Matrix Model for Polyakov Loops,
String Field Theory In The Temporal Gauge,
Winding String Condensation In Anti-de Sitter Space
And Field Theory Of D-branes

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Abstract

Closed string eld theory is constructed by stochastically quantizing a matrix model for Polyakov loops that describes phases of a large N gauge theory at finite temperature. Coherent states in this string eld theory describes winding string condensation which has been expected to cause a topology change from thermal AdS geometry to AdS-Schwarzschild black hole geometry. D-branes in this closed string eld theory is also discussed. Slightly extended version of a talk given at CosPA 2007, Nov. 13-15, Taipei, Taiwan.

Keywords: AdS-CFT correspondence; stochastic quantization; loop equations; string eld theory.

1 Introduction

AdS-CFT correspondence [1] provides a way to understand closed string theory which contains quantum gravity one of the most important but also the most challenging issues in theoretical physics using dual non-gravitational eld theory. However, the correspondence still remains as a conjecture. Therefore, it is important to investigate the dictionary between closed string theory and the dual eld theory. In this talk, I will explain my trial for translating gauge eld theory language into closed string eld theory language, in a simplified setting. The rest part of this talk is based on the work Ref. [2].

In this section, I brie y review the background materials. For more detail, please consult my lecture note Ref. [3] and references therein.

1.1 Matrix Model for Polyakov loops

The setting I choose to carry out my program is the AdS$_5$-CFT$_4$ correspondence (namely, the duality between closed string on AdS$_5$ $\times$ S$_5$ and $\mathcal{N} = 4$ super Yang-Mills theory with SU(N) gauge group) at finite temperature. I study the case where the Yang-Mills theory
lives on a spatial manifold $S^3$. One of the expected phenomena for Yang-Mills theory at
high temperature is the confinement-deconfinement phase transition. Although the space
on which the Yang-Mills theory lives on is compact ($S^3$), I will mostly consider the limit
$N \to \infty$ where the large $N$ phase transition can take place.

A class of order parameters for the confinement-deconfinement transition which I will
focus on are expectation values of Polyakov loops winding around the Euclidean time
direction for $n$ times:

$$P_n = \frac{1}{N} \text{tr} P e^{i R_0 \int d A_0};$$  

where $\text{tr}$ is the trace over $SU(N)$ gauge indices $P$ denotes the path ordering, and $R_0$

is the inverse temperature. To determine the phase which is realized by calculating the

expectation values of these operators, one can integrate out, in principle, all the fields
except the constant mode of the temporal component of the gauge field:

$$h P_n = Z \left[ dA_0 \right] P e^{S_{\text{eff}}(A_0)};$$  

(1.1)

In the following, I will use $A_0$ to denote the constant part. Actually, $A_0$ is identi
ced with $A_0 + 2 \pi$ by a gauge transformation, and it is suitable to use the variable $U_0$
e $A_0$:

$$h P_n = Z \left[ dU_0 \right] \frac{1}{N} \text{tr} U_0^n e^{S_{\text{eff}}(U_0^n)};$$  

(1.2)

where $S_{\text{eff}}$ follows from the change of variables. Eq. (1.2) is what I call the matrix

model for Polyakov loops$. In practice, it is not easy to perform the path integration of other

fields explicitly. However, there are general features which the effective action $S_{\text{eff}}(\text{tr} U^n)$

should have. In particular, the fields in the $N = 4$ super Yang-Mills theory are all in the

adjoint representation of $SU(N)$, and when compacted on the Euclidean time circle the

action has $Z_N$ symmetry. It follows that the effective action $S_{\text{eff}}(\text{tr} U^n)$ is also invariant

under the $Z_N$ action:

$$U_0 \sim U_0 e^{2 \pi i m};$$  

(1.3)

with $m$ integer. This is the property which characterizes the important physics of our

model, as I will explain in the next section.

