N=1 FORMULATION OF GENERAL N=2 YANG-MILLS SUPERGRAVITY COUPLINGS

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A B S T R A C T

We formulate general interactions of an N=2 Yang-Mills supermultiplet coupled to N=2 supergravity in terms of N=1 invariant functions. We show that the N=2 scalar potential of the complex scalar fields in the adjoint representation, superpartners of the Yang-Mills gauge fields, splits into a conventional gauge contribution as well as in a superpotential term contribution proportional to the SO(2) gauge coupling of N=2 de Sitter supergravity. The relation of these results to the σ model structure of $N \geq 4$ extended supergravities is also discussed, particularly in connection with the coset disintegration of scalar manifolds.

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Supersymmetric field theories of fundamental interactions¹⁾, including gravity²⁾, have recently aroused much interest as possible extensions of the standard gauge model of electroweak and strong interactions.

Lagrangians based on spontaneously broken $N = 1$ supergravity³⁾ nowadays provide phenomenologically acceptable models for particle physics with interesting new predictions in the 100-1000 GeV energy range where new particles, the superpartners of the known elementary particles, should be soon discovered⁴⁾. However, from a more fundamental point of view, $N = 1$ supergravity, being non-renormalizable, cannot be the final answer for the unification of fundamental forces, and new symmetries, perhaps extended supersymmetry, should possibly manifest themselves at higher energies.

In the present paper, we focus on the simplest extension of $N = 1$ local supersymmetry, namely $N = 2$ local supersymmetry⁵⁾. For computational reasons, it is important to have the fundamental Lagrangians written in the simplest possible way. In particular, if a possible scenario is envisaged⁶⁾, in which $N = 2$ supergravity is broken down to $N = 1$ or $N = 0$ supersymmetry, it is relevant to have a formulation of $N = 2$ Lagrangians in terms of $N = 1$ variables.

Our formulation is particularly useful in connection with the σ -model structure of $N \geq 4$ extended supergravities. In the $N = 2$ language, the scalar sector of these theories is given by an interaction of a Kählerian σ -model related to $N = 2$ vector multiplets⁷⁾ and a quaternionic σ -model related to $N = 2$ hypermultiplets^{8,9)}, these multiplets having a unique embedding in the $N \geq 4$ supergravity multiplets. We claim that in the case in which the quaternionic manifold of the hypermultiplet sector is also Kählerian these theories have a simple description in terms of $N = 1$ invariant functions. This is the case for $N = 4, 5$, and 6 extended supergravity. Remarkably enough, the general form of the scalar potential given in this article, as shown below, does indeed apply to these theories.

Our task is to formulate the most general $N = 2$ coupling of matter and Yang-Mills multiplets to supergravity in terms of the $N = 1$ invariant functions³⁾:

$$\mathcal{G}(z, z^*) = -J(z, z^*) + \ln |h(z)|^2 \quad (1)$$

and

$$\tilde{f}_{ab}(z) = \tilde{f}_{ba}(z) \quad (2)$$

which determine the most general coupling of a Yang-Mills-matter system to $N = 1$ supergravity. The z_i variables in Eqs. (1) and (2) denote the complex scalar fields of chiral supermultiplets, which in $N = 1$ supergravity can belong to arbitrary (generally complex) representations of the gauge group G .

Let us recall the properties of the functions $\mathcal{G}(z, z^*)$ and $\tilde{f}_{ab}(z)$. The function $\mathcal{G}(z, z^*)$ is a G -invariant function^{*}),

$$g^i T^a_i{}^j z_j = z^{*i} T^a_i{}^j g_j \quad (3)$$

containing the Kähler potential $J(z, z^*)$ and the superpotential $h(z)$. The scalar-kinetic terms are³⁾:

$$-g_i{}^j \partial_\mu z_j \partial_\mu z^{*i}, \quad g_i{}^j = -J_i{}^j \quad (4)$$

whilst the chiral part of the scalar potential is given by

$$e^{\mathcal{G}} \left[g^i (g^{-1})_i{}^j g_j - 3 \right] \quad (5)$$

The function $\tilde{f}_{ab}(z)$ is related to the Yang-Mills part of the Lagrangian³⁾. For instance, the part of the Lagrangian quadratic in the Yang-Mills field strengths is:

