

Worldvolume supersymmetry

Renata Kallosh*

Physics Department, Stanford University, Stanford, California 94305-4060

(Received 26 September 1997; published 24 February 1998)

A general set of rules is given on how to convert a local κ symmetry of a brane action and space-time supersymmetry into the global supersymmetry of the worldvolume. A Killing spinor adapted gauge for quantization of κ symmetry is defined for this purpose. As an application of these rules we perform the gauge fixing of the M-5-brane to get the theory of the (0,2) tensor supermultiplet in $d=6$. [S0556-2821(98)50206-8]

PACS number(s): 11.25.-w, 04.65.+e, 11.30.Pb

I. INTRODUCTION

The set of known κ -symmetric actions include p-branes and more recently D-p-branes [1–3] and M-5-branes [4,5]. The worldvolume fields of κ -symmetric p-brane actions comprise the maps $Z^M(\xi^i)$ from the worldvolume coordinates $\xi^i=0, \dots, p$ to the superspace $Z^M=(X^m, \theta^\mu)$. D-p-branes depend in addition on the worldvolume 1-form gauge potential and, M-5-branes depend on a 2-form gauge potential with the self-dual field strength. All these actions in a flat background have a global space-time supersymmetry as well as a local κ symmetry which is, in general, infinite reducible and difficult to deal with. The quantization was developed mostly in the light-cone gauge for the Green-Schwarz (GS) string and for the Bergshoeff-Sezgin-Townsend membrane. Recently it became possible in the case of D-p-branes to define an irreducible κ symmetry and to exhibit the worldvolume supersymmetry upon gauge fixing an irreducible κ symmetry [6]. The gauge fixing of D-p-branes was possible in a covariant way with respect to a 10-dimensional Lorentz symmetry [2,7,6].

The purpose of this note is to introduce the concept of irreducible κ symmetry and its consequent gauge fixing for a general case of κ -symmetric actions. We are not trying to achieve here the quantization covariant in embedding space-time, in general, although the experience with covariant quantization of D-p-branes is helpful. For the M-branes as different from D-p-branes, this type of covariant quantization is certainly not possible as the 32 component Majorana spinor forms the smallest representation of the 11-dimensional Lorentz group.

Our main purpose here is to find the best way to exhibit the worldvolume global supersymmetry of the brane. In particular we would like to get the supersymmetric action and global supersymmetry transformation rules for the (0,2) tensor multiplet in $d=6$ theory. Not very much is known about the tensor multiplets in $d=6$. In the case of (2,0) supersymmetry, the equations of motion describing the coupling of n tensor multiplets to supergravity have been constructed [8]. In the case of (1,0) supersymmetry the coupling of the tensor multiplet to Yang-Mills multiplet in the absence of supergravity is known [9]. The interest in the 6-dimensional supersymmetric theory of a tensor multiplet, in addition to that

it is a gauge-fixed M-5-brane theory, is also motivated by the expectation that in matrix theory [10], the theory of n interacting (0,2) tensor supermultiplets may play an important role [11].

We will use both the action of the M-5-brane [4] as well as the geometric approach to the M-5-brane developed in [12] based on superembedding the target superspace into the worldvolume superspace of the brane.

The relation between space-time supersymmetry, κ symmetry, and unbroken worldvolume supersymmetry was established in [7]. The unbroken worldvolume supersymmetry defining the Bogomol'nyi-Prasad-Sommerfield (BPS) states on the brane was found to be given by a universal formula

$$\delta\theta_{\text{unbr}}=(1-\Gamma)\epsilon=0, \quad (1)$$

where $(1+\Gamma)$ is the generator of κ symmetry $\delta_\kappa\theta=(1+\Gamma)\kappa$. Also the algebra of Noether supercharges of the M-5-brane classical action was studied in [13].

In this note we will find the worldvolume supersymmetry which appears in the gauge-fixed action of the M-5-brane.

