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About the importance of supersymmetry and superspace for supergravity

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Abstract

We consider in this paper the importance of the concepts of supersymmetry and superspace for the construction of supergravity theories, focusing the attention in particular on $D = 4$, $N = 1$ supergravity. The Einstein theory of general relativity, considered supersymmetric, brings to supergravity and the superspace gives a geometrical meaning to the supersymmetry transformations. These technical tools are compact and formally very elegant, interesting technics of innovation for science.

Keywords: *Supersymmetry, Superspace, Supergravity, Differential Geometry, Unified Theories.*

1. Introduction

From its discovery in 1974, supersymmetry has attracted the attention of physicists, mathematicians, scientists. The interest in this symmetry has well-founded reasons:

a) it is a new peculiar symmetry, and the history of science shows that considerations of symmetry led to advances in fundamental and theoretical physics;

b) being characterized by transforming bosons into fermions and vice versa, it represents quite different properties with respect to those resulting from the ordinary symmetries of high energy physics.

The simplest theory is supersymmetry $N = 1$, where N corresponds to the number of generators of supersymmetry, and supergravity is the local version of the supersymmetric theory. For better understanding how supergravity theory fits so well in the phenomenology of elementary particles, we remember that the current phenomenology is described by the "standard model" [1-3].
The standard model is based on the gauge group SU(3) x SU(2) x U(1) for strong, weak and electromagnetic interactions. With this model it is correctly described the particle physics up to energy regions of around 100 GeV. The model is not based on an effective Lagrangian, such as the Fermi theory of weak interactions, but it is a renormalizable field theory. In "grand unified models" [4-7] the gauge group SU(3) x SU(2) x U(1) is unified in larger groups, such as SU(5) at this mass scale, SO(10) or larger groups, such as E_6.
Assuming the validity of the standard model up to a grand unification scale of 10^{15} GeV, the weak interaction scale of 100 GeV is very small if compared with the grand unification scale and with the Planck scale (10^{19} GeV). If we consider these three scales as "input" parameters of the theory, the square mass of scalar particles in the Higgs sector should be chosen with accuracy of order of 10^{-34}, if compared to the Planck mass. Theories in which there is an adjustment of such accuracy are also called "non-natural".
The way to make "natural" such a theory could be a symmetry implying that the small parameters of the theory were exactly zero and the current values of them are related to the breaking of such symmetry. Supersymmetry has just the feature of making "natural" the standard model. This kind of argumentation is analogous to the situation of spin 1 particles. For having fundamental spin 1 massless particles in a theory, they are usually introduced as particles associated to connections of a gauge symmetry, i.e. a symmetry maintaining them without mass; non-zero masses arise through a spontaneous breaking of the corresponding symmetry.
If we want introduce supersymmetry in the standard model, next to each boson (fermion) of the model, a fermionic (bosonic) supersymmetric partner must be introduced, and for building acceptable models at phenomenological level, it needs an additional Higgs supermultiplet.
Compared to other alternatives, the introduction of supersymmetry is a good method for making "natural" the standard model. In addition, if supersymmetry is a local symmetry, it necessarily includes the gravity and is called "supergravity".

2. Supergravity models

The supergravity models have a higher predictive power than those based on global supersymmetry, because they allow to solve problems such as the "gauge hierarchy" of standard model. Supersymmetry cannot be applied to particle physics if it is not broken. If not, fermions and bosons would have the same mass, and this is in contrast with the experimental data. If supersymmetry is spontaneously broken, it occurs a "mass splitting" among fermions and bosons of the same multiplet.

One of the greatest obstacles encountered in the construction of grand unification theories with global supersymmetry was the fact that this mass splitting occurred in a wrong way. Even following the supersymmetry breaking, with resulting diversification of mass among fermions and bosons, the mass relation of supertrace of M^2:

$$Str\, M^2 = \sum_j (-1)^{2j}(2j+1)m_j^2 = 0 \qquad (1)$$

valid in absence of matter, remained still valid (in Eq. (1) the sum is understood on all particles with a given spin and on all spin). This fact is in contrast with experimental results, because it implies that the scalar fields cannot increase in mass if fermions (quarks and leptons) remain light, as it should be.

