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SUPERSTRINGS IN D = 10 FROM SUPERMEMBRANES IN D = 11

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ABSTRACT

The Type IIA superstring in ten dimensions is derived from the supermembrane in eleven dimensions by a simultaneous dimensional reduction of the world-volume and the space-time.

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It is well known that N = 2a supergravity in ten dimensions (g_{mn}, A_m, Φ; ψ_m, χ; A_{mnp}, A_{mn}) may be obtained by dimensional reduction from N = 1 supergravity in eleven dimensions ($\hat{g}_{\hat{m}\hat{n}}$; $\hat{\psi}_{\hat{m}}$; $\hat{A}_{\hat{m}\hat{n}\hat{p}}$). On the other hand, N = 2a supergravity is also the field theory limit of the Type IIA superstring. Does this imply a connection between D = 11 supergravity and strings? Bergshoeff, Sezgin and Townsend[1] have recently found a niche for D = 11 supergravity within the framework of extended objects, but the extended object in question is a three-dimensional membrane rather than a two-dimensional string[*)]. The purpose of this letter is to derive the Type IIA superstring from this supermembrane by a dimensional reduction of the world-volume from three to two dimensions and, simultaneously, a dimensional reduction of the space-time from eleven to ten.

To describe the coupling of a closed three-membrane to a d = 11 supergravity background, let us introduce world-volume co-ordinates $\hat{\xi}^{\hat{i}}$ ($\hat{i}$ = 1,2,3) and a world-volume metric $\hat{\gamma}_{\hat{i}\hat{j}}(\hat{\xi})$ with signature (-,+,+,). The target space is a supermanifold with superspace co-ordinates $\hat{z}^{\hat{M}} = (\hat{x}^{\hat{m}}, \hat{\theta}^{\hat{\mu}})$ where $\hat{m} = 1,\ldots,11$ and $\hat{\mu} = 1,\ldots,32$ with space-time signature $(-,+,\ldots,+)$. We also define $\hat{E}_{\hat{i}}{}^{\hat{A}} = (\partial_{\hat{i}}\hat{z}^{\hat{M}})\hat{E}_{\hat{M}}{}^{\hat{A}}(\hat{z})$ where $\hat{E}_{\hat{M}}{}^{\hat{A}}$ is the supervielbein and $\hat{A} = (\hat{a},\hat{\alpha})$ is the tangent space index ($\hat{a} = 1,\ldots,11$ and $\hat{\alpha} = 1,\ldots,32$). The action is then given by[1]

$$S = \int d^3\hat{\xi}\left[\frac{1}{2}\sqrt{-\hat{\gamma}}\,\hat{\gamma}^{\hat{i}\hat{j}}\hat{E}_{\hat{i}}{}^{\hat{a}}\hat{E}_{\hat{j}}{}^{\hat{b}}\eta_{\hat{a}\hat{b}} - \frac{1}{6}\varepsilon^{\hat{i}\hat{j}\hat{k}}\hat{E}_{\hat{i}}{}^{\hat{A}}\hat{E}_{\hat{j}}{}^{\hat{B}}\hat{E}_{\hat{k}}{}^{\hat{C}}\hat{A}_{\hat{C}\hat{B}\hat{A}} - \frac{1}{2}\sqrt{-\hat{\gamma}}\right] \tag{1}$$

Note that there is a Wess-Zumino term involving the super three-form $\hat{A}_{\hat{A}\hat{B}\hat{C}}(\hat{z})$ and also a world-volume cosmological term. In addition to world-volume diffeomorphisms, target space superdiffeomorphisms, Lorentz invariance and three-form gauge invariance, the action (1) is invariant under a fermionic gauge transformation[1] whose parameter $\hat{\kappa}^{\hat{\alpha}}(\hat{\xi})$ is a 32-component space-time Majorana spinor and a world-volume scalar. This is a generalization to the case of membranes of the symmetry discovered by Siegel[4] for the superparticle and Green and Schwarz[5] for the superstring in the form given by Hughes, Liu and Polchinski[6]. We shall return to this later in Eq. (23).

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*) It is interesting to note that the three-eight split SO(1,10) ⊃ SO(1,2) × SO(8) implied by the membrane had previously been invoked in Refs. 2) and 3) to exhibit the hidden SO(16) of D = 11 supergravity.