The strategy is to adopt here the rules of duality symmetric quantization in [14] where it was suggested to *gauge fix the infinite reducibility of the κ symmetry using the Killing spinors admitted by a consistent background of a given extended object*. This will give us a suitable way to get the worldvolume supersymmetry. However we will not restrict ourselves to these classes of gauges only. In fact we will work out the general class of gauges which will serve the purpose of quantization of κ symmetry. It is expected that the physical matrix elements of the theory are independent of the choice of the gauge. However the global symmetries of the theories may take different forms in different gauges. This freedom will be used for the simplest possible description of the worldvolume supersymmetric theories.

II. IRREDUCIBLE κ SYMMETRY

The class of actions we consider have 32-dimensional global space-time supersymmetry and the local κ supersymmetry are

$$\delta_\epsilon\theta=\epsilon, \quad \delta_\epsilon X^m=\bar{\epsilon}\Gamma^m\theta, \quad (2)$$

$$\delta\theta=(1+\Gamma)\kappa, \quad \delta X^m=\bar{\theta}\Gamma^m\delta\theta, \dots \quad (3)$$

*Email address: kallosh@physics.stanford.edu

Here the ellipsis means the transformation of the Born-Infeld or tensor field. Γ is a function of the fields of the brane and depends on ξ^i therefore. The matrix $\Gamma(\xi)$ squares to 1 and has a vanishing trace:

$$\text{tr } \Gamma = 0, \quad \Gamma^2 = 1, \quad (1 + \Gamma)(1 - \Gamma) = 0; \quad (4)$$

i.e., $1 + \Gamma$ is a projector which makes a 32-dimensional parameter of κ supersymmetry effectively only 16-dimensional. Let us pick up some constant, ξ^i -independent projectors

$$\mathcal{P}_\pm = \frac{1}{2} (1 \pm \gamma), \quad (5)$$

which can divide any 32-dimensional spinor into 2 parts. Here again we assume that

$$\text{tr } \gamma = 0, \quad \gamma^2 = 1, \quad (1 + \gamma)(1 - \gamma) = 0. \quad (6)$$

This ξ^i -independent projector will be used to fix the gauge. We will call the gauge adapted to the Killing spinor when

$$\gamma = \Gamma|_{\text{cl}}, \quad (7)$$

i.e., the constant projector $1 + \gamma$ is the κ -symmetry projector $1 + \Gamma$ taken at the values of fields which form a classical solution describing the relevant bosonic brane. The Killing spinor of a space-time geometry naturally cannot depend on the coordinates of the worldvolume. We will see it in an example of a M-5-brane later. In general we do not require any relations between possible projectors for gauge fixing and κ -symmetry generators. We will find out later some constraints which are required to make a projector defining the gauge fixing possible.

The steps to gauge fix κ symmetry and get the worldvolume global supersymmetry in the most general case are the following:

- (1) Find the basis in which γ is diagonal so that

$$\mathcal{P}_+ = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \quad \mathcal{P}_- = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \quad (8)$$

and split all spinors accordingly:

$$\theta = \begin{pmatrix} \theta^\alpha \\ \theta^{\alpha'} \end{pmatrix}, \quad \kappa = \begin{pmatrix} \kappa^\alpha \\ \kappa^{\alpha'} \end{pmatrix}, \quad \epsilon = \begin{pmatrix} \epsilon^\alpha \\ \epsilon^{\alpha'} \end{pmatrix}. \quad (9)$$

- (2) On this basis define the block structure of $1 \pm \Gamma$ as follows:

$$1 + \Gamma = \begin{pmatrix} 1 + C & (1 - C^2)A^{-1} \\ A & 1 - C \end{pmatrix}, \\ 1 - \Gamma = \begin{pmatrix} 1 - C & -(1 - C^2)A^{-1} \\ -A & 1 + C \end{pmatrix}, \quad (10)$$

where the 16×16 dimensional matrices C and A commute,

$$AC - CA = 0. \quad (11)$$

The matrices $1 \pm \Gamma$ have vanishing determinants and rank 16, which means that the 16-dimensional matrices $1 \pm C$ and A are invertible.

- (3) If some choice of a projector \mathcal{P}_\pm leads to noninvertible A or $1 \pm C$, this projector cannot be used for quantization. Examples include $d=10$ covariant gauges for the Green-Schwarz string.

