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Symmetries of the boundary of $AdS_5 \times S^5$ and harmonic superspace

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Abstract: We study the boundary limit of the bulk isometries of $AdS \times S$. The superconformal symmetry is realized on the coordinates of the AdS boundary, the fermionic superspace coordinates, and the harmonics on the sphere. We show how these may be related to the coordinates of an off-shell harmonic superspace of SCFT living on the boundary. In the special case of $d = 4$, $\mathcal{N} = 2$ super Yang-Mills theory, a truncation of the $\mathcal{N} = 4$ SYM dual to type-IIB string theory compactified on $AdS_5 \times S^5$, we identify the bosonic space $\mathrm{SU}(2)/\mathrm{U}(1)$ of the $\mathcal{N} = 2$ harmonic superspace (known before as auxiliary) with the S^2 submanifold of the S^5.

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There is a growing interest in the AdS/CFT correspondence conjecture [1]. One of the basic arguments in favor of this conjecture concerning $\mathcal{N} = 4$ Yang-Mills theory is the fact that the superisometry of the AdS superspace forms the same SU$(2,2|4)$ supergroup as the symmetries of the $\mathcal{N} = 4$ Yang-Mills field theory, which supposedly lives on the boundary of the AdS space. The superspaces with the bosonic $AdS_{p+2} \times S^{d-p-2}$ geometry and the proper form field were recently constructed in [2] and their superisometries were found in closed form in [3]. The purpose of this note is to motivate a connection between the limit to the boundary ($\rho \to \infty$) of the bulk $AdS_5 \times S^5$ superspace with the harmonic superspace [6] of the off-shell 4-dimensional $\mathcal{N} = 2$ Yang-Mills theory.

The superisometries found in [3] for the $AdS_5 \times S^5$ case are governed by the supercoset structure $G/H = \mathrm{SU}(2,2|4)/(\mathrm{SO}(1,4) \times \mathrm{SO}(5))$ [5, 2]. They are of the form

$$\begin{aligned}
\delta\theta|_{\text{bulk}} &= \delta\theta(x, \rho, u, \theta \,|\, \epsilon, \eta, a, \lambda_M, \lambda_D, \Lambda_K, \Lambda_R)\,, \\
\delta x|_{\text{bulk}} &= \delta x\,(x, \rho, u, \theta \,|\, \epsilon, \eta, a, \lambda_M, \lambda_D, \Lambda_K, \Lambda_R)\,, \\
\delta\rho|_{\text{bulk}} &= \delta\rho(x, \rho, u, \theta \,|\, \epsilon, \eta, a, \lambda_M, \lambda_D, \Lambda_K, \Lambda_R)\,, \\
\delta u|_{\text{bulk}} &= \delta u(u, \theta \,|\, \epsilon, \eta, a, \lambda_M, \lambda_D, \Lambda_K, \Lambda_R)\,.
\end{aligned} \tag{1}$$

Here, x are the coordinates of the 4-dimensional space along the boundary of the AdS_5 space, ρ is the AdS_5 coordinate orthogonal to the boundary, which is located at $\rho = \infty$. The 32 fermionic coordinates θ are the fermionic coordinates of type IIB string theory/supergravity and finally u are harmonics of S^5 sphere, which may be given as functions of the angles on the sphere, i.e. $u(\phi)$. Apart from dependence on the coordinates of the superspace $[x, \rho, u(\phi), \theta]$, the superisometries depend on global parameters of superconformal transformations $\epsilon, \eta, a, \lambda_M, \lambda_D, \Lambda_K, \Lambda_R$. These include supersymmetry ϵ, special supersymmetry η, translations a, Lorentz transformations λ_M, dilatations λ_D, special conformal transformations Λ_K and R-symmetry Λ_R.

Under these transformations (which have to be supplemented by the compensating transformations of the frame from the stability group $(\mathrm{SO}(4,1) \times \mathrm{SO}(5))$ the geometry of the $AdS_5 \times S^5$ superspace is invariant. The expressions for the superisometries are rather complicated and they are defined in [3] in terms of the superisometries at $\theta = 0$, i.e. by the Killing vectors and Killing spinors $\Sigma(x, \rho, u(\phi))$ of the bosonic part of the superspace, and by the structure constants of the SU$(2,2|4)$ algebra.