To see how the dimensional reduction works, let us first focus our attention on the purely bosonic sector for which the action (1) reduces to

$$S = \int d^3\hat{\xi} \left[\frac{1}{2} \sqrt{-\hat{\gamma}}\, \hat{\gamma}^{\hat{i}\hat{j}}\, \partial_{\hat{i}} \hat{x}^{\hat{m}}\, \partial_{\hat{j}} \hat{x}^{\hat{n}}\, \hat{g}_{\hat{m}\hat{n}}(\hat{x}) - \frac{1}{2} \sqrt{-\hat{\gamma}} + \frac{1}{6} \varepsilon^{\hat{i}\hat{j}\hat{k}}\, \partial_{\hat{i}} \hat{x}^{\hat{m}}\, \partial_{\hat{j}} \hat{x}^{\hat{n}}\, \partial_{\hat{k}} \hat{x}^{\hat{p}}\, \hat{A}_{\hat{m}\hat{n}\hat{p}}(\hat{x}) \right] \tag{2}$$

Varying with the respect to the metric $\hat{\gamma}_{\hat{i}\hat{j}}$ yields the embedding equation

$$\hat{\gamma}_{\hat{i}\hat{j}} = \hat{g}_{\hat{i}\hat{j}} \equiv \partial_{\hat{i}} \hat{x}^{\hat{m}}\, \partial_{\hat{j}} \hat{x}^{\hat{n}}\, \hat{g}_{\hat{m}\hat{n}}(\hat{x}) \tag{3}$$

while varying with respect to $\hat{x}^{\hat{m}}$ yields the equation of motion

$$\frac{1}{\sqrt{-\hat{g}}} \partial_{\hat{i}} \left(\sqrt{-\hat{g}}\, \hat{g}^{\hat{i}\hat{j}}\, \partial_{\hat{j}} \hat{x}^{\hat{m}} \right) + \hat{\Gamma}_{\hat{n}\hat{p}}{}^{\hat{m}}\, \partial_{\hat{i}} \hat{x}^{\hat{n}}\, \partial_{\hat{j}} \hat{x}^{\hat{p}}\, \hat{g}^{\hat{i}\hat{j}} = \frac{1}{6} \hat{F}^{\hat{m}}{}_{\hat{n}\hat{p}\hat{q}}\, \partial_{\hat{i}} \hat{x}^{\hat{n}}\, \partial_{\hat{j}} \hat{x}^{\hat{p}}\, \partial_{\hat{k}} \hat{x}^{\hat{q}}\, \frac{\varepsilon^{\hat{i}\hat{j}\hat{k}}}{\sqrt{-\hat{g}}} \tag{4}$$

where $\hat{F}_{\hat{m}\hat{n}\hat{p}\hat{q}}$ is the field-strength of $\hat{A}_{\hat{m}\hat{n}\hat{p}}$

$$\hat{F}_{\hat{m}\hat{n}\hat{p}\hat{q}} \equiv 4\, \partial_{[\hat{m}} \hat{A}_{\hat{n}\hat{p}\hat{q}]} \ . \tag{5}$$

We now make a two-one split of the world-volume co-ordinates

$$\hat{\xi}^{\hat{i}} = (\xi^{i}, \rho) \qquad i = 1,2 \tag{6}$$

and a ten-one split of the space-time co-ordinates

$$\hat{x}^{\hat{m}} = (x^{m}, y) \qquad m = 1,\ldots,10 \tag{7}$$

in order to make the partial gauge choice

$$\rho = y \tag{8}$$

which identifies the eleventh space-time dimension with the third dimension of the world-volume. The dimensional reduction is then effected by demanding that

$$\partial_\xi x^m = 0 \tag{9}$$

and

$$\partial_y \hat{g}_{\hat{m}\hat{n}} = 0 = \partial_y \hat{A}_{\hat{m}\hat{n}\hat{p}} . \tag{10}$$