- (4) Introduce the irreducible 16-dimensional κ symmetry by the constraint

$$\mathcal{P}_- \kappa = \frac{1}{2} (1 - \gamma) \kappa = 0. \quad (12)$$

In our basis this means that 16 components of κ symmetry vanish

$$\kappa = \begin{pmatrix} \kappa^\alpha \\ 0 \end{pmatrix} \quad \kappa^{\alpha'} = 0. \quad (13)$$

Irreducible κ symmetry takes the form

$$\delta_\kappa \theta^\alpha = (1 + C)^\alpha_\beta \kappa^\beta, \\ \delta_\kappa \theta^{\alpha'} = A^{\alpha'}_\beta \kappa^\beta. \quad (14)$$

- (5) Consider a combination of 16-dimensional irreducible κ symmetry and 32-dimensional space-time supersymmetry

$$\delta_{\kappa, \epsilon} \theta^\alpha = (1 + C)^\alpha_\beta \kappa^\beta + \epsilon^\alpha, \\ \delta_{\kappa, \epsilon'} \theta^{\alpha'} = A^{\alpha'}_\beta \kappa^\beta + \epsilon^{\alpha'}. \quad (15)$$

- (6) Fix the 16-dimensional irreducible κ symmetry by imposing 16 gauge conditions

$$\mathcal{P}_+ \theta = \frac{1}{2} (1 + \gamma) \theta = 0 \Rightarrow \theta = \begin{pmatrix} 0 \\ \theta^{\alpha'} \end{pmatrix} \quad \theta^\alpha = 0. \quad (16)$$

- (7) Find the relation between κ and ϵ which will keep the gauge $\theta^\alpha = 0$

$$\kappa^\beta = -[(1 + C)^{-1}]^\beta_\alpha \epsilon^\alpha. \quad (17)$$

- (8) Finally get the 32-dimensional supersymmetry transformation¹ of 16 $\theta^{\alpha'}$ living on the brane

$$\delta_{\epsilon, \epsilon'} \theta^{\alpha'} = -A^{\alpha'}_\beta [(1 + C)^{-1}]^\beta_\alpha \epsilon^\alpha + \epsilon^{\alpha'}. \quad (18)$$

This is the *general answer*. Given a κ symmetry of the action is known and the right choice of the constant projector is made, which supplies us with 16×16 matrices C and A , we have the answer for the worldvolume supersymmetry.

For example for D-p-branes we have for p even $\gamma = \Gamma_{11}$, $C = 0$ and an invertible A can be found in [2,7,6] together with the total procedure, described here in steps 1–8. This is an example when both $1 + C$ and A are invertible for a given choice of γ . With the same choice of γ type IIA GS string will have a noninvertible $A = 0$ and this gauge is not acceptable as one can verify.

¹If the reparametrization symmetry is fixed by choosing a static gauge, the space-time spinors (former scalars on the worldvolume) like $\theta^{\alpha'}$ and $\epsilon^\alpha, \epsilon^{\alpha'}$ become worldvolume spinors.

III. THE THEORY OF THE (0,2) TENSOR SUPERMULTIPLER IN $D=6$

We will give here a brief description of the gauge-fixing procedure of the M-5-brane theory which provides the supersymmetric action for (0,2) tensor supermultiplet in $d=6$. The Padova-Kharkov manifestly $d=6$ general coordinate invariant M-5-brane action is [4]

$$S_{M-5}(X^m(\xi), \theta^\mu(\xi), A_{jk}(\xi), a(\xi)) = \int d^6\xi (L_0 + L_{WZ}), \quad (19)$$

where

$$L_0 = -\sqrt{-\det(g_{ij} + \tilde{H}_{ij})} + \sqrt{\frac{-g}{4(\partial a \cdot \partial a)}} (\partial_i a) \times (H^*)^{ijk} H_{jkl} (\partial^l a), \quad (20)$$

$$L_{WZ} = \frac{1}{6!} \varepsilon^{i_1 \dots i_6} [C_{i_1 \dots i_6}^{(6)} + 10 H_{i_1 i_2 i_3} C_{i_4 i_5 i_6}^{(3)}]. \quad (21)$$