At first glance the expressions for the isometries do not have a well defined limit at $\rho \to \infty$. For example, the metric has terms with positive and negative powers of ρ:

$$g_{mn} = \rho^2 \delta_{mn}\,, \qquad g_{\rho\rho} = \left(\frac{R}{\rho}\right)^2, \tag{2}$$

where R is the radius of curvature of the AdS_5 space as well as of the sphere S^5. Another example is the translation in direction of the boundary Σ^m and the compensating Lorentz transformation $\Sigma^{m\rho}$ between the boundary directions x and bulk direction ρ which look like[1]

$$\Sigma^m = \rho\xi^m(x) + \left(\frac{R^2}{\rho}\right)\Lambda^m_K \tag{3}$$

$$\Sigma^{m\rho} = \left(\frac{\rho}{R}\right)\xi^m(x) - \left(\frac{R}{\rho}\right)\Lambda^m_K\,. \tag{4}$$

Also, we see the dependence on ρ in the Killing spinors of the $AdS_5 \times S^5$ space, which depend on the harmonics[2] of the five sphere ${u_i}^I(\phi)$:

$$\begin{pmatrix} \Sigma^I_\alpha \\ \bar{\Sigma}^{\dot\alpha\, I} \end{pmatrix} = \begin{pmatrix} \left(\frac{\rho}{R}\right)^{1/2} \epsilon(x)^i_\alpha \\ \left(\frac{R}{\rho}\right)^{1/2} \bar\eta^{\dot\alpha\, i} \end{pmatrix} {u_i}^I(\phi)\,, \tag{5}$$

where

$$\epsilon(x)_\alpha{}^i = \epsilon_\alpha{}^i + (x^m\sigma_m)_{\alpha\dot\alpha}\bar\eta^{\dot\alpha\, i}\,, \tag{6}$$

and ϵ and $\bar\eta$ are the parameters of the Q-supersymmetry and S-supersymmetry resp. We have found that this irregular dependence of the bulk isometries on ρ can be perfectly organized if we use two important technical tools.

- We use the Killing gauge in the superspace [2], since in this gauge the gravitino vanishes not only at $\theta = 0$ for the bosonic background but also to all orders in θ which makes various calculations doable and easy. In this gauge[3] we find the limit to the boundary $\rho \to \infty$ in which the radial direction ρ decouples.

- The superisometries in the bulk were found in the AdS basis of the superalgebra which treats *the bulk direction on equal footing with the boundary directions* since there is a manifest $\mathrm{SO}(4,1) \times \mathrm{SO}(5)$ symmetry, mixing bulk and boudary directions. The limit to the boundary, however, has to be performed in the superconformal decomposition of the algebra which has only manifest $\mathrm{SO}(1,3)$ symmetry in the AdS_5 sector, reflecting the split of the AdS coordinates into x and ρ.

[1]Here we write down components of the G-covariant Killing field. The relation to the H-covariant Killing vectors and compensating Lorentz transformation has been given in [3].

[2]We use a two-component notation, which means that we work with a representation of γ-matrices in 5 dimensions (AdS) for which γ_5 is diagonal. The $AdS_5 \times S^5$ Killing spinor consists of four 4-dimensional Dirac spinors transforming under the SU(4) with index $i = 1,2,3,4$ and the index $I = 1,2,3,4$ labels the spinorial representation of the stability group on the sphere SO(5). More details on Killing spinors in terms of the harmonics will be given in a future publication.

[3]In a subsequent paper [4] we will choose a gauge which is different from the Killing gauge and which is designed for decoupling at the boundary not only the radial variable ρ but also one half of θ's.

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In the superconformal decomposition the translation in the ρ-direction becomes a dilatation operator D, translations along the boundary coordinates x combined with the Lorentz transformations mixing the ρ and x directions give 4 translation and 4 special conformal transformations along the boundary directions. The important property of this basis of the superconformal algebra is that *every generator* $\mathbf{T}_\Lambda$ *has a particular conformal weight*:

$$[D, \mathbf{T}_\Lambda] = W(T_\Lambda)\mathbf{T}_\Lambda\,. \tag{7}$$

The generators form the SU$(2,2|4)$ superalgebra with the structure constants $f_{\Lambda\Sigma}{}^{\Delta}$

$$[\,\mathbf{T}_\Lambda, \mathbf{T}_\Sigma\,\} = f_{\Lambda\Sigma}{}^{\Delta}\mathbf{T}_\Delta\,. \tag{8}$$