A suitable choice of ten-dimensional variables is now given by

$$\hat{g}_{\hat{m}\hat{n}} = \Phi^{-2/3} \begin{bmatrix} g_{mn} + \Phi^2 A_m A_n & \Phi^2 A_m \\ \Phi^2 A_n & \Phi^2 \end{bmatrix}$$

$$\begin{aligned} \hat{A}_{\hat{m}\hat{n}\hat{p}} &= (\hat{A}_{mnp} , \hat{A}_{mny}) \\ &= (A_{mnp} , A_{mn}) \end{aligned} \tag{11}$$

From (3), the induced metric on the world-sheet is now given by

$$\hat{g}_{\hat{i}\hat{j}} = \Phi^{-2/3} \begin{bmatrix} g_{ij} + \Phi^2 A_i A_j & \Phi^2 A_i \\ \Phi^2 A_j & \Phi^2 \end{bmatrix} \tag{12}$$

where

$$g_{ij} \equiv \partial_i x^m \partial_j x^n g_{mn} , \quad A_i \equiv \partial_i x^m A_m . \tag{13}$$

Note that

$$\sqrt{-\hat{g}} = \sqrt{-g} \tag{14}$$

Substituting these expressions into the field equations (4) yields in the case $\hat{x}^{\hat{m}} = x^m$

$$\frac{1}{\sqrt{-g}}\,\partial_i\left(\sqrt{-g}\,g^{ij}\,\partial_j x^m\right) + \Gamma_{np}{}^m\,\partial_i x^n\,\partial_j x^p\,g^{ij} = \frac{1}{2}\,F^m{}_{np}\,\partial_i x^n\,\partial_j x^p\,\frac{\varepsilon^{ij}}{\sqrt{-\hat{g}}} \qquad (15)$$

where F_{mnp} is the field-strength of A_{mn}

$$F_{mnp} \equiv 3\,\partial_{[m} A_{np]} = \hat{F}_{mnpy} \qquad (16)$$

In the case $\hat{x}^{\hat{m}} = y$, (4) is an identity, as it must be for consistency. But (15) is just the ten-dimensional string equation of motion derivable from the action

$$S = \int d^2\xi \left[\frac{1}{2}\sqrt{-\gamma}\,\gamma^{ij}\,\partial_i x^m\,\partial_j x^n\,g_{mn} + \frac{1}{2}\,\varepsilon^{ij}\,\partial_i x^m\,\partial_j x^n\,A_{mn}\right] \qquad (17)$$

Comparing with (2), we see that the overall effect is to reduce the eleven-dimensional membrane to a ten-dimensional string, to replace the three-form by a two-form in the Wess-Zumino term and to eliminate the world-volume cosmological constant. Note that the other ten-dimensional bosonic fields A_{mnp}, A_m and Φ have all decoupled. They have not disappeared from the theory, however, since their coupling still survives in the fermionic θ sector, to which we shall turn shortly. First, we make some remarks.

As is well known, the dimensional reduction (10) corresponds to a Kaluza-Klein compactification of space-time on a circle in which one discards all the massive modes. The difference from conventional Kaluza-Klein is that by identifying the eleventh space-time dimension with the third dimension on the world-volume as in (8), the world-volume is also compactified on the same circle. The condition (9) means that we are discarding the massive world-sheet modes at the same time. By retaining all the U(1) singlets but only the U(1) singlets, these truncations are guaranteed to be consistent[7)] with the membrane equations of motion and, as we shall see, with the equations of motion of the background fields. As an extra check on consistency, we have been careful to substitute the Kaluza-Klein ansatz into the equations of motion rather than directly into the action. The signal for consistency is that the $\hat{x}^{\hat{m}} = y$ component of the field equations (4) is an identity. Having established consistency one may then, if so desired, substitute directly into the action (2) and integrate over ρ. The result is not quite the action (17) but an equivalent one which yields the same equations of motion. To see this, let us recall that since we are now treating $\hat{\gamma}_{\hat{i}\hat{j}}$ and $\hat{x}^{\hat{m}}$ as independent variables in (2), we should make independent ansätze for both. Thus we write

$$\hat{\gamma}_{\hat{i}\hat{j}} = \phi^{-2/3}\begin{bmatrix} \gamma_{ij} + \phi^2 V_i V_j & \phi^2 V_i \\ \phi^2 V_j & \phi^2 \end{bmatrix} \tag{18}$$