Here $g = \det(g_{ij})$, and

$$(H^*)^{ijk} = \frac{1}{3! \sqrt{-g}} \varepsilon^{ijk i' j' k'} H_{i' j' k'},$$

$$\tilde{H}^{ij} = \frac{1}{\sqrt{-(\partial a \cdot \partial a)}} (H^*)^{ijk} \partial_k a. \quad (22)$$

The generalized field strength of the tensor field is

$$H_{ijk} = \partial_{[i} A_{jk]} - C_{ijk}^{(3)}, \quad (23)$$

where $C_{ijk}^{(3)}$ is the pullback of the superspace 3-form gauge potential $C^{(3)}$. The induced worldvolume metric $g_{ij}(\xi) = E_i^a E_j^b \eta_{ab}$, where η is the $D=11$ Minkowski metric and $E_i^a = \partial_i Z^M E_M^a$. The worldvolume six-form $C_{i_1 \dots i_6}^{(6)}$ is induced by the superspace 6-form gauge potential. The auxiliary worldvolume scalar field $a(\xi)$ serves to achieve the manifestly $d=6$ general coordinate invariance of the M-5-brane action. The κ -symmetry transformations and supersymmetry of space-time fermions are

$$\delta_{\kappa, \epsilon} \theta = (1 + \Gamma) \kappa + \epsilon, \quad (24)$$

where

$$\Gamma = \Gamma_{(0)} + \Gamma_{(3)} \quad (25)$$

and

$$\Gamma_{(0)} = \frac{1}{6! \sqrt{|g|}} \varepsilon^{i_1 \dots i_6} \gamma_{i_1} \dots \gamma_{i_6} \quad \Gamma_{(3)} = \frac{1}{2 \cdot 3!} h_{ijk} \gamma^{ijk},$$

$$i = 0, \dots, 5, \quad m = 0, \dots, 10, \quad \gamma_i = E_i^m \Gamma_m. \quad (26)$$

Here we are using the form of κ -symmetry transformations found originally in the superembedding approach [12] and proved later to be also a symmetry transformation of the M-5-brane action in [15]. The worldvolume field h_{ijk} of [12]

turns out to be a nonlinear function of the fields in the action, whose explicit form can be found in [15]. Note that due to the self-duality of h and the nilpotency of $\Gamma_{(3)}$, Γ can also be given in a form [7]

$$\Gamma = e^{\Gamma_{(3)} \Gamma_{(0)}}, \quad (\Gamma_{(3)})^2 = 0. \quad (27)$$

The gauge fixing of the M-5-brane action is inspired by the superembedding [12] of the space-time superspace with coordinates X^m, Θ^μ into worldvolume superspace with coordinates ξ^i, θ^α . We split $m = (i, a')$, $\mu = (\alpha, \alpha')$. The superembedding is $X^i = \xi^i, \Theta^\alpha = \theta^\alpha$ and $X^{a'} = X^{a'}(\xi, \theta), \Theta^{\alpha'} = \Theta^{\alpha'}(\xi, \theta)$. To be as close to this as possible in the bosonic action of the 5-brane we have to require that in our action

$$X^i = \xi^i, \theta^\alpha = 0 \quad (28)$$

and the fields of the (0,2) tensor multiplet remaining in the action which depend on ξ are

$$X^{a'}(\xi), \theta^{\alpha'}(\xi), A_{ij}(\xi), a(\xi), \quad a' = 1, 2, 3, 4, 5,$$

$$\alpha' = 1, 2, \dots, 16. \quad (29)$$

Thus we have 5 scalars $X^{a'}(\xi)$, a 16-component spinor $\theta^{\alpha'}(\xi)$ which can be considered (see below) as a chiral $d=6$ spinor with a $USp(4)$ symplectic Majorana-Weyl reality condition θ_s^α , a tensor $A_{ij}(\xi)$ with the self-dual field strength and an auxiliary scalar $a(\xi)$. The 11d 32×32 Γ^m matrices have to be taken in the basis which correspond to the split of the target superspace into the superspace of the 5-brane and the rest [12]. This reflects the $Spin(1,5) \times USp(4)$ symmetry of the six-dimensional theory. An 11d Majorana spinor decomposes as