^{*}) We use the following conventions for gauge indices: $i, j, k, \dots$ refer to arbitrary representations of G , while $a, b, c, \dots$ always refer to the adjoint representation. Moreover,

$$g^i = \partial \mathcal{G} / \partial z_i; \quad g_i = \partial \mathcal{G} / \partial z^{*i} \quad \text{and} \quad g^i_j = \partial^2 \mathcal{G} / \partial z_i \partial z^{*j}$$

$$-\frac{1}{4} \text{Re} \tilde{f}_{ab} F_{uv}^a F_{uv}^b + \frac{i}{4} \text{Im} \tilde{f}_{ab} F_{uv}^a \tilde{F}_{uv}^b \quad (6)$$

whilst the gauge contribution to the scalar potential is

$$\frac{1}{2} (\text{Re} \tilde{f})^{-1 ab} D_a D_b$$

$$D_a = g g^i T_{ai}^j z_j = -g J^i T_{ai}^j z_j \quad (7)$$

g denoting the Yang-Mills gauge coupling constant. Spontaneous symmetry-breaking in local supersymmetry occurs whenever the vacuum state corresponds to³⁾

$$\{ \langle e^{g/2} g_i \rangle, \langle D_a \rangle \} \neq 0 \quad (8)$$

We now consider the case of $N = 2$ supergravity coupled to matter. We use three different multiplets of physical fields:

i) the supergravity multiplet⁵⁾

$$(e_{m\mu}, \psi_{\mu\pm}, B_\mu) \quad (9)$$

containing the vierbein field, two Majorana gravitinos, and a $U(1)$ gauge field (graviphoton);

ii) the Yang-Mills multiplet¹⁰⁾

$$(A_\mu^a, \Omega_\pm^a, z^a) \quad a = 1, \dots, n = \dim G \quad (10)$$

containing the Yang-Mills gauge bosons, two gauginos and a complex scalar field;

iii) the hypermultiplet¹¹⁾

$$(\xi^i, A_\pm^i) \quad i = 1, \dots, 2r \quad (11)$$

transforming as a $2r$ -dimensional representation of G and containing $2r$ Majorana spinors and $4r$ scalars satisfying a reality property which should be respected by the representation of the gauge group G .

The $N = 2$ system has an over-all $SO(2) \times G$ gauge invariance. We identify the $SO(2)$ with the gauge invariance of the B_μ field^{*}). We denote by g' its gauge coupling constant. This gauge invariance acts on the $\pm$ indices in formulae (9) to (11), and the only scalars which are not $SO(2)$ inert are thus the scalar fields of the hypermultiplet (11).

Couplings of Abelian vector multiplets¹³⁾ or hypermultiplets¹⁴⁾ to $N = 2$ supergravity have been constructed first using the Noether method. The development of $N = 2$ tensor calculus^{7,8,15,16)} allowed more general actions to be obtained. In particular, for the coupling of vector multiplets to supergravity, it was shown by de Wit et al.⁷⁾ that there exist more general actions, whose scalar sector describes a σ -model with a Kähler structure. The Kähler potential is in this case

$$J = \ln Y \quad ; \quad Y = z^{*I} N_{IJ} z^J \quad (12)$$

where the index I runs over the values 0 to $n = \dim G(z^0 = 1)$. The action is constructed from a function $f(z^a)$ which is a G -invariant analytic function in the complex variables z^a . N_{IJ} and Y in Eq. (12) are then given by

$$\begin{aligned} N_{00} &= \frac{1}{2} \left(f - f_a z^a + \frac{1}{2} f_{ab} z^a z^b \right) + c.c. , \\ N_{0a} &= \frac{1}{4} (f_a - f_{ab} z^b) + c.c. , \\ N_{ab} &= \frac{1}{4} f_{ab} + c.c. , \\ Y &= \frac{1}{2} \left[f + f^* + \frac{1}{2} (f_a - f_a^*) (z^{*a} - z^a) \right] \\ &\quad \left(f_a = \partial f / \partial z^a , \quad f_{ab} = \partial^2 f / \partial z^a \partial z^b \right) \end{aligned} \quad (13)$$

^{*}) Other possibilities are discussed elsewhere¹²⁾.