where γ_{ij}, V_i and ϕ are, a priori, unrelated to g_{ij}, A_i and Φ of (12). Substituting into the action (2) and integrating over ρ yields

$$S = \int d^2\xi \left[\frac{1}{2}\sqrt{-\gamma}\,\phi^{2/3}\,\Phi^{-2/3}\left(\gamma^{ij} g_{ij} + \gamma^{ij}(A_i - V_i)(A_j - V_j) + \phi^{-2}\Phi^2\right) - \frac{1}{2}\sqrt{-\gamma} + \frac{1}{2}\varepsilon^{ij}\,\partial_i x^m\,\partial_j x^n\,A_{mn}\right] \tag{19}$$

Since the equations of motion for γ_{ij}, V_i and ϕ are algebraic, we may eliminate all of them to yield the action

$$S = \int d^2\xi \left[\sqrt{-g} + \frac{1}{2}\varepsilon^{ij}\,\partial_i x^m\,\partial_j x^n\,A_{mn}\right] \tag{20}$$

which is the action we would have obtained by writing (2) in Nambu-Goto form

$$S = \int d^3\hat{\xi}\left[\sqrt{-\hat{g}} + \frac{1}{6}\varepsilon^{\hat{i}\hat{j}\hat{k}}\,\partial_{\hat{i}}\hat{x}^{\hat{m}}\,\partial_{\hat{j}}\hat{x}^{\hat{n}}\,\partial_{\hat{k}}\hat{x}^{\hat{p}}\,\hat{A}_{\hat{m}\hat{n}\hat{p}}\right] \tag{21}$$

Alternatively, we may eliminate just V_i and ϕ to obtain (17). It is interesting to note that the string action (17) we obtain by dimensional reduction is conformally invariant even though the membrane theory we started from was not.

The foregoing discussion is readily generalized to a superspace setting. To facilitate a discussion of the fermionic symmetry, it is convenient to eliminate the world-volume metric as an independent variable. In this way we avoid having to discuss the rather complicated transformation rule for the metric. The action (1) then takes on its Nambu-Goto form

$$S = \int d^3\hat{\xi} \left[\sqrt{-\det \hat{E}_{\hat{i}}{}^{\hat{a}} \hat{E}_{\hat{j}}{}^{\hat{b}} \eta_{\hat{a}\hat{b}}} - \frac{1}{6} \varepsilon^{\hat{i}\hat{j}\hat{k}} \hat{E}_{\hat{i}}{}^{\hat{A}} E_{\hat{j}}{}^{\hat{B}} E_{\hat{k}}{}^{\hat{C}} \hat{A}_{\hat{C}\hat{B}\hat{A}} \right] \tag{22}$$

It is invariant under the transformation[1)]

$$\begin{aligned} \delta \hat{z}^{\hat{a}} &\equiv \delta \hat{z}^{\hat{M}} \hat{E}_{\hat{M}}{}^{\hat{a}} = 0 \\ \delta \hat{z}^{\hat{\alpha}} &\equiv \delta \hat{z}^{\hat{M}} \hat{E}_{\hat{M}}{}^{\hat{\alpha}} = \hat{\kappa}^{\hat{\beta}} (1 + \hat{\Gamma})_{\hat{\beta}}{}^{\hat{\alpha}} \end{aligned} \tag{23}$$

where

$$\hat{\Gamma}_{\hat{\beta}}{}^{\hat{\alpha}} = \frac{1}{6\sqrt{-\hat{g}}} \varepsilon^{\hat{i}\hat{j}\hat{k}} \hat{E}_{\hat{i}}{}^{\hat{a}} \hat{E}_{\hat{j}}{}^{\hat{b}} \hat{E}_{\hat{k}}{}^{\hat{c}} (\hat{\Gamma}_{\hat{a}\hat{b}\hat{c}})_{\hat{\beta}}{}^{\hat{\alpha}} \tag{24}$$

In (24) $\hat{g}_{\hat{i}\hat{j}}$ is the metric on the world-volume induced from the bosonic metric on superspace,

$$\hat{g}_{\hat{i}\hat{j}} = \hat{E}_{\hat{i}}{}^{\hat{a}} \hat{E}_{\hat{j}}{}^{\hat{b}} \eta_{\hat{a}\hat{b}} \tag{25}$$

