Boundary S-matrix in a $(2, 0)$ theory of AdS_3 Supergravity

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With Bindusar Sahoo

Introduction

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- AdS_3 Supergravity has been playing an interesting role in String Theory after the discovery of BTZ black holes, since these arise as a factor in the near horizon geometry of certain class of black holes in string theory.
- The statistical and gravity analysis of entropy for such black holes, in the presence of higher derivative terms, matches with the Cardy formula for the degeneracy of states in 2 dimensional CFT.
- Kraus and Larsen (hep-th/0506176,0508218) argued using ADS/CFT correspondence that if the three dimensional theory has extended Supersymmetry, then the entropy is completely determined in terms of the coefficients of gauge as well as gravitational Chern Simons terms and does not receive any higher derivative corrections.

- Later, David, Sahoo and Sen (arxiv:0705.0735) gave the bulk interpretation of the above result and looked for the non-renormalizability of the entropy of a BTZ black hole in a theory with $(0, 4)$ supersymmetry and higher.

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- They showed that the boundary S-Matrix does not get renormalized and therefore the bulk action does not get renormalized except for the terms which can be removed by field redefinition.
- Gupta and Sen (arxiv:0710.4177) came up with a result that one can obtain a direct field redefinition in the bulk to absorb the higher derivative pieces to see the non-renormalizabilty of action.

- This induces the redefinition of currents in the boundary and hence the S-matrices calculated from two actions related by field redefinition in the bulk are the same upto unitary transformation.

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- From above arguments, all $(2,0)$ actions are related by field redefinitions, implies the S-matrix with and without higher derivative terms are related by unitary transformation, in turn implies Kraus and Larsen's non-renormalization of black hole entropy, even for $(2,0)$ theories.
- We were, however, interested in distinguishing the set of higher derivative terms that alter the boundary S-matrix, computed using the standard supergravity action, upto trivial/non-trivial unitary transformation.

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- Terms which can render the full action to be invariant under a set of supersymmetry transformation laws different from the original ones. Such terms can be removed by field redefinition and hence the change in S-Matrix will be a non-trivial unitary transformation.

Plan of the Talk

- Standard $\mathcal{N} = (2,0)$ supergravity action

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- Boundary S-matrix involving correlators of $U(1)$ current and supersymmetry current

$N = (2,0)$ Supergravity action

- The $N = (2,0)$ sugra action including gravitational Chern Simons term is written as:

$$\mathcal{S}_0 = \int d^3x[eR + 2m^2e - \frac{a_L}{2}\epsilon^{MNP}A_M\partial_N A_P$$
$$+\frac{i}{4}a_L\epsilon^{MNP}(\bar{\psi}_M(\mathcal{D}_N\psi_P) - (\mathcal{D}_N\bar{\psi}_M)\psi_P)]$$
$$-K\int d^3x\ \epsilon^{MNP}[(\frac{1}{2}\omega_{Mcd}\partial_N\omega_P{}^{dc} + \frac{1}{3}\omega_{Mbc}\omega_N{}^{cd}\omega_{Pd}{}^{b})$$
$$-\frac{im}{8}e_M{}^a\bar{\psi}_N\gamma_a\psi_P],$$

with $\quad a_L = K + \frac{1}{m},$

and $\quad \mathcal{D}_M\psi_N = \partial_M\psi_N - \frac{1}{2}B_M{}^a\gamma_a\psi_N + \frac{i}{2}A_M\psi_N,$

First and Second order Formulation

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- In second order, ω_M^{ab} is treated as a dependent gauge field.
- The $(2,0)$ supergravity theory, without the gravitational Chern-Simons terms, is supersymmetric in both the formulations under the same supersymmetric transformation laws.
- Both the formulations also give rise to the same equations of motion.

