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COUNTERTERMS IN EXTENDED
SUPERGRAVITIES

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**COUNTERTERMS IN EXTENDED
SUPERGRAVITIES**

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To the memory of Felix Berezin

The geometrical invariants, integrals over the whole supermanifold, respecting all necessary symmetries of the theory, are shown to exist starting from the 8-th (4-th) loop approximation in the $N=8$ ($N=4$) on-shell supergravity. 3-loop counterterms, which are integrals over some subsupermanifolds, are presented on linearized level in $N=4$ and $N=8$ theories. The corresponding 3-loop non-linear invariants are discussed.

There is a considerable reduction of ultraviolet divergences in supersymmetric theories. In supergravity this reduction is connected, firstly, with vanishing of some superinvariants on shell, as occurs in the one-loop approximation in supergravities $N = 1, 2$ [1]. Secondly, it is connected with the fact that not all gravitational invariants have supersymmetric partners, as e.g. in the two-loop approximation in $N=1$ theory [2], where the gravitational invariant looks like $\kappa^2 \sqrt{g} (R_{\mu\nu\lambda\epsilon})^2$, and κ is the gravitational coupling constant. However in the three-loop approximation in supergravities $N = 1, 2$ the supersymmetric invariants, generalizing the term $\kappa^4 \sqrt{g} (R_{\mu\nu\lambda\epsilon})^4$, were pointed out, and they do not vanish on shell [3]. These invariants have been expressed also in terms of linearized superfields [4,5], full non-linear superfields [6], and also have been expressed in terms of geometrical objects of the theory (like torsion and curvature tensors) with the help of integrals over the whole supermanifold [7].

Let us call the standard geometrical invariant in extended supergravity the following:

$$S_N^{\ell} = (\kappa^2)^{\ell-1} \int dV \mathcal{L}(R_{MN PQ}, T_{MN}^P), \quad (1)$$

where $\mathcal{L}$ is some scalar, constructed from curvature and torsion tensors in tangent space. The integration in (1) goes over the whole supermanifold with invariant volume $dV = dx d\theta d\bar{\theta} \text{Ber } E$, where Berezinian E is a superdeterminant of the vielbein, and ℓ is the number of loops. Dimensional

considerations show that

$$\dim \mathcal{L} = 4 - 2N + 2(\ell - 1). \quad (2)$$

Taking into account that $\mathcal{L}$ contains only torsion and curvature tensors one can easily verify that $\dim \mathcal{L} \geq 2$, i.e.

$$\ell \geq N. \quad (3)$$

It follows from (3) that the standard geometrical invariants like (1) give contributions beginning from 3-d loop for $N=3$ supergravity, from 4-th loop for $N=4$ and from 8-th loop for $N=8$.

In the important paper of Brink and Howe [8] all components of the superspace curvature and torsion in the on-shell $N=8$ theory were expressed, by solving the Bianchi identities, through one superfield W_{ijk}^a , which is one of the components of the torsion *),

$$T_{\dot{c}\dot{d}ijk}^a = \varepsilon_{\dot{c}\dot{d}} W_{ijk}^a. \quad (4)$$

Thus it follows that in the $N=8$ theory the standard geometrical invariants like (1) do not exist up to the 8-loop level but appear in all orders beginning from the 8-loop level, e.g. $\ell=8$.

*) We use throughout the paper the notations from [8], where in tangent space all indices $\rightarrow$ MNPQ, spinor and internal $\rightarrow$ ABCD, spinor $\rightarrow$ abcd..., $\dot{a}\dot{b}\dot{c}\dot{d}$ internal $SU(N) \rightarrow ijk\dots$, vector $\rightarrow \mu\nu\dots$. The corresponding indices in curved space are denoted by $m, n, p, q, \dots$, $\alpha, \beta, \dots$, $\dot{\alpha}, \dot{\beta}, \dots$, $i, j, k, \dots$, $\mu, \nu, \dots$.