1.2 Gravitational phase transition in asymptotically AdS space

Let us start from the classical gravity regime, i.e. $N \to \infty$ with large 't Hooft coupling. In

this case, from the classical approximation of the Euclidean path integral gravity, one

observes a phase transition at some temperature, the low temperature phase is the semi

AdS geometry and high temperature phase is Euclidean AdS-Schwarzschild black hole

glometry (Hawking-Page phase transition$^5$). In Fig. 1, the Euclidean time and the

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$^1$Actually, because of the $Z_N$ symmetry the expectation value of a single Polyakov loop is zero. When we use the large $N$ saddle point approximation, a contribution from each saddle point is not zero, and I will mostly discuss such contribution in this note.

$^2$Actually we haven’t constructed quantum (completion) of the gravitational theory, so here we are assuming the existence of such theory.
radial directions are depicted. This phase transition was identified as the holographic dual of the confinement-deconfinement phase transition [6,7]. One of the evidences for this identification comes from the dictionary of the AdS-CFT correspondence for calculating the expectation value of Wilson/Polyakov loops from the closed string side [8,9]:

$$\mathcal{H}_i e^{T_{\text{st}} A}$$  \hspace{1cm} (1.5)

where $A$ is an area of string worldsheet in the gravitational background which ends on the Polyakov loop on the boundary, and $T_{\text{st}}$ is the string tension. From the Eq. (1.5), one observes that the difference of the topology of the target space is reflected in the expectation value of the Polyakov loops: A string worldsheet with disk topology (the leading order in the $1=\mathcal{N}$ expansion) can wrap the AdS-Schwarzschild black hole geometry but cannot wrap the thermal AdS geometry, see Fig. 1. In the case of 't Hooft coupling, Eq. (1.5) should be replaced with path integral for closed string action in the gravitational background with string $^0$ corrections. Precisely speaking, in the AdS$_5$-CFT$_4$ correspondence what is given by the right hand side of Eq. (1.5) is not the ordinary Wilson/Polyakov loop expectation value, but the generalization of it including the adjoint scalars in $\mathcal{N} = 4$ super Yang-Mills theory [9]. Since we could consistently integrate out these scalars in the gauge theory side to obtain (1.3), it would be reasonable to assume that we can also consistently integrate out the degrees of freedom in the closed string side to obtain a consistent closed string theory in two dimensions. Then, the dictionary Eq. (1.5), or with appropriate string corrections in the right hand side, will give expectation values of the Polyakov loops of our matrix model.

1.3 Winding string condensation?

In the case of string theory in a flat space, when a compactified circle shrinks to the size near the string scale the winding mode of the string becomes tachyonic (in the case of superstring, this happens when fermions are anti-periodic in the circle direction). It is tempting to interpret the Hawking-Page phase transition as a result of winding string condensation: In the case of open string, tachyon condensation describes the annihilation of D-brane [10,11,12]. One can expect that similarly when winding strings condense, it causes a disappearance of space-time. The topology change from the thermal AdS

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$^3$Having a tachyonic mode is not necessary for condensation.
Figure 2: Is Hawking-Page phase transition winding string condensation?

geometry to the AdS-Schwarzschild black hole geometry may be understood as a result of this kind of winding string condensation (Fig. 2) [13,14,15,16,17,18]. In order to describe such condensation, eld theory would be the most suitable formalism. However, since closed string eld theories are quite complicated, and currently known formalism are not manifestly background independent (see e.g. Refs. [19,20,21]), it has been quite hard to describe condensation of string eld and the change of the background. However, in the AdS-CFT correspondence the background independence of the closed string side is partially realized since if one fixes the boundary eld theory, only the asymptotic geometry is fixed: States in the boundary theory correspond to normalizable modes in the bulk. Therefore, we can expect to learn something about background independence if we can construct closed string eld theory in the AdS-CFT correspondence. Fortunately, in the present simplified setting there is a formalism of closed string eld theory available, which I will explain in the next section.

2 String eld theory in the temporal gauge

String eld theory in the temporal gauge is a way to construct a closed string eld theory from given one-matrix model [22]. The name follows from the temporal gauge fixing on the worldsheet of non-critical string [23,24]. A good review of the subject is Ref. [25].

