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A SUPERSPACE ACTION FOR $N = 2$ SUPERGRAVITY

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A B S T R A C T

The action for $N = 2$ supergravity can be presented as the invariant volume of the chiral subspaces of the real $N = 2$ superspace. The invariant volume of the real superspace itself is shown to vanish. The real basis form of the action contains covariant Grassmann δ functions involving $N = 2$ prepotentials explicitly.

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At present there exist different superspace formulations of $N = 2$ supergravity¹⁻⁴⁾. They reproduce the set of fields and transformation laws known from the component approach⁵⁻⁷⁾. However, the action formula of Refs. 6) and 7) has not yet been presented in a superspace form. This should lead to the conclusion that the $N = 2$ superspace $\{(x^m, \theta^{\mu i}, \bar{\theta}_{\mu i})\}$ is not a suitable framework for this purpose. Indeed, as we show in the present paper, this superspace is quite peculiar: it is "empty", i.e., its invariant volume vanishes.

In Ref. 8), we pointed out that there is a submanifold^{*)}, namely the chiral subspace $\{(x_L^m, \theta_L^{\mu i})\}$ (or its right-handed conjugate), the invariant volume of which could be the action for $N = 2$ supergravity. Here this conjecture is confirmed. The invariant proposed is investigated in terms of component fields in the linearized limit, and is shown to correspond to the results of Refs. 6) and 7).

The action discussed can also be presented as an integral over the whole $N = 2$ superspace, but then it involves a Grassmann δ function, an object familiar from flat supersymmetry. In order to covariantize it properly, one explicitly needs (without derivatives) the prepotentials introduced in Ref. 8).

1. Since the construction of the action proposed is essentially based on the prepotential approach of Ref. 8), we should first briefly recall some of the ideas of that approach. The superspace we start with is complex:

$$\{(x_L^m, \theta_L^{\mu i}, \bar{\theta}_{\mu i}^L)\}, \quad \{(x_R^m, \theta_R^{\mu i}, \bar{\theta}_{\mu i}^R)\} \quad (1)$$

where

$$x_R^m = (x_L^m)^*, \quad \theta_R^{\mu i} = (\bar{\theta}_{\mu i}^L)^+, \quad \bar{\theta}_{\mu i}^R = (\theta_L^{\mu i})^+.$$

In this superspace, the following gauge group is defined

$$\begin{aligned} \delta x_L^m &= \lambda^m(x_L, \theta_L), & \delta x_R^m &= \bar{\lambda}^m(x_R, \bar{\theta}_R), \\ \delta \theta_L^{\mu i} &= \lambda^{\mu i}(x_L, \theta_L), & \delta \bar{\theta}_{\mu i}^R &= \bar{\lambda}_{\mu i}(x_R, \bar{\theta}_R), \\ \delta \bar{\theta}_{\mu i}^L &= \bar{\rho}_{\mu i}(x_L, \theta_L, \bar{\theta}_L); & \delta \theta_R^{\mu i} &= \rho^{\mu i}(x_R, \theta_R, \bar{\theta}_R). \end{aligned} \quad (2)$$

*) Note that the necessity to use integrals over various submanifolds of superspace in extended supersymmetry has been pointed out in the literature^{9,10)}.

Note the existence of invariant chiral subspaces, $\{(x_L, \theta_L)\}$ and $\{(x_R, \bar{\theta}_R)\}$; their volume will be the action for $N = 2$ supergravity. The parameters $\rho(\bar{\rho})$ are restricted by the conditions (infinitesimally)

$$\partial_R^{(\mu} \rho^{v)}_{(i} \rho_{j)} = 0, \quad \partial_R \rho_{\mu i} \rho^{\mu j} = 0 \quad (3)$$

where $\partial_R = \partial/\partial\theta_R$; (i,j) , (μ,ν) mean symmetrization; internal symmetry indices are raised and lowered with the help of ϵ^{ij} , ϵ_{ij} . These conditions are consistent with the group composition law and their rôle is to restrict the tangent space group (both in x - and in superspace) to the Lorentz group.