$$S_{N=8}^{L=8} = (k^2)^2 \int d^4x d^{12}\theta \text{Bec} E (W_{ijk}^a \bar{W}_{\dot{a}}^{ijk})^2 =$$

$$= k^{14} \int d^4x (R_{abcd} D_{u_2} \dots D_{u_5} R_{\dot{a}\dot{b}\dot{c}\dot{d}})^2 + \dots \quad (5)$$

The first geometrical invariant in the N=4 theory is the 4-loop counterterm

$$S_{N=4}^{L=4} = (k^2)^2 \int d^4x d^{16}\theta \text{Bec} E (W_a^{\dot{a}} \bar{W}_{\dot{a}}^a)^2, \quad (5')$$

where

$$\bar{W}_{\dot{a}}^a = \varepsilon_{\dot{a}ijk} T^{ijk}{}_{bc} \varepsilon^{bc} \quad (4')$$

Superinvariants like (1), and in particular (5), (5') respect all on-shell symmetries of the theory, i.e. general covariance in superspace and tangent space symmetries, internal (e.g., local SU(8) in (5)) and Lorentz symmetry.

In extended supergravities some geometrical invariants different from (1) also may exist since in superspace we have a "constrained" geometry, when some components of torsion are equal to zero or to the flat space value. This is a consequence of the existence of some prepotentials from which all geometrical objects are constructed as it is known in details in N=1 theory [9]. The simplest example of such invariants are the integrals over the left (right) superspace from chiral fields like $\int d^4x d^4\theta (d^4x d^4\bar{\theta})$ [9]. In the Yang-Mills supersymmetric theories the most interesting example is the SU(4) theory [10] where $S = \int d^4x \bar{D}^i \gamma^5 D_i T_{\tau} \bar{\lambda}^i \gamma^5 \lambda_i$, i.e. instead of integration over $d^{16}\theta$ we have an integration only over $d^4\theta$.

In what follows we try to use the linearized approximation to find the candidates for the three-loop counterterms. Let us note that extended supergravities $N \leq 4$ [11] on shell can be described by means of the following linearized chiral superfields *).

In the theory $N=1$ there is a tree-component spinor superfield [5] (a two-component spinor notations are used)

$$W_{abc} = \Phi_{abc} + \theta^d R_{abcd}, \quad (6)$$

where Φ_{abc} (R_{abcd}) is the spin $3/2$ (2) field strength. For the $N=2$ theory we have

$$W_{ab} = F_{ab} + \theta_i^c \Phi_{abc}^i + \frac{1}{2!} \theta_i^d \theta_j^c \varepsilon^{ij} R_{abcd}, \quad (7)$$

F_{ab} being the spin 1 field strength.

For $N=3$ the lowest component of the spinor superfield is a spin $1/2$ field f_a :

$$W_a = f_a + \theta_{ic} F_{ab}^i + \frac{1}{2!} \theta_{ic} \theta_{jc} \varepsilon^{ijk} \psi_{abc} + \frac{1}{3!} \theta_{ic} \theta_{jc} \theta_{kd} \varepsilon^{ijk} R_{abcd}. \quad (8)$$

At last for $N=4$ the lowest component of the scalar superfield is the scalar field Φ :

$$W = \Phi + \theta_{ia} f_a^i + \frac{1}{2!} \theta_{ia} \theta_{jb} F_{ab}^{ij} + \frac{1}{3!} \theta_{ia} \theta_{jb} \theta_{kc} \varepsilon^{ijk} \psi_{abc} + \frac{1}{4!} \theta_{ia} \theta_{jb} \theta_{kc} \theta_{ld} \varepsilon^{ijkl} R_{abcd}. \quad (9)$$

*) All dependence on κ is absorbed by an obvious rescaling of spin 0, $1/2$, 1, $3/2$ fields.

