Multibrane solutions in cubic superstring field theory

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Abstract

Using the elements of the so-called $KBc\gamma$ subalgebra, we study a class of analytic solutions depending on a single function $F(K)$ in the modified cubic superstring field theory. We compute the energy associated to these solutions and show that the result can be expressed in terms of a contour integral. For a particular choice of the function $F(K)$, we show that the energy is given by integer multiples of a single D-brane tension.
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1 Introduction

After the discovery of the first analytic solution for tachyon condensation in open bosonic string field theory [1], there has been a remarkable amount of work regarding the analytic set up of the theory. One line of research is concerned with the algebraic structure of the string field algebra based on Witten’s associative star product [2, 3, 4, 5, 6, 7]. Many authors have used the so-called $KBC$ subalgebra to understand systematically the construction of analytic solutions and perform computations by means of purely algebraic manipulations [8, 9, 10, 11, 12, 13].

Consequently, using the elements of the $KBC$ subalgebra, it was possible to rewrite many gauge equivalent tachyon vacuum solutions [5]. These solutions have been successfully used to prove Sen’s conjecture [14, 15]. Moreover, the possibility of constructing another set of solutions besides the well known tachyon vacuum solution was studied [16, 17, 18, 19, 20, 21, 22]. In recent work [23, 24], the possibility of describing multibrane configurations by employing a class of analytic solutions of the string field equation of motion in open bosonic string field theory was discussed.

In the context of the modified cubic string field theory [25], the analytic construction of the tachyon vacuum solution was analyzed first by Erler [26]. Then further discussions were given in a set of papers [27, 28, 29, 30, 31], where the so-called $KBC\gamma$ subalgebra was introduced [32, 33]. Many gauge equivalent tachyon vacuum solutions were discovered and the computation of the energy associated to these solutions was performed analytically and numerically given results in agreement with Sen’s conjecture. However, the description of multibrane configurations by means of some general set of solutions constructed out of elements in the $KBC\gamma$ subalgebra was not considered.

In this paper, we explore the possibility of describing multibrane configurations by constructing a class of analytic solutions of the string field equation of motion in the
modified cubic superstring field theory. These solutions will be expressed in terms of elements in the $KBc\gamma$ subalgebra. As discussed in reference \[32\], there is a well established prescription to find solutions which follows two steps: (i) find a naive identity based solution of the string field equation of motion, and (ii) perform a gauge transformation on the identity based solution such that the resulting string field $\Psi$ unambiguously reproduces a finite value for the energy computed from the cubic string field action

$$U(\Psi) = \frac{1}{2}\langle \Psi Q \Psi \rangle + \frac{1}{3}\langle \Psi \Psi \Psi \rangle,$$  \hspace{1cm} (1.1)$$

where $Q$ is the BRST operator of the open Neveu-Schwarz superstring theory. In the correlator $\langle \cdots \rangle$ we must insert the operator $Y_{-2}$ at the open string midpoint. The operator $Y_{-2}$ can be written as the product of two inverse picture changing operators $Y_{-2} = Y(i)Y(-i)$, where $Y(z) = -\partial \xi e^{-2\phi}c(z)$. The string field $\Psi$ which has ghost number 1 and picture number 0 belongs to the small Hilbert space of the first-quantized matter+ghost open Neveu-Schwarz superstring theory.

In the case of the modified cubic superstring field theory, in addition to the basic string field elements $K$, $B$ and $c$, we need to include the super-reparametrization ghost field $\gamma$ \[11, 26, 28, 32\]. These basic string fields satisfy a set of algebraic relations, and with the help of these relations we can construct the following identity based solution

$$\Psi_I = (c + B\gamma^2)(1 - K),$$  \hspace{1cm} (1.2)$$

which formally satisfies the string field equation of motion $Q\Psi_I + \Psi_I \Psi_I = 0$ of the cubic theory. This solution was shown to be gauge equivalent \[32\] to the solution found by Gorbachev \[28\].

A class of analytic solutions of the string field equation of motion in the modified cubic superstring field theory can be derived by performing a rather general gauge transformation on the identity based solution

$$\Psi = U_F(Q + \Psi_I)U_F^{-1},$$  \hspace{1cm} (1.3)$$

where the element of the gauge transformation can be explicitly constructed in terms of the basic string fields $K$, $B$ and $c$

$$U_F = F \left(1 + cB \frac{K - 1 + F^2}{1 - F^2}\right), \quad U_F^{-1} = \left(1 - cB \frac{K - 1 + F^2}{K}\right) \frac{1}{F}$$  \hspace{1cm} (1.4)$$

with $F = F(K)$ being an arbitrary function of $K$.