If we neglect the vector B_μ [as we omit a multiplet of spins $(\frac{3}{2}, 1)$ in the comparison between $N = 2$ and $N = 1$], we obtain kinetic terms as in formula (6) with

$$\tilde{f}_{ab} = -\frac{1}{4} f_{ab} + \frac{Y_a Y_b}{z^{*I} Y_I} \quad , \quad (14)$$

$$Y_a = \frac{\partial Y}{\partial z^a} = N_{aI} z^{*I} \quad , \quad Y_0 = N_{0I} z^{*I}$$

From Eq. (14) we notice that the $N = 2$ Yang-Mills metric $\tilde{f}_{ab}$ has a non-analytic part $y_a y_b / (z^{*I} Y_I)$. This term comes from the elimination of an (antisymmetric tensor) auxiliary field^{12,16)} of the spin $(\frac{3}{2}, 1)$ multiplet so it cannot be directly derived from the $N = 1$ superspace Lagrangian of Ref. 3.

The "minimal coupling" is the case where

$$f = 1 - z^a z^a \quad (15)$$

leading to

$$N_{00} = 1 \quad , \quad N_{0a} = 0 \quad , \quad N_{ab} = -\delta_{ab} \quad (16)$$

The linear invariance of f is now extended to $SO(n, \mathbb{C})$. The complex form of G , $G_{\mathbb{C}}$, is a maximal subgroup of $SO(n, \mathbb{C})$. The corresponding function y is:

$$Y = 1 - z^a z^{*a} \quad , \quad (17)$$

whose linear invariance is now $U(n)$. The scalar kinetic terms derived from the Kähler potential

$$J = \ln (1 - z^a z^{*a}) \quad (18)$$

have the structure of a CP^n sigma model with scalar fields living on a Grassmannian manifold $U(n, 1)/U(n) \otimes U(1)$.

For the couplings of hypermultiplets to $N = 2$ supergravity, Bagger and Witten⁹⁾ used the Noether method to show that the scalar sector always describes a σ -model with a quaternionic structure. Some of these models were already obtained by the tensor calculus^{7,8,15)}. Combined general couplings of hypermultiplets and vector multiplets have been studied by de Wit et al.⁷⁾.

We temporarily neglect hypermultiplets and confine ourselves to the general local coupling of vector multiplets described by the G-invariant analytic function $f(z)$,

$$f_b T_a{}^b{}_c z^c = 0 \quad (19)$$

where $iT_a{}^b{}_c$ are the (real) structure constants of G. The over-all scalar potential of the coupled $N = 2$ Yang-Mills supergravity system has been established by de Wit et al.^{7,12,16}, and it reads:

$$V = -8g'^2 (N^{-1})^{00} - 16g'^2 Y^{-1} - g^2 Y^{-2} N_{ab} (z^{*c} T_c{}^a{}_d z^d) (z^{*e} T_e{}^b{}_m z^m) \quad (20)$$

where g is the coupling constant of the gauge group G, whilst g' is the coupling constant of the $SO(2)$ local symmetry of gauged $N = 2$ supergravity¹⁷). It is apparent that the gauge part of V has the D^2 structure which is familiar from $N = 1$ supergravity.

In the case of "minimal coupling" [Eqs. (16) to (18)], one finds for the potential

$$V_{min} = -8g'^2 \left(1 + \frac{2}{1-z^a z^{*a}} \right) + \frac{g^2}{(1-z^a z^{*a})^2} |z^{*c} T_c{}^b{}_d z^d|^2 \quad (21)$$

All stationary points, supersymmetry, and symmetry-breaking patterns for this potential have been studied in Ref. 18.

Our aim is to recast formula (20) in the form given by formulae (5) and (7), namely to find the gauge-invariant function $\mathcal{G}$ given by formula (1). The answer turns out to be extremely simple: we claim that the function $\mathcal{G}$ which reproduces the Yang-Mills sector of $N = 2$ supergravity coupled to gauge multiplets is simply given by:

$$\mathcal{G} = \ln \left(\frac{8g'^2}{Y} \right) = \ln(8g'^2) - \ln Y \quad (22)$$

This means that the superpotential is fixed to be a constant

$$h(z) = 2\sqrt{2} g' \quad (23)$$

proportional to the $SO(2)$ gauge coupling constant g' . As we will show below, the same expression for $\mathcal{G}$ will give the potential for $N = 4$ and $N = 5$ supergravities.