$$\psi = (\psi_{\hat{\alpha}s}, \psi_s^{\hat{\alpha}}), \quad (30)$$

where $s = 1, 2, 3, 4$ is an $USp(4)$ index and $\hat{\alpha} = 1, 2, 3, 4$ is a 6d Weyl spinor index with upper (lower) indices corresponding to anti-chiral (chiral) spinors, respectively. The 6d spinors satisfy a Majorana-Weyl reality condition. The relevant representation of 11d Γ^m is

$$\Gamma_{\hat{\alpha}s, \hat{\beta}t}^i = \eta_{st} (\sigma^i)_{\hat{\alpha}\hat{\beta}}, \quad (31)$$

where η_{st} is the $USp(4)$ antisymmetric invariant metric and σ^i the 6d chirally projected gamma-matrices, etc., [12]. In terms of 16-component spinors we have $\psi_{\hat{\alpha}s} = \psi^{\alpha'}$, $\psi_s^{\hat{\alpha}} = \psi^\alpha$.

Thus we choose a projector γ to be a chiral projector of the 6-dimensional space times the unit matrix. In the basis above this means that

$$\gamma = \Gamma \Big|_{cl} = \frac{1}{6!} \varepsilon^{i_1 \dots i_6} \gamma_{i_1} \dots \gamma_{i_6} \Big|_{cl} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \quad (32)$$

Here the subscript cl means that we take $X_{cl}^{a'} = \text{const}$, $\theta_{cl} = 0, (h_{ijk})_{cl} = 0, (E_i^j)_{cl} = \delta_i^j, (E_i^{a'})_{cl} = 0$, and the field-independent part of the κ -symmetry generator $1 + \Gamma$ provides us with the projector for gauge-fixing κ symmetry. Note that

this is exactly the projector which specifies the M-5-brane Killing spinor in the target space.²

The gauge-fixed theory is given by the classical action in the gauge (28). Since both the reparametrization symmetry and κ symmetry are fixed in a unitary way, there are no propagating ghosts. We do not gauge fix the Maxwell theory of the tensor fields as our main purpose is to get the full theory of the (0,2) tensor supermultiplet in $d=6$.

The action for a tensor multiplet is an action of a M-5 brane in a Killing spinor adapted gauge with vanishing $X^i - \xi^i$ and $\theta^\alpha(\xi)$:

$$\begin{aligned} S_{(0,2)}(X^{a'}(\xi), \theta^{\alpha'}(\xi), A_{jk}(\xi), a(\xi)) \\ = S_{M-5}(X^{a'}(\xi), \theta^{\alpha'}(\xi), A_{jk}(\xi), a(\xi), X^i - \xi^i \\ = 0, \theta^\alpha(\xi) = 0). \end{aligned} \quad (33)$$

To find the exact nonlinear worldvolume supersymmetry transformations of the $S_{(0,2)}$ action, we may now proceed using the rules from the previous section. In addition to gauge fixing the spinor theta, we have to gauge fix the infinite reducible κ symmetry. We choose as before

$$\theta^\alpha = 0 \quad \kappa^{\alpha'} = 0. \quad (34)$$

To extract from the generator of κ -symmetry Γ the matrices C and A which define the worldvolume supersymmetry, we have to take into account that in the flat 11-dimensional background

$$\Gamma = \frac{1}{6! \sqrt{|g|}} \epsilon^{i_1 \dots i_6} (\gamma_{i_1} \dots \gamma_{i_6} + 40 \gamma_{i_1} \gamma_{i_2} \gamma_{i_3} h_{i_4 i_5 i_6}), \quad (35)$$

$$\gamma_i = (\delta_i^j - i \bar{\theta}^j \partial_i \theta) \Gamma_j + \partial_i X^{a'} \Gamma_{a'}. \quad (36)$$