In order for (22) to be invariant under this transformation, it is necessary that the background supergeometry be constrained. The constraints found in Ref. 1) are

$$\begin{aligned} &\hat{T}_{\hat{\alpha}\hat{\beta}}{}^{\hat{c}} = -i (\hat{\Gamma}^{\hat{c}})_{\hat{\alpha}\hat{\beta}} \quad ; \quad \hat{F}_{\hat{\alpha}\hat{\beta}\hat{c}\hat{d}} = i (\hat{\Gamma}_{\hat{c}\hat{d}})_{\hat{\alpha}\hat{\beta}} \\ &\hat{F}_{\hat{\alpha}\hat{\beta}\hat{\gamma}\hat{\delta}} = \hat{F}_{\hat{\alpha}\hat{\beta}\hat{\gamma}\hat{d}} = 0 \end{aligned} \tag{26}$$

$$\hat{T}_{\hat{\alpha}\hat{b}\hat{c}} = \eta_{\hat{b}\hat{c}} \hat{\Lambda}_{\hat{\alpha}} \quad ; \quad \hat{F}_{\hat{\alpha}\hat{b}\hat{c}\hat{d}} = (\hat{\Gamma}_{\hat{b}\hat{c}\hat{d}})_{\hat{\alpha}}{}^{\hat{\beta}} \hat{\Lambda}_{\hat{\beta}} \tag{27}$$

Although these equations are not the standard equations of on-shell D = 11 supergravity in superspace[8)], they are equivalent to them. That is to say, by suitable redefinitions of the superconnections and parts of the supervielbein, we may set $\hat{\Lambda}_{\hat{\alpha}}$, $\hat{T}_{\hat{\alpha}\hat{\beta}}{}^{\hat{\gamma}}$ and $\hat{T}_{\hat{a}\hat{b}}{}^{\hat{c}}$ to zero,

$$\hat{T}_{\hat{\alpha}\hat{b}}{}^{\hat{c}} = \hat{T}_{\hat{\alpha}\hat{\beta}}{}^{\hat{\gamma}} = \hat{F}_{\hat{\alpha}\hat{b}\hat{c}\hat{d}} = 0 \tag{28}$$

Equations (26) and (28) are the on-shell supergravity equations, as may be checked using the Bianchi identities. Since we are always free to make such redefinitions, we may take the superspace constraints to be (26) and (28). This is therefore a stronger result than that given in Ref. 1); the fact that conventional constraints can be imposed was noted in the context of N = 1 D = 10 supersymmetric particles and strings in Ref. 9).

The Kaluza-Klein ansatz for the N = 1 D = 11 supervielbein is

$$\hat{E}_{\hat{M}}{}^{\hat{A}} = \begin{bmatrix} \hat{E}_M{}^a & \hat{E}_M{}^\alpha & \hat{E}_M{}^{11} \\ \hat{E}_y{}^a & \hat{E}_y{}^\alpha & \hat{E}_y{}^{11} \end{bmatrix} \tag{29}$$

$$= \begin{bmatrix} E_M{}^a & E_M{}^\alpha + A_M \chi^\alpha & \Phi A_M \\ 0 & \chi^\alpha & \Phi \end{bmatrix} \tag{30}$$

where $E_M{}^A = (E_M{}^a, E_M{}^\alpha)$ is the N = 2a D = 10 supervielbein, A_M the superspace U(1) gauge field and Φ and χ^a are superfields whose leading components are the dilaton and the dilatino respectively. In writing (23), we have made a partial D = 11 local Lorentz gauge choice to set $\hat{E}_y{}^a = 0$. For the superspace three-index potential $\hat{A}_{\hat{M}\hat{N}\hat{P}}$ we have

$$\hat{A}_{MNP} = A_{MNP} \tag{31}$$

$$\hat{A}_{MNy} = A_{MN} \tag{32}$$

All of the D = 10 superfields $E_m{}^A$, χ^α, A_m, Φ, A_{MN}, A_{MNP} are taken to be independent of y. Note also that ten-dimensional spinor indices run from 1 to 32 so that α and $\hat{\alpha}$ can be identified. With $\hat{z}^{\hat{M}} = (z^M, y)$ we also impose

$$\partial_\rho z^M = 0 \tag{33}$$

and fix

$$y = \rho \tag{34}$$

Substituting the ansätze (30), (31) and (32) into (22) and using (33) and (34) yields the action for a type IIA superstring coupled to a supergravity background

$$S = \int d^2\xi \left[\Phi \sqrt{-\det E_i{}^a E_j{}^b \eta_{ab}} - \frac{1}{2} \varepsilon^{ij} \partial_i z^M \partial_j z^N A_{NM} \right] \tag{35}$$