The situation changed when it was found that in theories with local supersymmetry, as supergravity, Eq. (1) becomes:

$$Str\, M^2 = \Delta m^2\,, \qquad (2)$$

with Δm^2 linear combination of the square mass of gravitino and of $D^\alpha D^\alpha$, with D^α auxiliary field of vector multiplet. This discovery opened the way to application of $N = 1$ spontaneously broken supergravity for describing the phenomenology of particles at low energies. Scenarios with the following key features have been obtained:

1) $N = 1$ supergravity is coupled to n scalar multiplets, divided into:

a) a visible sector containing quarks, leptons and Higgs particles, together with their superpartners. These particles are assigned to the chiral representations of SU(3) x SU(2) x U(1), or grand unification groups G;

b) an invisible sector whose particles are singlets under SU(3) x SU(2) x U(1) or G, and have no interaction with the visible sector, except for the gravitational one.

2) The Kähler potential $G(z,\bar{z})$ is invariant with respect to the grand unification group G, "gauged" by a convenient vector multiplet, and it is chosen in such a way that the scalar fields of the invisible sector give a vacuum expectation value breaking supersymmetry [8].

3) The M_S scale of supersymmetry breaking is intermediate between the scale of weak interactions $M_W = 10^2$ GeV and the Planck scale $M_P = 10^{19}$ GeV:

$$M_S = \sqrt{M_W\, M_P} \cong 10^{10}\, GeV\,. \qquad (3)$$

4) The gravitino becomes massive "eating" the freedom degrees of goldstino and its mass $m_{3/2}$ is of order of the weak scale M_W. Inserting this information in Eq. (2), phenomenological plausible mass splitting are obtainable and this implies that the indirect effects of gravity cannot be discarded at these energies. With respect to the gauge hierarchy problem, the relation between the grand unification scale $M_X = 10^{15}\, GeV$ and the weak scale M_W is resolved by the supersymmetry breaking, which prohibits quadratic divergences. The super-Higgs phenomenon plays therefore a key role at global level, leading to supersymmetry breaking and to Eq. (2) [9,10].

Although it is possible to build $D = 4$ supergravity models with many supersymmetry charges, from the phenomenological viewpoint the theory with one supersymmetric charge, i.e. $N = 1$ supergravity, presents very interesting features. The spectrum of the known fermions at low energies (the region of 100 GeV) implies that they are in complex representations of the gauge group; this fact is not compatible with the extended supersymmetry $N > 1$, which allows real representations of the particles with respect to the considered gauge groups. With $N = 1$ supersymmetry it is possible to work with complex chiral representations of particles.

The supersymmetric theories are invariant with respect to a set of transformations, which change the spins of particles of half a unit, transforming bosons into fermions and vice versa. These transformations are generated by a Majorana spinor Q, which satisfies the following algebra:

$$[Q, P_\mu] = 0, \qquad (4)$$

$$\{Q, \overline{Q}\} = -2\gamma_\mu P^\mu\,, \qquad (5)$$

where P^μ is the traslation generator.

If we implement this algebra with spacetime parameters, i.e. if supersymmetry is local, even translations are local. A local translations invariance is substantially equivalent to an invariance with respect to general coordinate transformations, at least in the second order formalism of gravity, when connections are expected just resolved in terms of metric. So a theory, which is invariant under local supersymmetry transformations, includes necessarily the gravity [11].

Supersymmetry has been considered for many years as a very interesting mathematical structure from the point of view of quantum field theory, but not at particle physics level. The supersymmetry algebra appears formally as a possible extension of Lorentz and Poincarè algebras, which constitute the basis of the relativity theory.

The supersymmetry generators, acting on ordinary fields, create new fields. In the case of one spinorial generator, interesting situation by the phenomenological point of view, leptons and quarks are transformed into spin 0 partners, photons and gluons into spin 1/2 partners. Supersymmetry binds spin 1 particles with spin 1/2 particles, and spin 1/2 particles with spin 0 particles, but not directly the known particles. This was only an apparent problem of supersymmetry, because the existence of new particles, which are the superpartners of the ordinary ones, has been considered.

The photon and the SU(3) color octet of gluons have spin 1/2 partners called respectively "photino" and "gluino". "Wino" and "zino" are the spin 1/2 superpartners of $W^{\pm}$ and Z respectively. For leptons and quarks, the possibility, that does not require a great extension of the gauge group, consists in connecting them to new spin 0 particles called "sleptons" and "squarks" [3,12].

The theory is formulated by combining the gravitational multiplet, which contains the spin 2 graviton and its spinorial partner of spin 3/2 to massless supermultiplets of matter. They are of two types:

i) the vectorial supermultiplets, which have an index in the adjoint representation of the gauge group;

ii) the chiral supermultiplets, or "Wess-Zumino" supermultiplets, consisting of a spin 1/2 Majorana spinor and of a complex scalar.

After the spontaneous breaking of gauge invariance, some of gauge vector multiplets acquire mass, while the corresponding Wess-Zumino fields are deleted.