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- But the story drastically changes, for "Second Order formulation", after including the gravitational Chern-Simons term in the action.
- In the first order formulation of the theory, the action is supersymmetric, under the previously defined supersymmetric transformation laws, even after including the gravitational Chern Simons term.
- Also, one gets the same equations of motion as derived for the theory without the gravitational Chern Simons term.

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- The equations of motion also gets modified, and the first order spectrum belongs to a subset of the second order.
- We are interested in the correlation functions of CFT operators dual to this common sector, and hence will use the corresponding equations of motion in our analysis of boundary S-matrix.

Super-Covariant field strengths

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- Example-
  Riemann tensor $R_{MN}{}^{ab}$ (which is the field strength associated with ω_M^{ab}) is not covariant with respect to the supersymmetry transformations and we need to covariantize it, as

$$\widetilde{\mathcal{R}}_{MN}{}^{ab} = R_{MN}{}^{ab} - 2\delta^{(Q)}_{\frac{1}{2}\psi_{[M}}\omega_{N]}{}^{ab},$$

Equations of motion

- The equations of motion derived from the action :

$$\mathcal{R}_a{}^M - \frac{1}{2}\mathcal{R}e_a{}^M - m^2 e_a{}^M = 0,$$

$$\widehat{F}_{MN} \equiv 2\partial_{[M}A_{N]} - \frac{1}{2}\bar{\psi}_{[M}\psi_{N]} = 0,$$

$$G_{MN} \equiv 2\mathcal{D}_{[M}\psi_{N]} = 0 \quad \bar{G}_{MN} \equiv 2\mathcal{D}_{[M}\bar{\psi}_{N]} = 0,$$

where

$$\mathcal{R}_{MN}{}^{ab} = R_{MN}{}^{ab} + \frac{i}{4}\varepsilon^{abc}\bar{\psi}_{[M}\gamma_c\psi_{P]},$$

$$\mathcal{R}_M{}^a = e_b{}^N\mathcal{R}_{MN}{}^{ab},$$

$$\mathcal{R} = e_a{}^M\mathcal{R}_M{}^a,$$

- $\widehat{F}_{MN}$ and G_{MN} are supersymmetric covariant field strengths for the gauge field A_M and Rarita-Scwhinger field ψ_M respectively and $\mathcal{R}_{MN}{}^{ab}$ is the supersymmetric covariant Riemann tensor modulo some terms proportional to G_{MN}.

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- Also,

$$D_M \mathcal{R}_{NP} = 0,$$

  Where D_M is the usual covariant derivative defined using the torsion free connections.
- Thus, from the equations of motion, we see that the terms containing supersymmetric covariant field strengths and/ or their covariant derivatives vanish onshell.

Effect of Higher derivative terms

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- Therefore, if some terms vanish as a result of using equations of motion, then those terms will not contribute to the boundary S-Matrix.
- We will now look at the different sort of higher derivative terms that could affect the onshell action.

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- The contribution of these terms to the equations of motion will be terms containing supersymmertic covariant field strengths and /or their super-covariant derivatives.
- Such terms will necessarily vanish when the original equations of motion are satisfied, and therefore will not affect the boundary correlators.

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- Therefore, the solutions obtained for the original equations of motion will still solve the equations of motion in the presence of these higher derivative terms.
- Hence, the correlators in the gauge+fermionic sector will not be affected by these terms.

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- And since, by our argument the current correlators do not get renormalized, this implies that the stress tensor correlators also do not get renormalized.

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- There can be a general higher derivative term in the action that can keep the full action invariant under a modified set of supersymmetry transformation laws.
- Such terms can modify the equations of motion and will not vanish onshell, changing the boundary S-matrix.
- But, since such terms can be removed by field redefinition, therefore the boundary S-matrix can be related to the boundary S-matrix calculated from the standard sugra action, by a unitary transformation.

Boundary S-Matrix

- Now we will look at the boundary S-matrix involving two and three point correlation function of the operators dual in the gauge+fermionic sector of the theory.