To derive this result, we need to calculate the potential of the $N = 1$ theory specified by the two functions $\tilde{f}_{ab}$ [Eq. (14)] for the coupling of the $N = 1$ Yang-Mills multiplet and $\mathcal{G}$ [Eq. (22)] for the chiral multiplet in the adjoint representation. The chiral part of this potential is given by Eq. (5). From the logarithmic form (22) for $\mathcal{G}$ we derive*)

$$\begin{aligned} \mathcal{G}_{\bar{a}b} &= - \frac{Y_{\bar{a}b}}{Y} + \frac{Y_{\bar{a}} Y_b}{Y^2} \\ (\mathcal{G}^{-1})^{a\bar{b}} &= -Y(Y^{-1})^{a\bar{b}} - \frac{(Y^{-1})^{a\bar{c}}}{1-W} Y_{\bar{c}} Y_d (Y^{-1})^{d\bar{b}} \end{aligned} \quad (24)$$

where

$$W = \frac{1}{Y} Y_a (Y^{-1})^{a\bar{b}} Y_{\bar{b}} \quad (25)$$

The chiral potential is then

$$V = 8g'^2 \frac{1}{Y} \left(\frac{W}{W-1} - 3 \right) \quad (26)$$

This form of the $N = 1$ potential is valid without any assumption for Y . Notice, however, that in our $N = 2$ case:

*) $\bar{a}$ denotes derivatives with respect to z^{*a} .

$$\frac{\partial^2 Y}{\partial z^a \partial z^{*b}} = N_{ab} \quad (27)$$

The expression for W [Eq. (25)] in $N = 2$ is

$$Y(1-W) = z^{*I} N_{IJ} z^J - z^{*I} N_{Ia} (Y^{-1})^{ab} N_{bJ} z^J \quad (28)$$

The only non-vanishing contribution comes from $I = J = 0$. The identity

$$(N_{00} - N_{0a} Y^{-1}{}^{ab} N_{b0}) (N^{-1})^{00} = 1 \quad (29)$$

which can be proved using

$$\begin{aligned} N_{00} (N^{-1})^{00} + N_{0a} (N^{-1})^{a0} &= 1, \\ N_{b0} (N^{-1})^{00} + N_{bc} (N^{-1})^{c0} &= 0, \\ Y^{-1}{}^{ab} N_{bc} &= \delta_c^a, \end{aligned} \quad (30)$$

then implies

$$Y(1-W) = \frac{1}{(N^{-1})^{00}} \quad (31)$$

The form (26) is now the first line of the $N = 2$ potential (20).

We turn now to the gauge part, to identify the second line of Eq. (20) with Eq. (7). First, we note that the equation for the gauge invariance of f [Eq. (19)] can be derived with respect to z^d , giving:

$$f_{db} T_a{}^b{}_c z^c + f_b T_a{}^b{}_d = 0 \quad (32)$$

The expression for $\mathcal{G}$ [Eq. (22)] yields

$$D_a = -g \frac{1}{Y} Y_b T_a{}^b{}_c z^c \quad (33)$$

We then use Eq. (14) for y_b , the definition of N [Eq. (13)], and Eq. (32) to obtain

$$\mathcal{D}_a = -\frac{g}{4Y} \left(z^{*d} f_{db} T_a^b{}_c z^c - f_{cb}^* T_a^b{}_d z^{*d} z^c \right) \quad (34)$$