Translations P_m have weight $+1$, special conformal transformations K_m have -1, dilatations D, Lorentz transformations M_{mn} and R-symmetry transformations $U_i{}^j$ have weight 0. The supersymmetries Q have weight $+1/2$ and special supersymmetries S have weight $-1/2$. It turns out that the superconformal basis of the superalgebra displays the ρ dependence of isometries in a very clear way. We have found that all isometries Σ at $\theta = 0$ in the superconformal basis are homogeneous in ρ, which is expected because the ρ direction is associated with dilatations and every conformal operator has a specific Weyl weight, and they scale according to the conformal weight of the corresponding operator:

$$\Sigma^\Lambda(x^m, \rho, u(\phi)) = \rho^{W(\Lambda)}\underline{\Sigma}^\Lambda(x^m, u(\phi)) = \mathcal{R}^\Lambda{}_{\underline{\Lambda}}(\rho)\underline{\Sigma}^{\underline{\Lambda}}(x^m, u(\phi))\,. \tag{9}$$

Now, the matrix $\mathcal{R}^\Lambda{}_{\underline{\Lambda}}(\rho)$ carries all dependence on the radial variable and the fields $\underline{\Sigma}^{\underline{\Lambda}}(x^m, u(\phi))$ depend only on the bosonic coordinates of the boundary, and the harmonics of the sphere.

This property and the explicit form of the isometries in [3] allows us to reabsorb all dependence on ρ into the new ρ-dependent structure "constants" of the algebra. The crucial observation at this point is that the structure constants of the algebra have the property that for any component $f_{\Lambda\Sigma}^{\Delta}$

$$W(T_\Lambda) + W(T_\Sigma) = W(T_\Delta) \tag{10}$$

holds. This identity shows then that in the 'underlined' basis the structure "constants" $f_{\underline{\Lambda\Sigma}}^{\underline{\Delta}}(\rho)$ are numerically nothing but the old constants $f_{\Lambda\Sigma}^{\Delta}$, since

$$\begin{aligned} f_{\underline{\Lambda\Sigma}}^{\underline{\Delta}}(\rho) &\equiv (\mathcal{R}^{-1})_{\Delta}^{\underline{\Delta}}(\rho)\mathcal{R}_{\underline{\Lambda}}^{\Lambda}(\rho)\; f_{\Lambda\Sigma}^{\Delta}\; \mathcal{R}_{\underline{\Sigma}}^{\Sigma}(\rho) \\ &= \rho^{W(T_\Lambda)+W(T_\Sigma)-W(T_\Delta)}\; \delta_{\underline{\Lambda}}^{\Lambda}\delta_{\Delta}^{\underline{\Delta}}\delta_{\underline{\Sigma}}^{\Sigma}\; f_{\Lambda\Sigma}^{\Delta} = \delta_{\underline{\Lambda}}^{\Lambda}\delta_{\Delta}^{\underline{\Delta}}\delta_{\underline{\Sigma}}^{\Sigma}\; f_{\Lambda\Sigma}^{\Delta} \end{aligned} \tag{11}$$

i.e. the ρ-dependence cancels out. This gives us control over the limit $\rho \to \infty$ in all expressions for superisometries. We find that the bulk-boundary isometry correspondence has the following form:

$$\begin{aligned}\delta\theta|_{\text{bulk}} &= \delta\theta|_{\text{boundary}}(x,u,\theta)\\ \delta x|_{\text{bulk}} &= \delta x|_{\text{boundary}}(x,u,\theta) + \frac{1}{\rho^2} f(x,u,\theta)\\ \delta(u)|_{\text{bulk}} &= \delta u|_{\text{boundary}}(u,\theta)\end{aligned} \tag{12}$$

The isometry in the radial direction blows up in the limit $\rho \to \infty$:

$$\delta\rho|_{\text{bulk}} = \rho g(x,u,\theta)\,, \tag{13}$$

but decouples from the boundary isometries.

We do not specify here the functions of (x,u,θ) introduced above as they are still rather complicated, but they can be read off from the generic expressions for the isometries in the bulk, given explicitly in [3].

Thus we have extracted the ρ-dependence of the isometries in the superconformal basis and realized the algebra on coordinates of the boundary space (x,u,θ). In the bulk we have a spontaneously broken form of the superconformal symmetry since ρ occurs explicitly in the transformations. However at the boundary $\rho \to \infty$ where the ρ dependence is absent, we have a realization of the superconformal symmetry without spontaneous breaking. Note that the boundary of the superspace naturally includes the 4 bosonic coordinates of the boundary of the AdS_5 space, the fermionic coordinates θ, and *the harmonics of the S^5 sphere, which are not decoupled at the boundary*!