The physical (real) superspace $\{(x^m, \theta^{\mu i}, \bar{\theta}_{\mu i})\}$ is embedded as a hypersurface in the complex superspace:

$$\begin{aligned} x^m &= \frac{1}{2} (x_L^m + x_R^m), \quad \theta^{\mu i} = \theta_L^{\mu i}, \quad \bar{\theta}_{\mu i} = \bar{\theta}_{\mu i}^R; \\ H^m(x, \theta, \bar{\theta}) &= \frac{1}{2i} (x_L^m - x_R^m), \\ H^{\mu i}(x, \theta, \bar{\theta}) &= -\theta_L^{\mu i} + \theta_R^{\mu i}, \quad \bar{H}_{\mu i}(x, \theta, \bar{\theta}) = \bar{\theta}_{\mu i}^L - \bar{\theta}_{\mu i}^R. \end{aligned} \quad (4)$$

The transformation laws of this hypersurface and its co-ordinates follow directly from Eq. (2). The superfunctions H defining the hypersurface are in fact the prepotentials of the theory. This means that on the basis of Eqs. (2) - (4), one can construct the familiar differential geometry formalism, i.e., introduce vielbeins E_M^A , connections ω_{AB}^C , torsions T_{AB}^C , etc., all expressed in terms of the prepotentials. Having calculated explicitly the independent torsion components (which is most easily done in normal gauge⁸⁾) and comparing their values at $\theta = 0$ with the set of fields of Refs. 6) and 7), one sees that the prepotentials should be restricted by the constraints

$$T_{\alpha(i}^{\mu j} \rho_{j)} = 0; \quad (5)$$

$$\text{Im}(D_{(i}^{\alpha} T_{\alpha j)} + a T_{(i}^{\alpha} T_{\alpha j)}) = 0, \quad T_{\alpha i} \equiv T_{\alpha i, \beta j}^{\beta j}. \quad (6)$$

The coefficient a in Eq. (6) will be specified later on.

The explicit form of Eq. (5) in terms of prepotentials is⁸⁾:

$$F_{\alpha(i}^{-1} \underline{\tau} \bar{F}_{\beta j)}^{-1} \underline{\dot{\tau}} [\Delta_{\underline{\tau}}, \bar{\Delta}_{\underline{\dot{\tau}}}] H^m(\sigma_m)^{jk} = 0 \quad (7)$$

where

$$\Delta_{\underline{\tau}} = \partial_{\underline{\tau}} + i \partial_{\underline{\tau}} H^m (\delta_m^n + i \partial_m H^n)^{-1} \partial_n, \quad \bar{\Delta}_{\underline{\dot{\tau}}} = (\Delta_{\underline{\tau}})^+,$$

$$F_{\underline{\alpha}} \underline{\tau} = \delta_{\underline{\alpha}} \underline{\tau} + \Delta_{\underline{\alpha}} H^{\underline{\tau}}, \quad \bar{F} = F^+, \quad \underline{\tau} = \tau k, \quad \underline{\dot{\tau}} = \tau l, \quad \text{etc.}$$

The form of Eq. (6) can be easily worked out using the results of Ref. 8).

As we shall see below, both constraints (5) and (6) play an essential rôle in the construction of the action.

2. The straightforward generalization of the action formula for $N = 1$ supergravity¹¹⁾ is the invariant volume of the $N = 2$ superspace

$$S = \int d^4 x d^4 \theta d^4 \bar{\theta} \cdot \text{Ber}(E_M^A) \quad (8)$$

where $\text{Ber}(E_M^A)$ is the superdeterminant of the vielbeins. However, the x space Lagrangian corresponding to the action (8) has the wrong dimension cm^{-4} . Moreover, the integral (8) turns out to vanish (see below, Section 4).