To distinguish the ordinary particles by their partners under symmetry, also the "R-parity" has been defined:

a) Higgs and gauge bosons, the spin 1/2 leptons and quarks are "R-even";

b) their superpartners (photino, gluino, heavy fermions, sleptons and squarks) are "R-odd".

The R-even sector of a supersymmetric gauge theory is similar to an ordinary gauge theory, but with more "constraints" due to supersymmetry. The conservation of R-parity implies that ordinary particles cannot exchange R-odd particles at lower order; spin 1/2 leptons and quarks exchange only gauge or Higgs bosons at classical level. R-odd particles are produced in pairs.

It is possible to define R not only as discrete, but also as continuous symmetry. The R-transformations act as phase transformations on spin 0 fields, as phase transformations or γ_5 on spin 1/2 fields. The R-invariance can also be helpful to limit a Lagrangian density beyond the constraints already imposed by supersymmetry, gauge invariance, conservation of baryon and lepton numbers. These restrictions may be necessary to have a spontaneous supersymmetry breaking.

There is no conflict, but complementarity between supersymmetry and grand unification approaches. The grand unification aims to a unified description of electromagnetic, weak and strong interactions, while supersymmetry seems the natural structure for the introduction of gravity.

The standard model which includes supergravity could appear apparently insignificant from a physical viewpoint, why not renormalizable. Field theories including gravity are not renormalizable and this is also the case of $N = 1$ classical supergravity. Initially it was hoped that the existence of supersymmetry would lead to cancellations of "infinites" of quantum theory; this is true, but only at the first perturbative orders. In general it is not possible to obtain a completely finite theory.

The problem of renormalizability of supergravity disappears, if it is not considered as "fundamental theory", but as "effective theory" of a superstring theory. By "effective theory" of a superstring theory we mean the theory obtainable integrating all massive modes of string theory in the path integral. Such a theory contains in general higher order derivatives, whose scale is fixed by the α' string constant. If we consider the terms which do not contain more than two derivatives of fields, it can be shown that the effective theories derived from superstring theories are the supergravity theories.

In particular, $N = 1$, $D = 4$ supergravity theories can be considered as the compactification from 10 to 4 dimensions of the heterotic string theory.

Considering the supergravity theory under this aspect, the problem of renormalizability vanishes, because the fundamental theory is the string theory, which appears to be finite [13-15].

3. Pure $D = 4$, $N = 1$ Supergravity

Gravity and the gauge theory of the Poincaré group ISO(1,3) in a 4-dimensional spacetime. The clarification of formal properties of gravity is vital for the formulation of its supersymmetric extension, i.e. supergravity.

The action of Einstein-Cartan can be written as:

$$A=\int_{M_4} R^{ab}(\omega)\wedge V^c\wedge V^d\,\varepsilon_{abcd}\,, \tag{6}$$

where M_4 is a 4-dimensional Riemannian manifold, R^{ab} is the 2-form of curvature:

$$R^{ab}=d\omega^{ab}-\omega^a{}_c\wedge\omega^{cb} \tag{7}$$

and V^a is the vierbein.

The action (6) is equivalent to the action of gravity, written with tensor formalism. Indeed:

$$R^{ab}\wedge V^c\wedge V^d\,\varepsilon_{abcd}=-4\,R^{ij}{}_{ij}\det V\,d^4x\,. \tag{8}$$

where $R^{ij}{}_{ij}=R^{\mu\nu}{}_{\mu\nu}=R$ is the scalar of curvature and $\det V=\sqrt{-g}=\sqrt{-\det g_{\mu\nu}}$.

(Latin letters indicate flat indices, Greek letters indicate curved indices)

Therefore, it is:

$$\int_{M_4} R^{ab}(\omega)\wedge V^c\wedge V^d\,\varepsilon_{abcd}=-4\int_{M_4} R\sqrt{-g}\,d^4x\,. \tag{9}$$

We have two gauge fields: the spin connection ω^{ab} and the vierbein V^a :

$$\omega^{ab}=\omega^{ab}{}_\mu\,dx^\mu\,, \tag{10}$$

$$V^a=V^a{}_\mu\,dx^\mu\,. \tag{11}$$

Working in the first order formalism, both gauge fields are treated as independent. The quantity $\{V^a,\omega^{ab}\}$ constitutes a multiplet in the adjoint representation of the Poincarè group. It is:

$$\mu^A(x)T_A=\omega^{ab}(x)J_{ab}+V^a(x)P_a\,, \tag{12}$$

where:

$$\mu^A(x)=\mu^A{}_\mu(x)\,dx^\mu \tag{13}$$

is the gauge field of Poincarè group, J_{ab} and P_a are the generators of Lorentz transformations and 4-dimensional translations respectively. The field strength associated to μ^A is defined as the following 2-form in the Poincarè Lie algebra-valued curvature:

$$R^A=d\mu^A+\frac{1}{2}C^A{}_{BC}\,\mu^B\wedge\mu^C\,, \tag{14}$$

Dividing the A index as $A=(ab,a)$, it is:

$$R^{ab}=d\omega^{ab}-\omega^a{}_c\wedge\omega^{cb}\,; \tag{15a}$$

$$R^a=dV^a-\omega^a{}_b\wedge V^b\equiv\mathcal{D}\,V^a. \tag{15b}$$

The associated Bianchi identities are given by:

$$\mathcal{D}\,R^{ab}=0, \tag{16}$$

$$\mathcal{D}\,R^a+R^{ab}\wedge V_b=0. \tag{17}$$

Therefore the Lorentz algebra-valued curvature is the field strength of the spin connection, while the vector-valued curvature, or torsion, is the field strength of the vierbein field.

The Einstein-Cartan action is invariant under general coordinate transformations generated by Lie derivatives; on fact, since the function inside Eq. (6) is written using only exterior products and exterior derivatives, the invariance under diffeomorphisms is guaranteed by the general transformation law of forms under diffeomorphisms.

The Einstein Lagrangian is invariant with respect to the Lorentz group SO(1,3) and to Lie derivatives; it is not invariant under pure gauge translations. Then a coordinate transformation is equivalent to a local gauge translation only if the torsion $R^a=0$, i.e. in the second order formalism.

By varying the action (6) with respect to the vierbein field, we obtain the Einstein equation of pure gravity:

$$R^{al}{}_{bl}-\frac{1}{2}\delta^a{}_b\,R=0\,. \tag{18}$$

By variation of ω^{ab} we obtain:

$$R^c\wedge V^d\,\varepsilon_{abcd}=0\;\rightarrow\;R^c=0\,. \tag{19}$$

It is possible to extend this formalism by coupling the Lagrangian describing the pure gravity with the Lagrangian describing the spin 3/2 Rarita-Schwinger field. Building indeed Lagrangians, which are invariant under transformations of local supersymmetry, the "gauging" of supersymmetry transformations necessarily involves the gauge field of supersymmetry:

$$\psi=\psi^\alpha Q_\alpha=\psi^\alpha{}_\mu(x)\,dx^\mu\,Q_\alpha\,, \tag{20}$$

where $\psi^\alpha{}_\mu(x)$ describes a massless spin 3/2 particle in four dimensions and Q_α is the supersymmetry generator. The spin 3/2 field, partner of graviton, describes the "gravitino". The corresponding interacting theory is the $D = 4$, $N = 1$supergravity.

Considering the viewpoint of a purely spacetime observer, which ignores the superspace, it is possible to build an action describing the coupling of the spin 2 and spin 3/2 fields, which is invariant under convenient supersymmetry transformations. Let's consider the Lagrangian of minimal coupling for the Rarita-Schwinger field. The free field Lagrangian in Minkowski space is:

$$\mathcal{L}_{\text{R.S.}} = \varepsilon^{\mu\nu\rho\sigma}\,\overline{\psi}_\mu \gamma_5 \gamma_\nu \partial_\rho \psi_\sigma\,, \tag{21}$$

with ψ_μ satisfying the Majorana condition $\psi^+ \gamma^0 = \psi^t C$. ψ_μ contains a spin 3/2 part and a spin 1/2 part; the second one can be eliminated fixing the gauge condition $\gamma^\mu \psi_\mu = 0$.

The motion equation following by $\mathcal{L}_{\text{R.S.}}$ is:

$$\varepsilon^{\mu\nu\rho\sigma} \gamma_5 \gamma_\nu \partial_\rho \psi_\sigma = 0\,, \tag{22}$$

which implies $\Box\psi_\mu = 0$, i.e. ψ_μ describes a massless spin 3/2 particle in Minkowski space.