Here we used the fact that the spinors are chiral and therefore $\bar{\theta} \Gamma^{a'} \partial_i \theta$ vanishes. Using Eq. (36) we may rewrite Γ as a sum of products of Γ 's

$$\Gamma = \sum_n \Gamma^{i_1 \dots i_n} F_{i_1 \dots i_n}(X^{a'}, \theta^{\alpha'}, h_{ijk}). \quad (37)$$

All terms with even number $n=2,4,6$ of $6 \Gamma^i$ will contribute only to C , all terms with odd number $n=1,3,5$ of Γ^i will contribute to A since Γ^i is off-diagonal in our basis. The dependence on diagonal matrices $\Gamma_{a'}$ is included in F . Thus

$$\Gamma = \Gamma_C + \Gamma_A = \begin{pmatrix} C & 0 \\ 0 & -C \end{pmatrix} + \begin{pmatrix} 0 & (1-C^2)A^{-1} \\ A & 0 \end{pmatrix}, \quad (38)$$

where

²An interesting possibility suggested by E. Bergshoeff of another gauge fixing the M-5-brane will use the new classical solution of Howe, Lambert, and West [12], with $(h_{ijk})_{cl} \neq 0$ describing the self-dual string soliton of the M-5-brane. Our quantization procedure may require modification when the BPS classical solutions on the brane are used for projectors.

$$\Gamma_C \equiv \begin{pmatrix} C & 0 \\ 0 & -C \end{pmatrix} = \sum_{n=2,4,6} \Gamma^{i_1 \dots i_n} F_{i_1 \dots i_n}(X^{a'}, \theta^{\alpha'}, h_{ijk}, a), \quad (39)$$

and

$$\begin{aligned} \Gamma_A \equiv \begin{pmatrix} 0 & (1-C^2)A^{-1} \\ A & 0 \end{pmatrix} \\ = \sum_{n=1,3,5} \Gamma^{i_1 \dots i_n} F_{i_1 \dots i_n}(X^{a'}, \theta^{\alpha'}, h_{ijk}, a). \end{aligned} \quad (40)$$

Finally the 32-dimensional supersymmetry transformation on the brane is given by

$$\delta_{\epsilon, \epsilon'} \theta^{\alpha'} = -A^{\alpha'}_{\beta} [(1+C)^{-1}]^{\beta}_{\alpha} \epsilon^{\alpha} + \epsilon^{\alpha'} \quad (41)$$

with $A(X^{a'}, \theta^{\alpha'}, h_{ijk}, a)$ and $C(X^{a'}, \theta^{\alpha'}, h_{ijk}, a)$ presented for the M-5-brane above.

The supersymmetry transformations of the bosonic fields, 5 scalars and a tensor, can be obtained using the combination of κ symmetry and space-time supersymmetry of these fields and the expression (41). The linearized form of the world-volume supersymmetry of the (0,2) tensor multiplet was given in [12]. In notation appropriate for a 6-dimensional theory for $\epsilon' = 0$,

$$\delta_{\epsilon} \theta_{\beta}^s = \epsilon^{\alpha t} (\frac{1}{2} \sigma_{\alpha \beta}^i (\gamma_b)_t^s \partial_i X^{b'} - \frac{1}{6} \sigma_{\alpha \beta}^{ijk} \delta_t^s h_{ijk}). \quad (42)$$

One can recognize here terms linear and cubic in Γ^i which form the linear approximation of our matrix A .

Note however that the full nonlinear action of the self-interacting tensor multiplet has also a symmetry under additional 16-component chiral spinor $\epsilon^{\alpha'} = \epsilon_{\alpha s}$. The one with the anti-chiral spinor $\epsilon^{\alpha} = \epsilon_s^{\alpha}$ in the linear approximation relates the spinor of the tensor multiplet to the derivative of scalars and to the tensor field strength. The nonlinear action has both chiral as well as anti-chiral supersymmetries.