The formulation of Ref. 8) provides another possibility. The invariant volumes of the left- and right-handed chiral subspaces $\{(x_L, \theta_L)\}, \{(x_R, \bar{\theta}_R)\}$

$$S_L = \kappa^{-2} \int d^4 x_L d^4 \theta_L \cdot \text{Ber}(\ell_{\hat{M}}^{\hat{A}}), \quad (9a)$$

$$S_R = S_L^* = \kappa^{-2} \int d^4 x_R d^4 \bar{\theta}_R \cdot \text{Ber}(\tau_{\hat{M}}^{\hat{A}}) \quad (9b)$$

produce Lagrangians with the right dimension cm^{-2} (the gravitational coupling constant κ has the dimension cm). The real part of this complex invariant

$$S = \frac{1}{2} (S_L + S_R) \quad (10)$$

will be shown to be indeed the action for $N = 2$ supergravity (the imaginary pseudoscalar combination of S_L and S_R vanishes for a certain value of the coefficient a in Eq. (6); see Section 6).

3. The "left- (right-) handed vielbeins" $\hat{\ell}_{\hat{M}}^{\hat{A}} (r_{\hat{M}}^{\hat{A}})$ are defined as follows [similar objects for $N = 1$ supergravity were introduced in Ref. 12)]. Consider a left-handed chiral superfield

$$\bar{D}_{\dot{\alpha}} \varphi = 0 \quad (11)$$

where $\bar{D}_{\dot{\alpha}}$ is the covariant spinor derivative. This chirality condition becomes most natural in a special, "left-handed" basis in superspace,

$$x_L^m = x^m + i H^m, \quad \theta_L^\mu = \theta^\mu, \quad \bar{\theta}_L^{\dot{\mu}} = \bar{\theta}^{\dot{\mu}} + \bar{H}^{\dot{\mu}}. \quad (12)$$

There Eq. (11) simply reads⁸⁾

$$\bar{\partial}_{\dot{\alpha}}^L \varphi \equiv \frac{\partial}{\partial \bar{\theta}_L^{\dot{\alpha}}} \varphi = 0. \quad (13)$$

Taking this into account, one can rewrite the derivatives $D_{\hat{A}}^{\varphi}$ ($\hat{A} = a, \underline{\alpha}$ but not $\underline{\dot{\alpha}}$) in the new basis

$$\begin{aligned} D_{\hat{A}} \varphi &= E_{\hat{A}}^{\hat{M}} \partial_{\hat{M}} \varphi = (E_{\hat{A}}^m + i E_{\hat{A}}^N \partial_N H^m) \partial_m^L \varphi + \\ &+ E_{\hat{A}}^{\mu} \partial_{\mu}^L \varphi \equiv \ell_{\hat{A}}^{\hat{M}} \partial_{\hat{M}}^L \varphi. \end{aligned} \quad (14)$$

To find the transformation properties of the newly-defined "left-handed" vielbeins $\hat{\ell}_{\hat{A}}^{\hat{M}}$ under the group (2) - (3), one has to compare the transformation laws of the Lorentz (tangent space) vector $D_{\hat{A}}^{\varphi}$ and the world superspace vector $\partial_{\hat{M}}^{\varphi}$ [remember Eq. (13)]. The result is:

$$\begin{aligned} \delta(\ell_{\hat{A}}^{\hat{M}}) &= L_{\hat{A}}^{\hat{B}} \ell_{\hat{B}}^{\hat{M}} + \ell_{\hat{A}}^{\hat{N}} \partial_{\hat{N}}^L \lambda^{\hat{M}} - \\ &- (\lambda^{\hat{N}} \partial_{\hat{N}}^L + \bar{\rho}^{\dot{\nu}} \bar{\partial}_{\dot{\nu}}^L) \ell_{\hat{A}}^{\hat{M}}. \end{aligned} \quad (15)$$

The first term in Eq. (15) is an induced Lorentz transformation [with parameters expressed in terms of $\rho^{\underline{\nu}}$, $\bar{\rho}^{\underline{\dot{\nu}}}$; see Ref. 8)]; the second one compensates for the transformations of $\partial_{\hat{M}}^{\varphi}$; the last one is the co-ordinate translation (2) in the basis (12).