In Ref. [26], the temporal gauge quantization was identified with the stochastic quantization plus the change of variables from matrix to loops. Let us first review the procedure of the stochastic quantization (see e.g. Ref. [27] for a review). To extract the essential point, I take a scalar eld theory in 0 dimension in the path integral formalism, i.e. ordinary integral, as an example. In this case, the expectation value of observable $F(\cdot)$ is given by

$$\langle F(\cdot) \rangle = \frac{1}{N^0} \int_{\mathcal{S}(\cdot)} e^{S(\cdot)} F(\cdot);$$
The stochastic quantization is a way to obtain the weight $e^{S(\cdot)}$ for the path integral as a result of stochastic processes. For this purpose, we prepare probability distribution $P(t; \cdot)$:

$$Z \int P(t; \cdot) = 1; \quad (2.2)$$

which satisfies the Fokker-Planck equation:

$$\frac{\partial}{\partial t} P(t; \cdot) = \frac{\partial}{\partial \theta} \frac{\partial}{\partial \theta} e^{S(\cdot)} P(t; \cdot) + H_{FP} P(t; \cdot); \quad (2.3)$$

The solution of Eq. (2.3) is given by

$$P(t; \cdot) = e^{\int_{FP} \theta(t; \cdot)} P(0; \cdot); \quad (2.4)$$

After taking the "stochastic time" $t \to t^+$, we obtain the path integral weight as a stationary configuration:

$$\lim_{t \to t^+} P(t; \cdot) = e^{S(\cdot)}; \quad (2.5)$$

The temporal gauge quantization can be phrased as a rewriting of the above formula by the operator formalism. Let us introduce "creation" and "annihilation" operators $\hat{y}, \hat{y}^\dagger$:

$$[\hat{y}; \hat{y}^\dagger] = 1; \quad (2.6)$$

We have the following map:

$$\hat{y}; \hat{y}^\dagger; \quad f(\hat{y}) = h \int \hat{y}^\dagger \hat{y}; \quad h \hat{y} = h \hat{y}; \quad [\hat{y}; \hat{y}^\dagger] = 0; \quad (2.7)$$

Here, $\hat{y}$ has nothing to do with the Hermitian conjugation. The relation between $\hat{y}$ and $\hat{y}^\dagger$ is rather that of coordinate and momentum. This point will be different in our model, as I will explain shortly.

Using the map (2.7), we can rewrite Eq. (2.1) as

$$Z \int d e^{S(\cdot)} F(\cdot) = \lim_{t \to t^+} Z \int e^{\int_{FP} \theta(\cdot)} P(0; \cdot) F(\cdot) = \lim_{t \to t^+} Z \int d h P(0; \cdot) e^{\int_{FP} \theta(\cdot)} F(\cdot) \hat{y}^\dagger \hat{y}; \quad (2.8)$$

By applying the temporal gauge quantization to our matrix model of Polyakov loops (1.3), we obtain a closed string field theory. The application of the stochastic quantization
plus change of variables to loops as possible explanation of the AdS-CFT correspondence was first discussed in Refs. [28,29,30]. An important feature of our model is the $Z_N$ symmetry Eq. (1.4), whose physical relevance is explained in the following.

I choose a map from path integral variables to operators as follows:

$$
\mathfrak{tr} U^n \propto P_n a_n^\gamma; \quad \mathfrak{tr} U^{-n} \propto P_{-n} a_n^\gamma;
$$

(2.9)

where I have introduced creation and annihilation operators for a string with winding number $n$ and $-n$ ($n > 0$), which satisfy the following commutation relations:

$$
[a_m; a_n^\gamma] = m \delta_{m, n}; \quad [a_m; a_n^\gamma] = m \delta_{m, n}.
$$

(2.10)

In the previous example of the temporal quantization, the operators introduced were mere like position and momentum operators. However, here since $\mathfrak{tr} U^n$'s are complex variables, we can instead use the usual creation and annihilation operators. There is a freedom in the choice of the overall normalization in the map (2.9), which does not affect the final result.