In the theories $N \leq 4$ at the linearized level on shell we have the following three-loop counterterm:

$$S_{N \leq 4}^{l=3} = \int d^4x d^{12}\theta \left(W_{a_1 \dots a_{rN}} \bar{W}_{\dot{a}_1 \dots \dot{a}_{rN}} \right)^2 = \quad (10)$$

$$= \int d^4x \left(R_{abcd} \bar{R}^{\dot{a}\dot{b}\dot{c}\dot{d}} \right)^2 + \dots$$

In the theories $N=1,2,3$ expression (10) has a natural geometrical (i.e. full non-linear) generalization. For example in the $N=3$ theory we have

$$S_{N=3}^{l=3} = \int d^4x d^{12}\theta \text{Ber } E \left(W_a \bar{W}^{\dot{a}} \right)^2, \quad (11)$$

where

$$\bar{W}^{\dot{a}} = \varepsilon_{ijk} \varepsilon^{ab} T^{\dot{a}}_{ab}{}^{ijk}, \quad (12)$$

i.e. the linearized volume is replaced by a full one, and the linearized superfield $\bar{W}^{\dot{a}}$ is replaced by a full one which is expressed through a torsion tensor in (12).

In the theory $N=4$ it is non-trivial to pass from (10) to geometrical objects, as it was done in (11), (12), since the scalar superfield W of zero dimension is not connected with torsion or curvature which have $\dim \geq 1/2$ (except for the zero dimensional $T^u_{ab} = G^u_{ab}$) as it follows from their definition by means of the commutator of two covariant derivatives.

Therefore we shall try to transform the expression

$$S_{N=4}^{l=3} = \int d^4x d^{16}\theta (W \bar{W})^2 \quad (13)$$

to the form like

$$\int d^4x (d^2\theta)_{x\bar{c}}^{ij} (\bar{D}_a^i W) (\bar{D}_a^j W) (\bar{D}_{x\bar{a}} \bar{W}) (\bar{D}_{c\bar{a}} \bar{W}) . \quad (14)$$

since at the linearised level

$$D_a^i W = W_a^i , \quad (15)$$

W_a^i being defined through torsion in (4'). We have found that in fact $S_{N=4}^{l=3}$ can be presented in the following form:

$$S_{N=4}^{l=3} = \int d^4x \mathcal{D}_{ii_1}^{jj_1} P^{mm_1 ii_1}_{nn_1 jj_1} \cdot \quad (16)$$

$$\cdot W_a^n W_a^{n_1} \bar{W}_{m\dot{a}} \bar{W}_{m_1\dot{a}} ,$$

where W_a^n is defined in (4'), and

$$\mathcal{D}_{ii_1}^{jj_1} \equiv \bar{Q}_{\dot{a}\dot{c}}^i \bar{Q}_{\dot{b}\dot{c}}^{j_1} Q_{i\dot{a}bc} Q_{j_1\dot{b}c} \quad (17)$$

where

$$Q_{i\dot{a}bc} \equiv \varepsilon_{ijkl} d\theta_a^i d\theta_b^{\dot{a}} d\theta_c^{\dot{b}} . \quad (18)$$

The projector P is defined as follows (round brackets mean symmetrisation):

$$P^{(mm_1)(ii_1)}_{(nn_1)(jj_1)} = \delta_{(n}^i \delta_{n_1)}^{i_1} \delta_{j_1}^{(m)} \delta_{j_1}^{m_1)} - \frac{2}{3} \delta_{(n}^{(i} \delta_{j_1}^{m_1)} . \quad (19)$$

$$\delta_{j_1}^{i_1} \delta_{n_1}^{m_1} + \frac{1}{15} \delta_n^{(m} \delta_{n_1}^{m_1)} \delta_{(j}^i \delta_{j_1}^{i_1)}$$

and possesses a property

$$\delta_i^j P_{(nn_1)(jj_1)}^{(mm_1)(ii_1)} = \dots = 0 \quad (20)$$

The projector P appears because the action of four spinor derivatives $D_a^n D_{a_1}^{n_1} \bar{D}_{m\dot{a}} \bar{D}_{m_1\dot{a}_1}$ on $W^2 \bar{W}^2$ produces not only superfields W_a^n but also non-geometrical terms like $\delta_n^m (\partial_{a\dot{a}} W) (D_a^{n_1} W) (\bar{D}_{m\dot{a}_1} \bar{W}) \bar{W}$. To exclude them we have introduced the projector P with the properties (20) and also have used the following property of the invariant (11-nearized) volume.