Now, consider the superdeterminant of $\hat{\ell}_M^{\hat{A}}$ (the inverse matrix of $\hat{\ell}_A^{\hat{M}}$):

$$\begin{aligned} \delta[\text{Ber}(\hat{\ell}_M^{\hat{A}})] &= \delta[\text{Ber}(\hat{\ell}_A^{\hat{M}})]^{-1} = -\text{Ber}(\hat{\ell}_M^{\hat{A}}) \cdot \hat{\ell}_N^{\hat{B}} \delta \hat{\ell}_B^{\hat{N}} \cdot (-1)^{\hat{N}} \\ &= -\text{Ber}(\hat{\ell}_M^{\hat{A}}) \cdot \partial_N^{\hat{L}} \hat{\lambda}^{\hat{N}} \cdot (-1)^{\hat{N}} - (\hat{\lambda}^{\hat{N}} \partial_N^{\hat{L}} + \bar{\mathcal{F}}^{\hat{N}} \bar{\partial}_{\hat{N}}^{\hat{L}}) \text{Ber}(\hat{\ell}_M^{\hat{A}}). \end{aligned} \quad (16)$$

Apart from the term $\bar{\mathcal{F}}^{\hat{N}} \bar{\partial}_{\hat{N}}^{\hat{L}}$ this is the transformation law of a scalar density for the left-handed chiral superspace $\{(x_L, \theta_L)\}$. Thus, to be able to write down the invariant (9a) we have to prove that $\text{Ber}(\hat{\ell}_M^{\hat{A}})$ is chiral,

$$\bar{\partial}_{\hat{\alpha}}^{\hat{L}} \text{Ber}(\hat{\ell}_M^{\hat{A}}) = 0. \quad (17)$$

This has already been done⁸⁾ using the explicit expression for $\text{Ber}(\hat{\ell}_M^{\hat{A}})$ and working in normal gauge. We shall not repeat it here, we shall only stress that in the proof the constraint (5) is essential.

4. Now we can prove that the invariant volume (8) of the real superspace vanishes.

To this end, let us rewrite the integral (8) in the left-handed basis (12):

$$\begin{aligned} \int d^4 x d^4 \theta d^4 \bar{\theta} \cdot \text{Ber}(E_M^A) &= \\ &= \int d^4 x_L d^4 \theta_L d^4 \bar{\theta}_L \cdot \text{Ber}\left(\frac{\partial z_L}{\partial \bar{z}}\right) \cdot \text{Ber}(E_M^A). \end{aligned} \quad (18)$$

A straightforward calculation using the identity

$$\det(\delta_m^n + A_m^{\hat{j}} B_{\hat{j}}^n) = \det^{-1}(\delta_{\hat{j}}^{\hat{n}} + B_{\hat{j}}^m A_m^{\hat{n}})$$

shows that the Berezinian of the change of variables in Eq. (18) is:

$$\text{Ber}\left(\frac{\partial z_L}{\partial \bar{z}}\right) = \det^{-1}(\delta_m^n + i \partial_m H^n) \cdot \det \bar{F}. \quad (19)$$

Then, comparing the explicit expressions for $\text{Ber}(E_M^A)$ and $\text{Ber}(\hat{\ell}_M^{\hat{A}})$ [see Ref. 8)] one gets

$$\text{Ber}(\hat{\ell}_M^{\hat{A}}) = \det^{-1}(\delta_m^n + i \partial_m H^n) \cdot \det \bar{F} \cdot \text{Ber}(E_M^A). \quad (20)$$

So, putting Eqs. (19) and (20) into Eq. (18), we find

$$\int d^4x d^4\theta d^4\bar{\theta} \cdot \text{Bez}(E_M^A) = \int d^4x_L d^4\theta_L d^4\bar{\theta}_L \cdot \text{Bez}(\ell_{\hat{M}}^{\hat{A}}). \quad (21)$$

However, the last integral vanishes because of the chirality property (17).