By rewriting the matrix model for Polyakov loop (1.3) using the map (2.9), we obtain a closed string field theory (see Ref. [2] for the detail):

$$
\mathfrak{h}_{F_{n}} = \frac{1}{N} \mathfrak{tr} U^n e^{S_{\text{eff}}(\mathfrak{tr} U^n)} = \frac{1}{N^2} \lim_{N \to \infty} \mathfrak{h}_{F_{n}} e^{\mathfrak{h}_{F_{n}} \{a_m^\gamma, a_n^\gamma\}} a_n^\gamma \mathfrak{d} i;
$$

(2.11)

where the final state $hfjw$ will be explained below.

The closed string field theory we have thus obtained is a peculiar type, in that it only contains winding modes. It is asymmetric under T-duality transformation since it does not contain momentum zero modes. This is similar to the case studied in Ref. [31,32]. The appearance of the stochastic time in the stochastic quantization is very suggestive for the AdS-CFT correspondence. In the AdS-CFT correspondence, the dimension of the space-time in which closed strings live is higher than that of the dual field theory, and because of this reason the AdS-CFT correspondence is regarded as a concrete realization of the idea called holography. What is particularly important is the radial direction of the AdS space which is related to the energy scale of the field theory. The stochastic time has a scaling dimension, and therefore it should be related to the radial direction. We have

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4 Similar formulas have appeared in 2D Yang-Mills theory [31,32], basically because it also reduces to a unitary matrix model.

5 However, in the $N \to \infty$ limit it whether to include 1-N factor in the right-hand sides of (2.9) makes a difference for the possible range of eigenvalues of the coherent states below and in the studies of $N$, so one should be careful in how to take the large $N$ limit. The norm should be carefully chosen in the double scaling $\lim_{N \to \infty}$ as studied in Refs. [33,34]. Here, I just chose the norm so that the fermionization formula discussed in the next section become simple. In this note I will not get into this point further and leave the above subtle point to the future study.

6 In Ref. [22] the stochastic time was identified with the worldsheet time in a certain gauge [24]. We may expect a relation between the target space time and the worldsheet time after an appropriate gauge xing.
this is a good way to understand the relation between the radial direction in the closed string side and the energy scale in the dual \( \text{eld} \) theory side remains to be seen, but I hope my work provides a support for this strategy.

The final state \( h_f j \) is specified by the stationarity condition

\[
h_f J^\mu_F = 0; \tag{2.12}
\]

The condition Eq. (2.12) may not uniquely determine the final state. Therefore, I will use the input from the matrix model. Then, the final state is determined by the phase of the gauge theory, which depends on the temperature. To describe the final state, it is convenient to introduce coherent states:

\[
h_w \bar{a}_n^y = h_w j_v_n; \tag{2.13}
\]

Then, in the con ned phase, the final state is given by

\[
h_0 j \tag{2.14}
\]

In the decon ned phase, it is given by

\[
h_w c \bar{c}_n j \tag{2.15}
\]

where \( w_c \) are the expectation value of the Polyakov loops calculated from the matrix model Eq. (2.13) describes the winding string condensation, as we wished at the end of the last section.

In our matrix model, the action had the \( Z_N \) symmetry (1.4). The Fokker-Planck Hamiltonian is also invariant under the \( Z_N \) transformation. This is translated into the closed string \( \text{eld} \) theory side as winding number conservation during the stochastic time evolution, in the \( N = 1 \) limit. However, in the decon ned phase, the winding number conservation is violated by the condensation of the winding string, since the coherent state is a superposition of states with different winding numbers. This is consistent with the topology of the AdS-Schwarzschild black hole geometry where the winding number is not a conserved quantity.

When \( N \) is finite, the winding number is conserved modulo \( N \). This is reminiscent to the stringy exclusion principle [35] (see also Ref. [29]). However, one should note that when \( N \) is finite, the notion of space-time is not classical [36], and hence the concept of winding number is not clear in the closed string side. For finite \( N \), one should also take into account the Mandelstam relations among the loops.