Up to now, the fact that the scalar fields span the adjoint representation has not been used: the matrix $(T_a)^b{}_c$ in Eq. (34) could be replaced by any representation. For the case of the adjoint representation, however, these matrices are antisymmetric in their lower indices. Hence, from Eq. (32), the quantity

$$f_{db} T_a^b{}_c z^c \quad (35)$$

is antisymmetric in the a, d indices. We then obtain

$$\mathcal{D}_a = \frac{g}{Y} N_{ab} (z^{*d} T_d^b{}_c z^c) \quad (36)$$

Using analogous manipulation we can prove that

$$Y_a z^{*b} T_b^a{}_c z^c = 0 \quad (37)$$

which allows us to replace N_{ab} in Eq. (36) by $-2 \operatorname{Re} \tilde{f}_{ab}$ [see Eq. (14)]. Equation (7) then yields

$$V_g = 2 \frac{g^2}{Y^2} \operatorname{Re} \tilde{f}_{ab} (z^{*d} T_d^a{}_c z^c) (z^{*e} T_e^b{}_m z^m) \quad (38)$$

which can indeed be identified with the second line in Eq. (20) using once more Eqs. (14) and (37).

To summarize, we have shown that the complete bosonic Lagrangian for $N = 2$ gauge multiplets coupled to $N = 2$ supergravity is completely specified in $N = 1$ formulation by the analytic function $f(z)$. Of course, we omitted the field B_μ

in the $N = 1$ formulation since this field belongs to the spin $(\frac{3}{2}, 1)$ multiplet which we neglected. As mentioned before, the elimination of an auxiliary field of this same multiplet is also responsible for the non-analytic term in the metric $\tilde{f}_{ab}$ as given in Eq. (14). This term does not allow the complete Yang-Mills part of the Lagrangian to be recast in an $N = 1$ superfield form as given in Ref. 3.

When the $SO(2)$ symmetry of supergravity is gauged, a chiral potential is induced, deriving from a fixed constant $N = 1$ superpotential proportional to the $SO(2)$ gauge coupling constant g' . Notice that there is no $SO(2)$ gauge potential, simply because the scalar fields of the Yang-Mills multiplet are neutral under $SO(2)$. On the contrary, an $SO(2)$ gauge potential would appear for the scalars of a hypermultiplet. The latter situation is explicitly realized in $N = 5$ supergravity.

Let us now consider some implications of our results for extended supergravities with $N \geq 4$. All these theories, in terms of $N = 2$ supersymmetry representations, contain vector multiplets, and thus, scalar fields whose potential should fit in with our description. For $N \geq 5$, these theories will also contain hypermultiplets. But we will show that, at least for $N = 5$, the scalars in these hypermultiplets also follow our prescription owing to the largest invariance of the manifold which contains all the scalar fields of the theory.

If we decompose $N \geq 4$ extended supergravity multiplets into $N = 2$ supermultiplets, we can regard the scalar sector of these theories, which describes a σ -model over the manifold G/H , as a particular interaction of a Kählerian σ -model¹⁹⁾ (related to the scalar fields of the $N = 2$ vector multiplets) with a quaternionic σ -model (related to the scalar fields of the $N = 2$ hypermultiplets). The same procedure also applies to $N = 4$ supergravity coupled to $N = 4$ Yang-Mills multiplets.

We call coset disintegration the decomposition of a σ -model associated with G/H in terms of σ -models associated with G_1/H_1 and G_2/H_2 , with $G_1, G_2 \subset G$ and $H_1, H_2 \subset H$.

Consider first the gravity multiplet of $N = 4$ supergravity. It contains a complex scalar field, obviously inert under both $SO(4)$ and the gauge group. This multiplet, when considered in terms of $N = 2$ supersymmetry, splits into the $N = 2$ gravity multiplet, an $SU(2)$ doublet of gravitino multiplets and one vector multiplet which contains the scalar field. Thus, the scalar potential of the $N = 4$ theory has to follow from our results. Moreover, it is known that this scalar field is a coordinate of the coset space $SU(1,1)/U(1)$. The corresponding Kähler potential (up to a field redefinition) is then exactly the same as in the "minimal" coupling case, $f(z) = 1 - z^2$ [Eq. (16)], and the potential is then obtained from

$$\mathcal{L} = \ln \left(8g'^2 (1 - zz^*)^{-1} \right) \quad (39)$$

which gives

$$V = -8g'^2 \left(\frac{2zz^*}{1 - zz^*} + 3 \right) \quad (40)$$

with vanishing gauge contributions for an $SO(4)$ -singlet complex field z . This result agrees with the result of Cremmer et al.²⁰⁾ for the gauging of $SO(4)$ supergravity*).