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- Now we will look at the boundary S-matrix involving two and three point correlation function of the operators dual in the gauge+fermionic sector of the theory.
- We begin by writing the Chern Simons form of the sugra action in Euclidean space

$$\mathcal{S} = ia_L \int d^3x \, \epsilon^{MNP} \left[\frac{1}{2} B_M{}^a \partial_N B_P{}^b \delta_{ab} + \frac{i}{6} \varepsilon_{abc} B_M{}^a B_N{}^b B_P{}^c \right.$$

$$- ia_R \int d^3x \, \epsilon^{MNP} \left[\frac{1}{2} B'_M{}^a \partial_N B'_P{}^b \delta_{ab} + \frac{i}{6} \varepsilon_{abc} B'_M{}^a B'_N{}^b B'_P{}^c \right]$$

$$+ i \frac{a_L}{2} \int d^3x \, \epsilon^{MNP} A_M \partial_N A_P$$

$$+ \frac{a_L}{4} \int d^3x \, \epsilon^{MNP} \left(\bar{\psi}_M \left(\mathcal{D}_N \psi_P \right) - \left(\mathcal{D}_N \bar{\psi}_M \right) \psi_P \right),$$

- Where

$$B_M{}^a = \frac{i}{2}\varepsilon^{abc}\omega_{Mbc} - me_M{}^a,$$

$$B'_M{}^a = \frac{i}{2}\varepsilon^{abc}\omega_{Mbc} + me_M{}^a,$$

$$\mathcal{D}_M\psi_N = \partial_M\psi_N - \frac{1}{2}B_M{}^a\gamma_a\psi_N + \frac{i}{2}A_M\psi_N,$$

$$\mathcal{D}_M\bar{\psi}_N = \partial_M\bar{\psi}_N + \frac{1}{2}B_M{}^a\bar{\psi}_N\gamma_a - \frac{i}{2}A_M\bar{\psi}_N,$$

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    - To solve the equations of motion arising out of the theory under a specified set of boundary condition for the fields
    - Put the above solution in the action and express the on-shell action as a functional of the boundary values of the fields
    - The above on-shell action then acts like a partition function for calculating CFT correlation function of relevant currents for which the boundary values of the dual fields acts like a source. This prescription is given by AdS/CFT correspondence.

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  - To solve the equations of motion arising out of the theory under a specified set of boundary condition for the fields
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  - The above on-shell action then acts like a partition function for calculating CFT correlation function of relevant currents for which the boundary values of the dual fields acts like a source. This prescription is given by AdS/CFT correspondence.
  - We will quantify all the above as we proceed

- The equations of motion, in the form notation, are obtained as:

$$
\begin{aligned}
dA &= \frac{1}{4}\bar{\psi} \wedge \psi, \\
d\psi - \frac{1}{2}B^a\gamma_a \wedge \psi &= -\frac{i}{2}A \wedge \psi, \\
d\bar{\psi} + \frac{1}{2}B^a \wedge \bar{\psi}\gamma_a &= \frac{i}{2}A \wedge \bar{\psi},
\end{aligned}
$$

- We solve these equations till first order, by imposing the following gauge conditions on ψ and $\bar{\psi}$:

$$\gamma^M \psi_M = 0 \qquad \bar{\psi}_M \gamma^M = 0,$$

- The full solution till first order iteration is:

$$
\begin{aligned}
A &= d\rho + \frac{1}{4}\bar{\phi}d\eta + \frac{1}{4}\bar{\eta}d\phi + \frac{1}{4}\bar{\phi}\phi dz, \\
\psi^{(1)} &= (x^0)^{-\frac{1}{2}}\left(1 - \frac{i}{2}\rho\right)(d\eta + \phi dz), \\
\psi^{(2)} &= (x^0)^{\frac{1}{2}}\left(1 - \frac{i}{2}\rho\right)d\phi, \\
\bar{\psi}^{(1)} &= (x^0)^{\frac{1}{2}}\left(1 + \frac{i}{2}\rho\right)d\bar{\phi}, \\
\bar{\psi}^{(2)} &= (x^0)^{-\frac{1}{2}}\left(1 + \frac{i}{2}\rho\right)(d\bar{\eta} - \bar{\phi}dz),
\end{aligned}
$$