$$\int d^4x d^{12}\theta \sim \int d^4x \mathcal{D}_{ii_1}^{jj_1} P_{(nn_1)(jj_1)}^{(mm_1)(ii_1)} \cdot \bar{D}_{m\dot{a}} \bar{D}_{m_1\dot{a}_1} D_a^n D_{a_1}^{n_1} \quad (21)$$

Further expression (16) can be written down in terms of geometrical objects, by means of differential forms [12, 7] in superspace.

$$E^M = dz^m E_m^M = dx^\mu E_\mu^M + d\theta^{\alpha} E_{\alpha}^M \quad (22)$$

where $dx^\mu (d\theta^{\alpha})$ are anticommuting (commuting) variables. These differential forms (22) are insufficient for constructing superinvariants. One should use also "dual" differential forms, introduced by Berezin [13].

$$\tilde{E}_M = E_M^\mu d\tilde{x}_\mu + E_M^a d\tilde{\theta}_a, \quad (23)$$

where $d\tilde{x}_\mu$ ($d\tilde{\theta}_a$) are commuting (anticommuting) variables.

In this case we come from linearized volume to the full one as follows [14]:

$$d^4x d^{4N}\theta \Rightarrow d^4x d^{4N}\theta \text{ Bec } E = \prod_{u=1}^4 E^u \prod_{A=1}^{4N} \tilde{E}_A. \quad (24)$$

Now we are in a position to write the linearized subvolume in (16) in terms of differential forms:

$$S_{N=4}^{l=3} = \int \prod_{u=1}^4 E^u \mathcal{D}_{i_1 i_2}^{j_1 j_2} P_{(n n_1)(j j_1)}^{(m m_1)(i i_1)} \cdot W_a^n W_a^{n_1} \bar{W}_{m_1} \bar{W}_{m, a} \quad (25)$$

where $\mathcal{D}$ and P are defined in (17) and (19) correspondingly, and a new definition of $Q_{i a b c}$ is the following:

$$Q_{i a b c} = \varepsilon_{ijkl} \tilde{E}_a^j \tilde{E}_b^k \tilde{E}_c^l, \quad (26)$$

E_u and $\tilde{E}_a^j$ being defined in (22) and (23). Now eq. (25) contains only geometrical objects, on linear level it coincides with (13) and therefore in this approximation it is a superinvariant. However, to be sure that the $N=4$ theory in fact has a full nonlinear 3-loop counterterm (25) one should verify whether the differential form in (25) is integrable, i.e. the integral does not change with the change of integration variables. Let us note that we deal with the integration over a subsupermanifold, since we have $d^{4N}\theta$ in (25) and not

$L \neq 0$.

Now let us discuss the linearized approximation in the theory N=8 [15]. On shell at this level we have a superfield

W_{ijkl} the lowest component of which is a scalar field $\phi_{ijkl} = \frac{1}{24} \epsilon_{ijklmnpq} \bar{\Phi}^{mnpq}$

This superfield is self-dual (in internal space):

$$W_{i_1 i_2 i_3 i_4} = \frac{1}{24} \epsilon_{i_1 i_2 i_3 i_4 j_1 j_2 j_3 j_4} \bar{W}^{j_1 j_2 j_3 j_4} \quad (27)$$

Let the indices i_k take only the values from some set of four numbers, e.g. 1, 2, 3, 4, and let the indices j_k take only the values from the complementary set of the other four numbers (from 1, 2, ..., 8), in our example they are 5, 6, 7, 8. Then it is useful to introduce the notion of "proper" basis for the superfield $W_{i_1 i_2 i_3 i_4}$.

$$W_{i_1 i_2 i_3 i_4} = W_{i_1 i_2 i_3 i_4} (X_{ad} + \sum_{i_k} \theta_{i_k} \bar{G}_{ad} \bar{\theta}^{i_k} - \sum_{j_k} \bar{\theta}^{j_k} \bar{G}_{ad} \theta_{j_k}, \theta_{i_k}, \bar{\theta}^{j_k}) \quad (28)$$