The $N = 5$ supergravity with local $SO(5)$ has been studied by de Wit and Nicolai²¹⁾. The scalar fields, transforming like a complex $\underline{5}$ of $SO(5)$, have kinetic terms given by a non-linear σ -model based on the manifold $SU(5,1)/SU(5) \otimes U(1)$. Their Kähler potential (up to a Kähler transformation and field redefinition) is

$$-J(z, z^*) = -\ln(Y) = -\ln(1 - z_i z_i^*) \quad , \quad (41)$$

$$i = 1, \dots, 5$$

*) Other gauging of $N = 4$ supergravity can be obtained in $N = 2$ by gauging the $SO(2)$ using a physical vector multiplet¹²⁾.

When the $N = 5$ gravity multiplet is decomposed into $N = 2$ multiplets, the scalar fields enter a $SO(3)$ triplet of vector multiplets containing three complex scalars which are $SO(2)$ singlets, the two remaining complex scalars being part of a hypermultiplet. First we can show that if we add to the Kähler potential $J(z, z^*)$ a constant superpotential such that the $\mathcal{G}$ function reads

$$\mathcal{G}(z, z^*) = \ln(8g'^2) - \ln(1 - z_i z_i^*) \quad (42)$$

as usual, we recover according to our rules, the $N = 5$ potential. It is very simple, using the $SO(5)$ transformation properties of the scalar fields to establish that the gauge part of the potential is

$$8g'^2 \frac{1}{Y^2} \left[(z_i z_i^*)^2 - (z_i z_i^*)(z_j^* z_j^*) \right], \quad (43)$$

while the chiral part of the potential defined by Eqs. (5) and (42) is

$$-8g'^2 - 16g'^2 Y^{-1} \quad (44)$$

as is usual in the "minimal" case. The sum of formulae (43) and (44) is precisely the potential found in Ref. 21. An obvious way to make clear the relation with $N = 2$ is to split the function $\mathcal{G}$ according to

$$J = \ln \left[\exp(J_1) + \exp(J_2) - 1 \right], \quad (45)$$

where

$$J_1 = \ln(1 - z_a z_a^*), \quad a = 1, 2, 3, \quad (46)$$

gives the Kähler potential for the scalar fields of the three vector multiplets which are coordinates of an $SU(3,1)/SU(3) \otimes U(1)$ manifold, whilst

$$J_2 = \ln(1 - z_4 z_4^* - z_5 z_5^*) \quad (47)$$

is the Kähler potential for the scalars of the hypermultiplet, in the manifold $SU(2,1)/SU(2) \otimes U(1)$, which is both Kählerian and quaternionic according to Bagger and Witten⁹).

It should be possible to extend our considerations to $N = 6$ and $N = 8$ supergravities. The $N = 6$ theory contains 15 complex scalar fields which are coordinates of the Kählerian manifold $SO^*(12)/U(6)$. When decomposed in terms of $N = 2$ multiplets, the $N = 6$ theory contains seven vector multiplets with scalars living in the manifold $O^*(8) \otimes SU(1,1)/U(4) \otimes U(1)$, and four hypermultiplets, the corresponding manifold being $SU(4,2)/SU(4) \otimes SU(2) \otimes U(1)$, which is Kählerian and quaternionic. Consequently, our prescription should also apply to the hypermultiplet sector of $N = 6$. The analogue for the $N = 8$ theory is the following: the 70 scalars parametrizing the coset $E_{7,7}/SU(8)$ are split into two pieces. First, 15 complex scalars belonging to 15 $N = 2$ vector multiplets span the Kähler manifold $SO^*(12)/U(6)$. Then, 40 real scalars, which are coordinates of the quaternionic manifold $E_{6,2}/SU(6) \otimes SU(2)$, are components of 20 $N = 2$ hypermultiplets. This last coset space is indeed the only non-Kählerian manifold present in the decomposition of all $N \geq 5$ extended supergravities. This is related to the fact that $E_{7,7}/SU(8)$ is not a Kähler manifold, and is a consequence of PCT self-conjugation of the $N = 8$ theory and of the 20 hypermultiplets contained in this theory.

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