Carrying out a suitable algebraic manipulations in the $KBc\gamma$ subalgebra, from the gauge transformation \(1.4\), we obtain the following set of solutions that depend on the single function $F(K)$

$$\Psi = Fc \frac{KB}{1 - F^2}cF + FB\gamma^2F.$$  \hspace{1cm} (1.5)$$
This solution was analyzed in references [26, 28] for the particular cases: \( F^2 = e^{-K} \) and \( F^2 = 1/(1 + K) \), where it was shown that the solutions describe the tachyon vacuum solution. Discussions related to the gauge equivalence of these solutions were given in reference [30]. Nevertheless, there had been no evaluation of the energy for a class of analytic solutions of the form (1.5) for a generic function \( F(K) \).

In order to compute the energy for the solution given by (1.5), it should be convenient to define the function \( G(K) = 1 - F^2(K) \). Under certain holomorphicity conditions satisfied by the function \( G(K) \), we will show that the expression for the energy can be written in terms of a contour integral

\[
U(\Psi) = -\frac{1}{2\pi^2} \oint \frac{dz}{2\pi i} \frac{G'(z)}{G(z)}.
\]  

(1.6)

To compute this integral (1.6), we need to consider a contour encircling the origin in the counterclockwise direction.

A function \( G(K) \) which satisfies the holomorphically conditions analyzed in this paper is given by

\[
G(K) = \left( \frac{K}{1 + K} \right)^n,
\]

(1.7)

where \( n \) is a non-negative integer, this is because it will count the number of D-branes.

Since the contour integral (1.6) is performed around a closed curve encircling the origin, to compute the integral we need to write the Laurent series of the integrand around \( z = 0 \) and pick up the coefficient in front of the term \( 1/z \). For the function \( G(K) \) defined by equation (1.7), it turns out that

\[
\frac{G'(z)}{G(z)} = \frac{n}{z} + \sum_{m \neq -1} b_m z^m,
\]

(1.8)

and consequently the contour integral (1.6) gives the following result

\[
U(\Psi) = -\frac{n}{2\pi^2},
\]

(1.9)

which is the expected result for a multibrane solution. Therefore, in the context of the modified cubic superstring field theory, as in the case of open bosonic string field theory, we should also expect a solution which describes the so-called multibrane configuration [23, 24].

This paper is organized as follows. In section 2, we study a class of analytic solutions of the string field equation of motion in the modified cubic superstring field theory. By performing an explicit gauge transformation, we show that these analytic solutions depending on a single function \( F(K) \) can be related to an identity based solution. In
section 3, by considering a generic function $F(K)$, we evaluate the energy associated to the analytic solution derived in the previous section. In section 4, for a particular choice of the function $F(K)$, we show that the energy of the solution is given by integer multiples of a single D-brane tension. In section 5, a summary and further directions of exploration are given.

## 2 Derivation of the solution

In this section, we are going to derive a rather general solution to the string field equation of motion in the modified cubic superstring field theory \cite{25}. Using the relations satisfied by the elements of the so-called $KBC\gamma$ subalgebra, the solution will be constructed by performing a gauge transformation on an identity based solution.

Let us remember that, in the superstring case, in addition to the basic string field elements $K$, $B$ and $c$, we need to include the super-reparametrization ghost field $\gamma$ \cite{11,26,28,32}. These basic string fields satisfy the algebraic relations

\begin{align}
\{B, c\} &= 1, \quad [B, K] = 0, \quad B^2 = c^2 = 0, \\
\partial c &= [K, c], \quad \partial \gamma = [K, \gamma], \quad [c, \gamma] = 0, \quad [B, \gamma] = 0, \quad (2.1)
\end{align}

and have the following BRST variations

\begin{align}
QK &= 0, \quad QB = K, \quad Qc = cKc - \gamma^2, \quad Q\gamma = c\partial \gamma - \frac{1}{2}\gamma \partial c. \quad (2.2)
\end{align}

Employing these basic string fields, we can construct the following identity based solution

\begin{align}
\Psi_I &= (c + B\gamma^2)(1 - K), \quad (2.3)
\end{align}

which formally satisfies the string field equation of motion $Q\Psi_I + \Psi_I \Psi_I = 0$, where in this case $Q$ is the BRST operator of the open Neveu-Schwarz superstring theory.