The complete action describing the coupling of the two fields is:

$$A = \int_{M_4} -4R\sqrt{-g}\, d^4x +$$

$$+4\,\overline{\psi}_\mu \gamma_5 \gamma_a\, \mathcal{D}_\nu \psi_\rho\, V^a{}_\lambda\, \varepsilon^{\mu\nu\rho\lambda}\, d^4x\,. \tag{23}$$

The part of the Lagrangian related to gravitino can be written with forms too. It is:

$$A = \int_{M_4} R^{ab} \wedge V^c \wedge V^d\, \varepsilon_{abcd} +$$

$$+4\,\overline{\psi} \wedge \gamma_5\, \gamma_a\, \mathcal{D}\psi \wedge V^a\,. \tag{24}$$

The three independent fields appearing in Eq. (24) are Eqs (10), (11) and:

$$\psi = \psi_\mu(x)\, dx^\mu\,. \tag{25}$$

By varying action with respect to $\omega^{ab}{}_\mu$, we obtain:

$$2R^c \wedge V^d\, \varepsilon_{abcd} = 0 \;\rightarrow\; R^c = 0\,, \tag{26}$$

with R^c defined by:

$$R^c = \mathcal{D}V^c - \frac{i}{2}\overline{\psi} \wedge \gamma^c \psi\,. \tag{27}$$

By varying vierbein and ψ fields, it is respectively:

$$2R^{ab} \wedge V^c\, \varepsilon_{abcd} + 4\,\overline{\psi} \wedge \gamma_5\, \gamma_d\, \mathcal{D}\psi = 0\,, \tag{28}$$

$$8\,\gamma_5\, \gamma_a\, \mathcal{D}\psi \wedge V^a - 4\gamma_5 \gamma_a \psi \wedge R^a = 0\,. \tag{29}$$

The Lagrangian (24) is invariant under Lorentz local transformations and spacetime diffeomorphisms, and also with respect to new transformations containing an anticommutative parameter ε, called "supersymmetry transformations" [3]:

$$\delta_\varepsilon V^a = i\,\bar{\varepsilon}\,\gamma^a \psi\,, \tag{30}$$

$$\delta_\varepsilon \psi = \mathcal{D}\varepsilon\,, \tag{31}$$

$$\delta_\varepsilon\, \omega^{ab}(1st\,order) = -2\,\varepsilon^{abrs}\,\bar{\varepsilon}\,\gamma_5 \gamma_m\, \rho_{rs} V^m -$$

$$-\;\; 2\,\varepsilon^{trs[a}\;\bar{\varepsilon}\,\gamma_5 \gamma_t\, \rho_{rs} V^{b]}. \tag{32}$$

4. Supergravity in superspace

In order to give geometric meaning to the transformations of supersymmetry, the previous spacetime fields $V^a{}_\mu$, ψ_μ, $\omega^{ab}{}_\mu$ are interpreted as 1-forms in superspace. In this way, the transformations of supersymmetry can be interpreted as Lie derivatives in superspace. With the extension to superspace, the 1-forms (V^a, ψ) can be considered as a single object $E^a = (V^a, \psi)$, said "supervielbein". (V^a, ψ) form a basis in the cotangent plane in a point P of superspace.

Supergravity can be "naturally" interpreted as a theory in superspace. The structure equations of superspace define the curvatures:

$$R^{ab} = d\omega^{ab} - \omega^a{}_c \wedge \omega^{cb} \equiv \mathcal{R}^{ab}, \tag{33}$$

$$R^a = \mathcal{D}V^a - \frac{i}{2}\overline{\psi} \wedge \gamma^a \psi\,, \tag{34}$$

$$\rho = \mathcal{D}\psi\,, \tag{35}$$

where now ω^{ab}, V^a, ψ are 1-forms in superspace, and R^{ab}, R^a, ρ are the corresponding curvatures. In a compact notation it is possible to write:

$$R^A = d\mu^A + \frac{1}{2} C^A{}_{BC}\, \mu^B \wedge \mu^C \,, \tag{36}$$

with:

$$R^A = \left(R^{ab}, R^a, \rho\right). \tag{37}$$

The Bianchi identities associated to curvatures (33-35) are [3,8,16]:

$$\mathcal{D}\, R^{ab} = 0 \,, \tag{38}$$

$$\mathcal{D}\, R^a + R^{ab} \wedge V_b - i\,\overline{\psi} \wedge \gamma^a\, \rho = 0 \,, \tag{39}$$

$$\mathcal{D}\, \rho + \frac{1}{4} R^{ab} \wedge \gamma_{ab}\, \psi = 0 \,. \tag{40}$$

5. Conclusions

Supersymmetry is a unifying and very elegant concept, whose algebra is based on both commutators and anticommutators. In supersymmetric field theories the technical notion of superspace is very useful. Introducing a field of spin 3/2, the Einstein theory of general relativity becomes supersymmetric; this led to the birth of supergravity. The superspace allows to give a geometrical meaning to the supersymmetry transformations. Supergravity theories are the effective theories of superstring theories, which are a way for the unification of all forces of Nature. These technical tools offer compactness, formal elegance, development of new technics for innovation of science.

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