In our formulation, the information of the background is encoded in the final state. The Fokker-Planck Hamiltonian does not contain the information of the condensation. This should be compared with the usual formulation of string \( \text{eld} \) theory [19,20]. See also Refs. [37] for a different but related formulation. If we consider higher dimensional case, for example the full AdS\(_5\)-CFT\(_4\) correspondence, the \( \text{eld} \) theory calculations contain divergences, and in particular the Fokker-Planck Hamiltonian needs regularization. The information of the background of the closed string, which corresponds to the phase of the gauge theory, can enter in the Hamiltonian if one uses a regularization which depends on the phase.

\footnote{\text{For related studies of loop equations, which is essentially the Fokker-Planck Hamiltonian applied to the Wilson loops, in the context of the AdS-CFT correspondence, see for example Refs. \[38,39\].}
3 Field theory of D -branes

D -branes played crucial roles in uncovering the non-perturbative aspects of string theory. D -branes are often referred to as solitons in string theory. In order to describe D -branes as solitons, the most suitable framework would be the field theory of strings. However, because closed string field theory is technically quite complicated, actual description of D -branes as solitons is quite limited at this moment. Therefore, it will be useful to gain insights by studying D -branes in our simple closed string field theory. In the following, I would like to construct creation and annihilation operators of D -branes.

The eigenvalues of gauge field compacted on a circle are identified with positions of D -branes in the T -dual coordinate. Since our matrix model has multi-trace interaction terms, the eigenvalues interact among them themselves, as opposed to the familiar single trace matrix models of non-critical strings. However, for the purpose of identifying creation and annihilation operators of D -branes, it would be enough to study free D -branes, i.e. the case where the potential term among eigenvalues are absent. This can be formally realized as zero temperature limit of the matrix model obtained from integrating out modes other than the temporal component of the gauge field in the free N = 4 super Yang-Mills theory. In this case, the action reduces to the logarithm of the Vandermonde determinant. If we pick out one eigenvalue from the rest, it may be regarded as position of a single D -brane. This consideration leads to the conclusion that adding one eigenvalue to the matrix model amounts to inserting following factor

\[ Z = \int_{0}^{\pi} dx \det \sin \frac{x}{2} (x, A_0) \]  

(3.1)

into the SU(N - 1) matrix model path integral, with x being the eigenvalue for the single D -brane. Eq. (3.1) can be rewritten as

\[ Z = \int_{0}^{\pi} dx \exp \left[ \frac{1}{n} \text{tr} U^{n-1} e^{inx} + \frac{1}{n} \text{tr} U^n e^{inx} \right] \]  

(3.2)

After the temporal gauge quantization, this is expressed by putting the following operator to the initial state, similar to what was found in Refs. [40,41] (see also [42,43,44]) in the case of Hermitian matrix models:

\[ Z = \int_{0}^{\pi} dx \; (x) (x) \]  

(3.3)

where

\[ (x) : e^{i(x)} :: \; \; (x) : e^{i(x)} :: \]  

(3.4)

and :: denotes the appropriate operator ordering (see e.g. Ref. 45), and

\[ (x) = 0 + i p_0 \; x + \sum_{n \neq 0}^{\infty} \frac{1}{n} e^{inx} ; \]  

\[ (x) = 0 + i p_0 \; x + \sum_{n \neq 0}^{\infty} \frac{1}{n} e^{inx} ; \]  

(3.5)

This may also look like interaction among eigenvalues, but we normally regard it as just giving the Fermi statistics.
where

\[ \begin{align*}
  p_{n a_n^2}; & \quad p_{n a_n}; \\
  p_{n a_n^2}; & \quad p_{n a_n}; \quad (n > 0);
\end{align*} \tag{3.6} \]