One can now try to understand what the role of these harmonics is from the point of view of the SCFT in 4 dimensions. Their structure and transformation laws suggest a connection to the auxiliary coordinates of the off-shell harmonic superspace of the 4-dimensional Super Yang-Mills theory. We will study the simplest example and *derive the $\mathcal{N}=2$ $d=4$ off-shell harmonic superspace* [6] *of the super Yang-Mills theory from the string theory/supergravity $AdS_5 \times S^5$ superspace.*

To find the correspondence with the SYM theory we will require only Q supersymmetry to be realized manifestly. The lagrangeans of the 4-dimensional $\mathcal{N}=2$ SYM theory have also a superconformal symmetry but this does not have to be a manifest property of the off-shell superfields. To do the truncation consistently we require that the special supersymmetry S, dilatation D and the special conformal symmetry K are no symmetries anymore. It means that we are fixing special supersymmetry to keep the $\bar\lambda^{\dot\alpha\, i}$, which is the component of θ along the special supersymmetry direction,[4] at $\bar\lambda^{\dot\alpha i}=0$. Thus we choose $\eta=0, \lambda_D=\Lambda_K=0$ simultaneously

[4] The 32 component fermionic coordinates θ can be decomposed in the same way as the Killing spinor cfr. (5),

$$\theta_{\hat\alpha}{}^I = \begin{pmatrix} \left(\frac{\rho}{R}\right)^{1/2}(\theta^i_\alpha + (x^m\sigma_m)_{\alpha\dot\alpha}\bar\lambda^{\dot\alpha\, i}) \\ \left(\frac{R}{\rho}\right)^{1/2}\bar\lambda^{\dot\alpha\, i}\end{pmatrix} u_i{}^I(\phi)\,,$$

which goes under the name *Killing Spinor gauge* [2].

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with $\bar{\lambda}^{\dot{\alpha} i} = 0$. The expressions for isometries are greatly simplified, in particular, the matrix $\mathcal{M}^2$, appearing in the isometries as given in [3], vanishes for the truncated theory. We are left with 1/2 of the fermionic coordinates, 4 bosonic coordinates x^m and harmonics $u_i{}^I$ on S^5. The fermionic coordinates related to Q-supersymmetry can be taken as four complex 2-component left-handed $d = 4$ spinors which we denote by θ^i_a, $i = 1, 2, 3, 4$ and $\alpha = 1, 2$. We derive from the superisometries in the bulk [3] that after truncation the remaining symmetries at the boundary are:

$$
\begin{aligned}
\delta\theta^i_\alpha &= \epsilon^i_\alpha + \frac{1}{4}(\lambda_{mn}\sigma^{mn}\theta^i)_\alpha + \theta^j_\alpha \Lambda_j{}^i \\
\delta x^m &= a^m + \lambda^{mn} x_n + i(\epsilon^i \sigma^m \bar{\theta}_i - \theta^i \sigma^m \bar{\epsilon}_i)\,.
\end{aligned} \tag{14}
$$

The symmetries of the sphere are given in terms of the coset representative (harmonics u) as follows

$$
g u(\phi) = u(\phi') h\,. \tag{15}
$$

Here, g is an element of SO(6), h is an element of SO(5), and ϕ' are the transformed angles of the sphere. Using indices for infinitesimal transformations we have

$$
\Lambda_i{}^j u_j{}^K(\phi) = u_i{}^K(\phi + \delta\phi) - u_i{}^K(\phi) + u_i{}^L(\phi) H_L{}^K\,, \tag{16}
$$

where $\Lambda_i{}^j$ are the parameters of the transformation from the SO(6) group in spinorial representation and $H_L{}^K$ are the parameters of the transformation from the stability group SO(5).

The truncated system of coordinates at the boundary has a symmetry realizing the truncated SU(2, 2|4) algebra without S, D, K. The algebra is the extended $\mathcal{N} = 4$ super Poincaré algebra in $d = 4$. It is realized on 4-dimensional coordinates x^m, on complex spinors θ^i_α and on harmonics $u_i{}^I$ of the S^5 depending on 5 angles of the sphere.

Now, we would like to perform more truncation of our boundary superspace to reproduce the $d = 4$ $\mathcal{N} = 2$ harmonic superspace of GIKOS. Thus we allow i to take values $i = 1, 2$ only in the algebra and we cut the harmonics on S^5 down to harmonics on S^2 simultaneously with cutting 5 angles to 2. The symmetries of the reduced system are:

$$
\begin{aligned}
\delta\theta^i_\alpha &= \epsilon^i_\alpha + (\lambda_{mn}\sigma^{mn}\theta^i)_\alpha + \theta^j_\alpha \Lambda_j{}^i \\
\delta x^m &= a^m + \lambda^{mn} x_n + i(\epsilon^i \sigma^m \bar{\theta}_i - \theta^i \sigma^m \bar{\epsilon}_i). \\
\delta u_i{}^K &= \Lambda_i{}^j u_j{}^K - u_i{}^L H_L{}^K
\end{aligned} \tag{17}
$$

where $\Lambda_i{}^j$ with $i, j = 1, 2$ are now the parameters of the SO(3) $\sim$ SU(2) subgroup of SO(6) and $H_I{}^J \equiv \Lambda$ $(I, J = 1, 2)$ is the parameter of the transformation of the stability subgroup SO(2) $\sim$ U(1). These are *precisely the super Poicaré transformations of the harmonic superspace in the central basis, as given in* [6]. This observation constitutes our main result.