Purely for convenience in superspace calculations, we have omitted an overall factor of $\Phi^{-2/3}$ in the ansatz (29); the factor of Φ in (35) can be removed by a suitable rescaling of the supervielbein. To find the fermionic symmetry of the dimensionally-reduced action (35), one substitutes the Kaluza-Klein ansätze into (23). It is straightforward to show that

$$\hat{\Gamma}_\beta{}^\alpha = \Gamma_\beta{}^\alpha = \frac{1}{2\sqrt{-g}} \varepsilon^{ij} E_i{}^a E_j{}^b \left(\Gamma_{ab} \Gamma_{11}\right)_\beta{}^\alpha \tag{36}$$

and that

$$\delta \hat{z}^\alpha = \delta z^\alpha \equiv \delta z^M E_M{}^\alpha = \kappa^\beta (1+\Gamma)_\beta{}^\alpha \tag{37}$$

However, y also transforms under (23):

$$\delta y = -\kappa^\beta (1+\Gamma)_\beta{}^\alpha A_\alpha \tag{38}$$

and a compensating infinitesimal world-volume diffeomorphism with parameter

$$\left(0 \, , \, 0 \, , \kappa^\beta (1+\Gamma)_\beta{}^\alpha A_\alpha \right) \tag{39}$$

must be made in order to maintain the gauge $y = \rho$.

Since (22) is invariant under (23) when the D = 11 field equations are satisfied, it follows that the reduced action (35) will be invariant under (37) if the N = 2a D = 10 supergravity field equations are satisfied. This is because the compactification of the N = 1 D = 11 field theory on a circle is known to yield the N = 2a D = 10 field theory, though to the best of our knowledge this is the first time it has been done in superspace. Note that all of the N = 2a supergravity fields are now coupled, including A_{mnp}, A_m and Φ which decoupled from the purely bosonic sector.

The transformation (37) can be recast into the Green-Schwarz[5),6)] form by introducing

$$\lambda^{i\alpha} = \frac{1}{2}\frac{\varepsilon^{ij}}{\sqrt{-g}} E_j{}^a \kappa^\beta (\Gamma_a \Gamma_{11})_\beta{}^\alpha \tag{40}$$

so that (37) becomes

$$\delta z^\alpha = E_i{}^a \left[\left(\lambda_+^{i\beta} + \frac{\varepsilon^{ij}}{\sqrt{-g}}\lambda_{+j}^\beta\right) + \left(\lambda_-^{i\beta} - \frac{\varepsilon^{ij}}{\sqrt{-g}}\lambda_{-j}^\beta\right)\right](\Gamma_a)_\beta{}^\alpha \tag{41}$$

where

$$\lambda_\pm^{i\alpha} = \frac{1}{2}\lambda^{i\beta}(1 \pm \Gamma_{11})_\beta{}^\alpha \tag{42}$$

In conclusion, we have succeeded in deriving [for the first time*)] the action of the Type IIA superstring coupled to an N = 2a D = 10 supergravity background starting from the action of the supermembrane coupled to the background of N = 1 supergravity in D = 11. The dimensional reduction corresponds to a compactification of both the space-time and the world-volume on the same circle and then discarding the massive modes. Classically, this is equivalent to letting the membrane tension α_3' tend to infinity and the radius of the circle R tend to zero in such a way that the string tension

$$\alpha_2' = 2\pi R \alpha_3'$$

remains finite. The Type IIA superstring is known to be a consistent quantum theory; the most urgent question for the supermembrane is whether it too is a consistent quantum theory in its own right.

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*) The Type IIB action is given in Ref. 10).

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