- Where η, ϕ, $\bar{\eta}$ and $\bar{\phi}$ are function of modified Bessel's functions as:

$$
\begin{aligned}
\eta &= \frac{1}{2\pi}\int d^2\vec{p}(x^0p)^2K_2(x^0p)e^{i\vec{p}.\vec{z}}\mathcal{A}_\eta(\vec{p}),\\
\phi &= \frac{1}{2\pi}\int d^2\vec{p}(x^0p)K_1(x^0p)e^{i\vec{p}.\vec{z}}(-2ip_z)\mathcal{A}_\eta(\vec{p}),\\
\bar{\eta} &= \frac{1}{2\pi}\int d^2\vec{p}(x^0p)^2K_2(x^0p)e^{i\vec{p}.\vec{z}}\mathcal{A}_{\bar{\eta}}(\vec{p}),\\
\bar{\phi} &= \frac{1}{2\pi}\int d^2\vec{p}(x^0p)K_1(x^0p)e^{i\vec{p}.\vec{z}}(2ip_z)\mathcal{A}_{\bar{\eta}}(\vec{p}),
\end{aligned}
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- Now we shall impose boundary conditions on the $\bar{z}$ components of fields, since we are working in $(2,0)$ theory.
- The boundary conditions on the gauge field and Rarita-Schwinger fields are

$$\lim_{x^0\to 0} A_{\bar{z}}(x^0,\vec{z}) = A^{(0)}_{\bar{z}}(\vec{z}),$$

$$\begin{aligned} \lim_{x^0\to 0}(x^0)^{\frac{1}{2}}\psi^{(1)}_{\bar{z}} &= \Theta^{(-)}_{\bar{z}}(\vec{z}), \\ \lim_{x^0\to 0}(x^0)^{\frac{1}{2}}\bar{\psi}^{(2)}_{\bar{z}} &= \Theta^{(+)}_{\bar{z}}(\vec{z}), \end{aligned}$$

- We need to add the following boundary action for consistency requirements

$$\mathcal{S}_{\texttt{bndy}} = \mathcal{S}_{\texttt{bndy}}[\psi, \bar{\psi}] + \mathcal{S}_{\texttt{bndy}}[A]$$

$$\mathcal{S}_{\texttt{bndy}}[\psi, \bar{\psi}] =$$

$$-\frac{ia_L}{2} \int d^2\vec{z}\, \bar{\psi}_z^{(1)}(x^0, \vec{z})\psi_{\bar{z}}^{(1)}(x^0, \vec{z})\Big|_{x^0=0}$$

$$-\frac{ia_L}{2} \int d^2\vec{z}\, \bar{\psi}_{\bar{z}}^{(2)}(x^0, \vec{z})\psi_z^{(2)}(x^0, \vec{z})\Big|_{x^0=0}$$

$$\mathcal{S}_{\texttt{bndy}}[A] = a_L \int d^2\vec{z}\, A_z(\vec{z}, x^0)A_{\bar{z}}(\vec{z}, x^0)|_{x^0=0},$$