The harmonics, introduced in [6] as auxiliary S^2 coordinates,[5] are coset representatives of SU(2)/ U(1). A common parametrization is

$$u(\phi_1, \phi_2) = \begin{vmatrix} u_1^- & u_1^+ \\ u_2^- & u_2^+ \end{vmatrix} = \begin{vmatrix} \cos\phi_1 & ie^{-i\phi_2}\sin\phi_1 \\ ie^{i\phi_2}\sin\phi_1 & \cos\phi_1 \end{vmatrix} . \tag{18}$$

They also appear explicitely in the Killing spinors on the $AdS \times S$ space [3]. Their main purpose is to allow for a change of fermionic variables from those transforming under SU(2) to those transforming under the U(1)

$$\theta_\alpha^\pm \equiv \theta_\alpha^i u_i^\pm \tag{19}$$

where we took $I = (+, -)$. It follows that

$$\delta\theta_\alpha^\pm = \epsilon_\alpha^i u_i{}^\pm + \frac{1}{4}(\lambda_{mn}\sigma^{mn}\theta^\pm)_\alpha \pm \theta_\alpha^\pm \Lambda\,. \tag{20}$$

The last term shows that $\theta^\pm$ transforms under the U(1) symmetry. This term came from the cancellation of the SU(2) transformation from the θ^i by the shift of angular variables and the remaining compensating U(1) transformation is the one with the parameter Λ.

The particular $\mathcal{N} = 2$ truncation performed can also be understood in the following way: the harmonic ($\mathcal{N} = 2$) superspace is constructed as a supercoset SU$(2, 2|2)$ with special supersymmetries, SO$(1, 3)$ Lorentz transformations, special conformal transformations, dilatations, and SO(2) transformations in the denominator [8]. This is to be contrasted with the AdS superspace which is built from the same isometry group, but with SO$(1, 4) \times$ SO(2) transformations in the denominator. Roughly speaking, going to the boundary of the AdS space and performing the truncation discussed above corresponds to singling out the (lower-dimensional) harmonic supercoset in the AdS supercoset. Then we can relate the ("auxilliary") harmonics of the harmonic superspace to the ("physical") sphere coordinates of the two-sphere, which is the two dimensional subspace of the five-sphere which the type-IIB theory is compactified on.

The ABC of the analytic $\mathcal{N} = 2$ superspace (reminding the chiral subspace of $\mathcal{N} = 1$ SUSY) follows as in [6]. One can shift the real 4-dimensional coordinates x by the bilinear combination of spinors so that there is an analytic subspace $x', \theta^+, \bar{\theta}^+, u$. Then one can construct unconstrained superfields which depend in this basis only on θ^+. The complete $\mathcal{N} = 2$ SYM theory with manifest off-shell supersymmetry is then

[5]The new bosonic coordinates relevant for extended supersymmetries were added to the superspace in the form of supertwistors and/or coset coordinates in [7]. But the origin of these additional coordinates which were used in [6] to construct an off-shell SYM theory was not clear so far to the best of our understanding. Now we seem to shed some light also on the physical origin of the *supertwistors* which may be related to the harmonic superspace.

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easily constructed. The SYM prepotential V^{++} is an unconstrained analytic superfield of U(1) charge +2, and the hypermultiplets q^+ are given by analytic superfields of charge +1.

This shows that the S^2 part of S^5 on which we compactify the superstring/supergravity plays a fundamental role in the existence of the off-shell hypermultiplet action and supergraph Feynman rules of $\mathcal{N} = 2$ SYM theory developed in [6]. We find here the long-anticipated presence of higher dimensions, however, they are not coming from the $d = 10$ SYM theory, but from string theory/supergravity on $AdS_5 \times S^5$ through the $AdS/SCFT$ correspondence. The harmonics of [6] find their place as the harmonics of the sphere which is part of the boundary of the $AdS_5 \times S^5$ space.

It would be very interesting to see whether a new (off-shell?) $\mathcal{N} = 4$ harmonic superspace can be constructed from the untruncated boundary isometries when the harmonics on the the full S^5 sphere are used.

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