In the above, we have trivially added the Hilbert space for decoupled zero modes, with appropriate initial and final states for zero modes. Eq. (3.4) is nothing but the fermionization formula familiar in 2D CFT on a circle. Note that the Fokker-Planck Hamiltonian is different from the Hamiltonian of the free boson. Thus, in our model the fermionization of the scalar field \((x)\) constructed from the string creation/annihilation operators, can be interpreted as change of variables to D-brane creation/annihilation operators. They are dual variables, in the sense of 2D bosonization. The eigenvalue \(x\) is interpreted as the position of the D-brane on the T-dual circle, and winding number \(n\) becomes momentum in the T-dual picture. The integration over the position \(x\) indicates that this is a quantum description. In terms of the original AdS\(_5\)-CFT\(_4\) language, the D-brane is identified with a D3-brane, or an Euclidean D2-brane in the T-dual picture. These D-brane variables are expected to be useful for analyzing non-perturbative effects of the string theory on asymptotically AdS space at finite temperature using the matrix model for Polyakov loops. See Refs. [33,34] for possible place for the application. See also Refs. [46,47] for other approaches to the fermionized descriptions of the AdS-CFT correspondence at finite temperature.

In the case of the Hermitian matrix model [40,41], the counterpart of the winding number was given by the length of the string. However, in that case, there appears a sort of negative string length, which should be associated with an annihilation of string with positive length. This makes a slight difference compared with our case. Here, the situation is more symmetric: The negative winding number just means that the string winds in the opposite direction in the Euclidean time. This difference between the Hermitian matrix model and our model arises from the imaginary number \(i\) in the exponent of the loop operators. This originates from the fact that the matrix in the Hermitian models is a "tachyon", whereas in our case it is a gauge field. The ways these fields couple to the boundary of the string worldsheet are different.

4 For CosPA, briefly

Since this symposium is for cosmology and particle astrophysics, I try to make contact here. If one interprets the stochastic time as our real time, i.e., if one can Wick rotate the stochastic time to Lorentzian signature, the Fig.1 can be interpreted as toy model for big bang universe (Fig.3). The rotated thermal AdS corresponds to big bang starting from big crunch, while the rotated AdS-Schwarzschild black hole geometry looks like the beginning of the universe out of nothing [48]. Whether which of these two scenarios is realized is determined by the radius of the Euclidean time circle (which should now be interpreted as "space").

Actually, it is not so straightforward to make the Wick rotation of the radial direction to time direction keeping the AdS-CFT correspondence [49]. One may still hope that our
Interpretation as big bang models.

Hamiltonian formulation may provide better way for rotating the time to the Lorentzian signature.

5 Sum m ary & future directions

In this talk, I have presented a formalism that translates gauge theory language into closed string field theory language, in a simplified setting of the AdS-CFT correspondence. The decon ned phase in the gauge theory side is translated into the winding string condensation in the closed string field theory. The winding string condensation captures the topological property of the AdS-Schwarzschild black hole geometry which is dual to the decon ned phase, in that the winding number is not conserved. Since at this moment the understanding of the field condensation in closed string field theory is still limited, I believe my result in the context of the AdS-CFT correspondence provides a useful starting point for studying the issues related to the background independence in closed string field theory.

In principle, the method I used, namely the combination of the stochastic quantization and the change of variables from matrix to loops, is applicable to the full AdS$_5$-CFT$_4$ correspondence. It should be the next direction to pursue.

In our setting, the starting point was the gauge theory, and we have constructed closed string field theory from the gauge theory. As a duality relation, it would be nice to have an independent definition of the closed string theory. But also note that there is a possibility that the gauge theory is more fundamental than the closed string theory, and if it is the case, our approach will turn out to be more fundamental.

I have also shown that the D-brane degrees of freedom is obtained by ferm ionization of the string field. This property is quite special to one matrix models, and points difficulties in constructing field theory of D-branes in higher dimensions: In higher dimensions, when one creates D-brane one also needs to create open strings that connect the created D-branes to other D-branes [50]. We can still hope that some features in our model will remain useful even in higher dimensional models. Indeed, interesting developments have been made in 26D bosonic string field theory [51, 52, 53] utilizing the insights obtained from
the experience in non-critical strings. It will be interesting to find the dual matrix model of 26D bosonic string field theory, if it exists, and apply our method.

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