an essential requirement for the consistency of the \( SO(32) \) five-brane theory. As mentioned in the introduction, one can also interpret the result as a “derivation” from the world-volume point of view of the Green-Schwarz mechanism. In fact, we can turn the argument around and from the requirement of world-volume anomaly cancellation get the transformations of \( B \) and \( B_6 \) which imply the modified Bianchi identity and equations of motion of \( H \).

In addition we have a prediction concerning the term (29) which must appear in the effective world-volume action of the five-brane. It would be interesting to have a confirmation of this result from the conformal theory point of view. We have also proved that the system with \( k \) coincident \( SO(32) \) five-branes is also anomaly free. The field content of the \( E_8 \times E_8 \) five-brane is still unknown and it is not clear whether there exists an effective local field theory describing it. Anomaly cancellation arguments of the type exposed here may help the clarification of this issue.
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