In this basis it depends only on "proper" θ_{i_k} and on "strange" $\bar{\theta}^{j_k}$ (in our example $i_k = 1, 2, 3, 4$; $j_k = 5, 6, 7, 8$). On the contrary, $\bar{W}^{j_1 j_2 j_3 j_4}$ depends only on "strange" θ_{i_k} and on "proper" $\bar{\theta}^{j_k}$ in accordance with the self-duality condition (27), i.e.

$$\bar{\theta}^{i_k} W_{i_1 i_2 i_3 i_4} = \theta_{j_k} \bar{W}^{j_1 j_2 j_3 j_4} = 0 \quad (29)$$

In the "proper" basis the on-shell superfield

has the form (square brackets mean antisymmetrization):

$$\begin{aligned}
 W_{i_1 i_2 i_3 i_4} &= \Phi_{i_1 i_2 i_3 i_4} + \theta_{[i_1} \chi_{i_2 i_3 i_4]} + \frac{1}{24} \varepsilon_{i_1 i_2 i_3 i_4} \\
 &\times j_1 j_2 j_3 j_4 \bar{\theta}^{j_1} \bar{\chi}^{i_2 j_2 j_3 j_4} + \theta_{i_1} \partial_{a a} \bar{\theta}^{i_1} \Phi_{j_1 i_2 i_3 i_4} + \\
 &+ \frac{1}{2} \theta_{i_1 a} \theta_{i_2 b} F_{i_3 i_4}^{ab} + \dots + \frac{1}{4!} (\theta_{i_1}^a \theta_{i_2}^b \theta_{i_3}^c \theta_{i_4}^d \cdot \\
 &\times R_{abcd} + \frac{1}{24} \varepsilon_{i_1 i_2 i_3 i_4} j_1 j_2 j_3 j_4 \bar{\theta}_a^{j_1} \bar{\theta}_b^{j_2} \bar{\theta}_c^{j_3} \bar{\theta}_d^{j_4} \cdot \\
 &\cdot \bar{R}^{abcd}) + \dots + \frac{1}{8!} \theta_{i_1}^a \theta_{i_2}^b \theta_{i_3}^c \theta_{i_4}^d \cdot \\
 &\cdot \bar{\theta}_a^{j_1} \bar{\theta}_b^{j_2} \bar{\theta}_c^{j_3} \bar{\theta}_d^{j_4} \partial_{a a} \partial_{b b} \partial_{c c} \partial_{d d} \Phi_{j_1 j_2 j_3 j_4}
 \end{aligned}
 \tag{30}$$

By the use of eq. (30) we present the linearized 3-loop invariant in the "proper" basis as follows:

$$S_{N=8}^{\ell=3} = \int d^4 x Q^{i_1 \dots i_4} \bar{Q}_{j_1 \dots j_4} W_{i_1 \dots i_4} \bar{W}_{j_1 \dots j_4} \tag{31}$$

where e.g. $i_k = 1, \dots, 4$; $j_k = 5, \dots, 8$, or any other subdivision of the numbers $1, \dots, 8$ into two groups i_k ; j_k can take place

$$Q^{i_1 \dots i_8} = D_{i_1}^{i_2} D_{i_2}^{i_3} D_{i_3}^{i_4} D_{i_4}^{i_5} D_{i_5}^{i_6} D_{i_6}^{i_7} D_{i_7}^{i_8} D_{i_8}^{i_9} \quad (32)$$

Expression (31) has the following properties:

$$D_{i_1}^{i_2} S = \bar{D}_{i_1}^{i_2} S = 0 \quad (33)$$

by construction, and

$$D_{i_1}^{i_2} S = \bar{D}_{i_1}^{i_2} S = 0 \quad (34)$$

due to eqs. (27), (29). Thus in eq. (31) we have $d^{16} \theta$ instead of $d^{32} \theta$, i.e. the integration over a subsupermanifold, and, nevertheless the action (31) is a superinvariant (linearised). It contains in particular the term $(R_{ab} \bar{R}_{cd})^2$ which is scalar in $SU(8)$. This means that other terms in (31) which are superpartners of this scalar are also scalars in $SU(8)$, though in eq. (31) we have some (arbitrary) subdivision of eight numbers into two groups, i.e. the action (31) is not a manifest $SU(8)$ scalar.