- After obtaining the solution to the equations of motion subject to the boundary conditions upto terms quadratic in the boundary values, we evaluate the action along with the boundary action, for these on-shell configuration of fields. We get

$$\begin{aligned}
&\mathcal{S}[A^{(0)}_{\bar{z}}, \Theta^{(+)}_{\bar{z}}, \Theta^{(-)}_{\bar{z}}] \\
= \;& -\frac{a_L}{\pi}\int d^2\,\vec{z}\,d^2\vec{w}\;\frac{1}{(z-w)^2}\;A^{(0)}_{\bar{z}}(\vec{w})\;A^{(0)}_{\bar{z}}(\vec{z}) \\
& -\frac{2ia_L}{\pi}\int d^2\vec{z}\,d^2\vec{w}\;\frac{1}{(z-w)^3}\;\Theta^{(+)}_{\bar{z}}(\vec{w})\;\Theta^{(-)}_{\bar{z}}(\vec{z}) \\
& -\frac{a_L}{\pi^2}\int\; d^2\vec{z}\,d^2\vec{w}\;d^2\vec{v}\;\frac{1}{(z-w)(z-v)(w-v)^2}\;H
\end{aligned}$$

$$\texttt{Where } H \;=\; A^{(0)}_{\bar{z}}(\vec{z})\Theta^{(+)}_{\bar{z}}(\vec{v})\;\Theta^{(-)}_{\bar{z}}(\vec{w})$$

- Then according to AdS/CFT conjecture, we have

$$\exp(-\mathcal{S}(A,\psi,\bar{\psi})) = \left\langle \exp\left(\frac{1}{2\pi}\int_{\partial} A\right)\right\rangle$$

$$\texttt{Where } A = J(\vec{z})A^{(0)}_{\bar{z}}(\vec{z}) + G^{(+)}(\vec{z})\Theta^{(-)}_{\bar{z}}(\vec{z}) + G^{(-)}(\vec{z})\Theta^{(+)}_{\bar{z}}(\vec{z}),$$

- This implies the following two and three point correlation functions

$$
\begin{aligned}
&\langle J(\vec{z_1}) J(\vec{z_2})\rangle \\
=\ & (2\pi)^2 \frac{\delta}{\delta A^{(0)}_{\bar z}(\vec{z_1})} \frac{\delta}{\delta A^{(0)}_{\bar z}(\vec{z_2})} e^{-\mathcal{S}} \Big|_{(A^{(0)}_{\bar z}(\vec{z}), \Theta^{(+)}_{\bar z}(\vec{z}), \Theta^{(-)}_{\bar z}(\vec{z}))=0} \\
&\left\langle G^{(+)}(\vec{z_1}) G^{(-)}(\vec{z_2})\right\rangle \\
=\ & (2\pi)^2 \frac{\delta}{\delta \Theta^{(-)}_{\bar z}(\vec{z_1})} \frac{\delta}{\delta \Theta^{(+)}_{\bar z}(\vec{z_2})} e^{-\mathcal{S}} \Big|_{(A^{(0)}_{\bar z}(\vec{z}), \Theta^{(+)}_{\bar z}(\vec{z}), \Theta^{(-)}_{\bar z}(\vec{z}))=0}
\end{aligned}
$$

$$\left\langle J(\vec{z_1})G^{(+)}(\vec{z_2})G^{(-)}(\vec{z_3})\right\rangle$$

$$= \quad (2\pi)^3 \; \frac{\delta}{\delta A^{(0)}_{\bar{z}}(\vec{z_1})} \frac{\delta}{\delta\Theta^{(-)}_{\bar{z}}(\vec{z_2})} \frac{\delta}{\delta\Theta^{(+)}_{\bar{z}}(\vec{z_3})} e^{-\mathcal{S}}\Bigg|_{(A^{(0)}_{\bar{z}}(\vec{z}),\Theta^{(+)}_{\bar{z}}(\vec{z}),\Theta^{(-)}_{\bar{z}}(\vec{z}))=}$$

- Using the evaluated onshell action, we get

$$\langle J(\vec{z_1})J(\vec{z_2})\rangle = 8a_L\pi\frac{1}{(z_1-z_2)^2}$$

$$\left\langle G^{(+)}(\vec{z_1})G^{(-)}(\vec{z_2})\right\rangle = 8ia_L\pi\frac{1}{(z_1-z_2)^3}$$

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- These are the expected conformal field theory results.

Conclusions

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THANK YOU