IV. CONCLUSION

We have presented here new possibilities to gauge fix κ symmetry which may be useful in the context of the new generation of κ -symmetric actions. In particular the most recent κ -symmetric theory describing an $SL(2, \mathbf{Z})$ covariant superstring [16] may need for quantization a Killing spinor of the background to keep the $SL(2, \mathbf{Z})$ symmetry of the quantized theory. The main emphasis of the new quantization is to take into account the Killing spinors of the background for making κ symmetry irreducible and for projecting out 1/2 of the space-time fermions. This leads in particular to a natural construction of globally supersymmetric theories on the worldvolume. Our main general result is for the space-time Killing spinor adapted gauges, given the κ -symmetry generator

$$\Gamma = \begin{pmatrix} C & (1-C^2)A^{-1} \\ A & -C \end{pmatrix},$$

the global supersymmetry on the world volume is

$$\delta\theta = -A(1+C)^{-1}\epsilon + \epsilon'.$$

As an application of this new quantization we have gauge fixed the M-5-brane action in a Killing spinor adapted gauge and obtained the nonlinear action and nonlinear supersymmetry of the self-interacting (0,2) tensor multiplet in $d=6$. A further study of this theory will be necessary to present a

more detailed and explicit structure of it. Even more effort may be required to construct the interaction of n of such tensor multiplets.

ACKNOWLEDGMENTS

I am grateful to E. Bergshoeff for the valuable comments on this work and information on $d=6$ tensor multiplets. This work is supported by the NSF Grant No. PHY-9219345.

-
- [1] M. Cederwall, A. von Gussich, B. E. W. Nilsson, and A. Westerberg, Nucl. Phys. **B490**, 163 (1997); M. Cederwall, A. von Gussich, B. E. W. Nilsson, P. Sundell, and A. Westerberg, *ibid.* **B490**, 179 (1997).
 - [2] M. Aganagic, C. Popescu, and J. H. Schwarz, Phys. Lett. B **393**, 311 (1997); Nucl. Phys. **B495**, 99 (1997).
 - [3] E. Bergshoeff and P. K. Townsend, Nucl. Phys. **B490**, 145 (1997).
 - [4] P. Pasti, D. Sorokin, and M. Tonin, Phys. Lett. B **398**, 41 (1997); I. Bandos, K. Lechner, A. Nurmagambetov, P. Pasti, D. Sorokin, and M. Tonin, Phys. Rev. Lett. **78**, 4332 (1997).
 - [5] M. Aganagic, J. Park, C. Popescu, and J. H. Schwarz, Nucl. Phys. **B496**, 191 (1997).
 - [6] R. Kallosh, Phys. Rev. D **56**, 3515 (1997).
 - [7] E. Bergshoeff, R. Kallosh, T. Ortín, and G. Papadopoulos, Nucl. Phys. **B502**, 149 (1997).
 - [8] L. J. Romans, Nucl. Phys. **B269**, 691 (1986).
 - [9] E. Bergshoeff, E. Sezgin, and E. Sokatchev, Class. Quantum Grav. **13**, 2875 (1996).
 - [10] T. Banks, W. Fischler, S. Shenker, and L. Susskind, Phys. Rev. D **55**, 5112 (1997).
 - [11] M. Berkooz, M. Rozali, and N. Seiberg, Phys. Lett. B **408**, 105 (1997); N. Seiberg, "Note on theories with 16 supercharges," hep-th/9705117.
 - [12] P. S. Howe and E. Sezgin, Phys. Lett. B **394**, 62 (1997); P. S. Howe, E. Sezgin, and P. C. West, *ibid.* **399**, 49 (1997); P. S. Howe, N. D. Lambert, and P. C. West, "The self-dual string soliton," hep-th/9709014.
 - [13] D. Sorokin and P. K. Townsend, Phys. Lett. B **412**, 265 (1997).
 - [14] R. Kallosh, Phys. Rev. D **52**, 6020 (1995).
 - [15] I. Bandos, K. Lechner, A. Nurmagambetov, P. Pasti, D. Sorokin, and M. Tonin, Phys. Lett. B **408**, 135 (1997).
 - [16] M. Cederwall and P. K. Townsend, "The manifestly $SL(2,\mathbf{Z})$ -covariant superstring," hep-th/9709002.