It is even more difficult than in N=4 theory to represent the linearised superinvariant (31) in geometrical terms. The scalar superfield W_{ijkl} is not a geometrical object. At the linearised level

$$D^{i_1} W_{i_2 j_3 k_4} = W_{i_2 j_3 k_4}^a$$

where the spinor superfield W_{ijkl}^a is expressed through torsion in eq.(4). Besides, at the linearised level

$$2nd \ W_{ijkl} = P_{ab} \ i_{jkl} \quad (35)$$

where there is an exact relation [8]

$$P_{\dot{a}\dot{a} ijkl} = \bar{D}_{\dot{a}i} W_{jkl\dot{a}} = \frac{1}{24} \varepsilon_{ijklmnpq} \bar{P}_{\dot{a}\dot{a}}{}^{mnpq} \quad (36)$$

We have not succeeded in acting a few spinor derivatives (from 16) in eq. (32) to come to geometrical superfields like W_{ijk}^a and its derivatives. But we have verified that when all 16 spinor derivatives in eq. (31) act on $W^{\dot{a}}$, the answer has the form *):

$$S_{N=8}^{E=3} = \int d^4x e [D_{\dot{a}}^m D_{\dot{b}}^n D_{\dot{c}}^p W_{mnp\dot{d}} \bar{D}_{\dot{m}\dot{a}} (a \cdot \bar{D}_{\dot{m}\dot{b}} \bar{D}_{\dot{m}\dot{c}} W^{\dot{a}}_{mnp\dot{d}})^2 + \dots + [D_{\dot{a}\dot{a}} P_{\dot{b}\dot{b}}{}^{mnpq}]^2 + [D_{\dot{a}\dot{a}} P_{\dot{b}\dot{b}}{}^{mnpq}]^2] \quad (37)$$

and all terms in eq. (37) are expressed through W_{mnp}^a and its derivatives, indices $m, n, p, \dots = 1, 2, \dots, 8$. Thus expression (37) contains only superfields which are tensors in local SU(8) group [16] and are global E_7 invariants as distinct from the original scalar superfield $W_{ijk\dot{a}}$, which corresponds to the fixed "symmetrical" gauge in SU(8) [15] and breaks E_7 symmetry.

In conclusion we would like to emphasize that in the

*) We have also introduced e , the determinant of the vierbein, to be closer to the exact nonlinear form.

theory $N=8$ on shell there definitely exist the standard geometrical invariants of the type (1), (5), starting from the 8-th loop. Therefore the hopes on the fundamental improvement of the ultraviolet behaviour of the $N=8$ supergravity should not be connected simply with the absence of the on-shell superinvariants. Of course, one may still hope that in supergravity some "miraculous" cancellation of divergences takes place similar to the cancellation which occurs in the first 3 loops (and higher?) of supersymmetric $SU(4)$ Yang-Mills theories [17], where the corresponding superinvariant does exist on shell, but appears with vanishing coefficient.

I am very grateful to V. Ogievetsky for the interest in this work and for many stimulating discussions.

Note added. After this paper has been written, we have seen the preprint "Counterterms for extended supergravity" by Howe and Lindström, where the 7-loop counterterm in the $N=8$ theory (3-loop counterterm in the $N=4$ theory) has been suggested at the linearized level. However the non-linear extension of the counterterm obtained in their paper violates local $SU(8)$ and global E_7 symmetries for the $N=8$ theory (the corresponding symmetries for the $N=4$ theory are also violated) since it depends on scalar superfield in the fixed $SU(8)$ "symmetric" gauge.

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