Moreover, the same arguments show that

$$\int d^4x d^4\theta d^4\bar{\theta} \cdot \text{Bez}(E_M^A) \cdot \Phi = 0 \quad (22)$$

where Φ is any left- (or right-) handed chiral superfield. This means that a large number of counterterms in the theory will automatically vanish.

5. The invariant S_L (9a) can now be rewritten in the real basis $(x^m, \theta^\mu, \bar{\theta}^{\dot{\mu}})$ using the relation (21)

$$\begin{aligned} S_L &= x^{-2} \int d^4x_L d^4\theta_L \cdot \text{Bez}(\ell_{\hat{M}}^{\hat{A}}) \equiv \\ &\equiv x^{-2} \int d^4x_L d^4\theta_L d^4\bar{\theta}_L \cdot \bar{\theta}_L^4 \cdot \text{Bez}(\ell_{\hat{M}}^{\hat{A}}) = \\ &= x^{-2} \int d^4x d^4\theta d^4\bar{\theta} \cdot (\bar{\theta} + \bar{H})^4 \cdot \text{Bez}(E_M^A). \end{aligned} \quad (23)$$

The quantity

$$(\bar{\theta} + \bar{H})^4 \equiv \frac{1}{4!} (\bar{\theta} + \bar{H})_{\dot{\mu}i} (\bar{\theta} + \bar{H})^{\dot{\mu}k} (\bar{\theta} + \bar{H})_{\dot{\nu}k} (\bar{\theta} + \bar{H})^{\dot{\nu}i} \quad (24)$$

appearing in Eq. (23) is in fact a covariantized version of the well-known Grassmann δ function^{13,14)}. From a geometrical point of view, it defines a hypersurface in the real superspace (the chiral subspace) and confines the integration in Eq. (23) to this smaller and apparently more adequate submanifold.

6. So, the proposed action formula for $N = 2$ supergravity is

$$S = \frac{1}{2}(S_L + S_R) = \frac{x^{-2}}{2} \int d^4x d^4\theta d^4\bar{\theta} \times \\ \times \det^{-1}(e_a^m) \cdot \det^{-1}F \cdot \det^{-1}\bar{F} \cdot [(\theta + H)^4 + (\bar{\theta} + \bar{H})^4] . \quad (25)$$

Here, $\text{Ber}(E_M^A)$ is written down explicitly⁸⁾ with e_a^m defined as

$$e_a^m = -\frac{1}{8}(\sigma_a)_{\alpha\dot{\alpha}} F^{-1\alpha i} \not{F}^{-1\dot{\alpha} \dot{\beta}}_i [\Delta_{\beta}, \bar{\Delta}_{\dot{\beta}}] H^m .$$

To show the relevance of this action, one could try to vary the prepotentials in Eq. (25) and obtain the correct equations of motion. Unfortunately, this is difficult because the prepotentials and, correspondingly, their variations, are restricted by the constraints (5) and (6). Even to perform the variation in the "linearized" limit is not much easier. Indeed, the action (25) contains, in particular, terms linear in the prepotentials, e.g.,

$$\bar{\theta}_{\dot{\mu}i} \bar{\theta}^{\dot{\mu}k} \bar{\theta}_{\dot{\nu}k} \bar{H}^{\dot{\nu}i} . \quad (26)$$

Since the solution of the constraints (5) and (6) for $\bar{H}^{\dot{\nu}i}$ should be non-linear in the prepotentials, the term (26) can actually contribute to the bilinear ("linearized") action. This implies that the constraints should be solved at least in the bilinear approximation, which is not much simpler to find than the exact solution.

Therefore we decided to check the relevance of the action (25) in terms of component fields, and in the linearized limit. According to Refs. 6) and 7), the linearized Lagrangian for $N = 2$ supergravity contains the term

$$\chi^{\underline{\alpha}}(x) \lambda_{\underline{\alpha}}(x) + \bar{\chi}_{\underline{\dot{\alpha}}}(x) \bar{\lambda}^{\underline{\dot{\alpha}}}(x) . \quad (27)$$

The spinors $\chi_{\underline{\alpha}}(x)$ and $\lambda_{\underline{\alpha}}(x)$ are auxiliary fields with dimensions $\text{cm}^{-3/2}$ and $\text{cm}^{-5/2}$. In Ref. 8), imposing the constraints (5) and (6), we achieved that in the WZ gauge the prepotentials described the same set of fields as in Refs. 6) and 7). So, if we find the term (27) in the invariant (25), we can be sure that it is the same action. Indeed, the term (27) is unique; it cannot be altered by field redefinitions, gauge fixing, etc.

Thus formulated, the problem is considerably simplified. The linear solution of the constraints (5) and (6) in the WZ gauge is (only the terms containing the left-handed spinors $\chi_\alpha, \lambda_\alpha$ without derivatives are considered):

$$\begin{aligned} H^m &= \frac{1}{2} (\sigma^m)_{\mu\nu} \bar{\theta}^{\mu i} \bar{\theta}^{\nu j} \bar{\theta}^k (\theta_k^\nu \theta_\nu^\ell \lambda_\ell^\mu - \theta^\mu{}^\ell \theta_\ell^\nu \lambda_{\nu k}), \\ H^{\mu i} &= \frac{3}{4} (\bar{\theta}^{\mu m} \bar{\theta}_m^n \theta_n^\nu \theta_\nu^i \lambda_\mu^\mu - \bar{\theta}^{\mu i} \bar{\theta}_i^m \theta_m^\nu \theta_\nu^n \lambda_\mu^\mu), \\ \bar{H}^{\mu i} &= \bar{\theta}^{\mu i} \theta^{\mu k} \chi_{\mu k} + \bar{\theta}^{\mu \ell} \bar{\theta}_\ell^\nu \bar{\theta}_\nu^k \theta^{\mu i} \lambda_{\mu k} + \frac{1}{2} \bar{\theta}^{\mu i} \theta^{\mu k} \theta_k^\nu \theta_\nu^\ell \lambda_{\mu \ell}. \end{aligned} \quad (28)$$

Then the bilinear corrections to the solution (28) are calculated, the result is inserted into Eq. (25), and the coefficient of the term $\chi^\alpha \lambda_\alpha$ is computed. It is interesting to mention that the second constraint (6) plays a significant rôle here: without it, the action would contain meaningless linear terms. Finally, one gets the following contributions from the terms S_L and S_R in Eq. (25):

$$S_L \rightarrow (7 + a) \chi^\alpha \lambda_\alpha, \quad S_R \rightarrow 6 \chi^\alpha \lambda_\alpha \quad (29)$$

where a is the coefficient of the bilinear term in the constraint (5).

Now it is clear that one should fix the value of a at $a = -1$ in order to have a non-vanishing scalar invariant (25), but not a pseudoscalar invariant $i(S_L - S_R)$. The latter should vanish, since one can hardly imagine a pseudoscalar invariant made of the component fields of Refs. 6) and 7). So, this is another explanation of the rôle of the non-linear term in the constraint (5), which was originally obtained in Ref. 15) as a consequence of additional constraints on the central charge curvature.

7. The superspace action formula (25) presented fills in a gap in the existing superspace description of $N = 2$ supergravity. The presence of the covariantized Grassmann δ functions in Eq. (25) with the explicit prepotentials therein explains why the action could not be constructed in approaches dealing with potentials (vielbeins, etc.) only.

However, the practical application of such an action is limited, due to the constraints (5) and (6) on the prepotentials. This, as well as the "emptiness" of the superspace $\{(x^m, \theta^\mu, \bar{\theta}^{\dot{\mu}})\}$ and the need to use a smaller chiral submanifold to construct the action, indicates that a new, more adequate superspace approach should be developed for extended supergravity.

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