With the help of this algebraic construction, let us derive a solution of the string field equation of motion by performing a gauge transformation on the identity based solution $\Psi_I = (c + B\gamma^2)(1 - K)$

\begin{align}
\Psi &= U_F(Q + \Psi_I)U_F^{-1}, \quad (2.4)
\end{align}

where $U_F$ is an element of the gauge transformation given by

\begin{align}
U_F &= F\left(1 + cB\frac{K - 1 + F^2}{1 - F^2}\right), \quad U_F^{-1} = \left(1 - cB\frac{K - 1 + F^2}{K}\right)\frac{1}{F} \quad (2.5)
\end{align}

with $F$ being a function of $K$. 5
Replacing (2.5) into (2.4) and using the identity based solution \[ \Psi_I = (c + B\gamma^2)(1 - K), \]
it is almost easy to derive the following solution
\[ \Psi = Fc\frac{KB}{1 - F^2}cF + FB\gamma^2F. \] (2.6)

In the context of the modified cubic superstring field theory, this solution was analyzed in references [26, 28] for the particular cases: \[ F^2 = e^{-K} \] and \[ F^2 = 1/(1 + K), \] where it was shown that the solutions describe the tachyon vacuum solution. Discussions related to the gauge equivalence of these solutions were given in reference [30]. Nevertheless, there had been no evaluation of the energy for a class of analytic solutions of the form (2.6) for a generic function \( F(K) \). In the next section, we are essentially going to perform that calculation.

## 3 Computation of the energy

In this section, by considering a generic function \( F(K) \), we are going to evaluate the energy of the analytic solution derived in the previous section. Let us mention that a similar computation was performed by Murata and Schnabl in the context of open bosonic string field theory [23, 24]. The energy of a solution of the form (2.6) can be computed from the kinetic term. After some simplifications, we obtain
\[
\langle \Psi Q\Psi \rangle = 2\left\langle \frac{K}{G}, (1 - G), K, (1 - G) \right\rangle - 2\left\langle \frac{K}{G}, (1 - G), \frac{K}{G}, (1 - G) \right\rangle \tag{3.1}
- \left\langle \frac{K}{G}, (1 - G), (1 - G) \right\rangle + \left\langle \frac{K}{G}, K, (1 - G), (1 - G) \right\rangle,
\]
where
\[ G = 1 - F^2; \] (3.2)
and to simplify the notation, we have defined
\[
\left\langle F_1, F_2, F_3, F_4 \right\rangle = \langle BF_1(K)cF_2(K)cF_3(K)\gamma^2F_4(K)\rangle \tag{3.3}
\]
for general \( F_i(K) \). The insertion of notation \( \langle \langle \cdots \rangle \rangle \) stands for a standard correlator with the difference that we must insert the operator \( Y_{-2} \) at the open string midpoint. The operator \( Y_{-2} \) can be written as the product of two inverse picture changing operators, \( Y_{-2} = Y(i)Y(-i) \), where \( Y(z) = -\partial\xi e^{-2\phi}c(z) \).

Let us assume that all functions \( F_i(K) \) can be written as a continuous superposition of wedge states,
\[
F_i(K) = \int_{0}^{\infty} d\alpha_i f_i(\alpha_i)e^{-\alpha_i K}. \tag{3.4}
\]
The validity of this assumption depends on some holomorphy conditions satisfied by the functions $F_i(K)$. These requirements were analyzed in \cite{7}. For a moment, let us implicitly suppose that the functions $F_i(K)$ satisfied the aforementioned requirements.

Plugging the integral representation of the functions $F_i$’s (3.4) into (3.3), we obtain the following quadruple integral

$$
\left\langle F_1, F_2, F_3, F_4 \right\rangle = \int_0^\infty d\alpha_1 d\alpha_2 d\alpha_3 d\alpha_4 f_1(\alpha_1) f_2(\alpha_2) f_3(\alpha_3) f_4(\alpha_4) \langle \{ Be^{-\alpha_1 K} e^{-\alpha_2 K} e^{-\alpha_3 K} e^{-\alpha_4 K} \} \rangle
$$

(3.5)

with the basic correlator $\langle \{ Be^{-\alpha_1 K} e^{-\alpha_2 K} e^{-\alpha_3 K} e^{-\alpha_4 K} \} \rangle$ given by \cite{20,21,32}

$$
\langle \{ Be^{-\alpha_1 K} e^{-\alpha_2 K} e^{-\alpha_3 K} e^{-\alpha_4 K} \} \rangle = \frac{s}{2\pi^2} \alpha_2, \text{ where } s = \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4. \quad (3.6)
$$

In what follows, we are going to use the $s$-$z$ trick introduced in \cite{23,24}. Basically the trick instructs us to insert the identity

$$
1 = \int_0^\infty ds \delta \left( s - \sum_{i=1}^4 \alpha_i \right) = \int_0^\infty ds \int_-i\infty^{+i\infty} \frac{dz}{2\pi i} e^{sz} e^{-z \sum_{i=1}^4 \alpha_i}, \quad (3.7)
$$

into the quadruple integral (3.5). This identity allows us to treat the variable $s$ as independent of the other integration variables $\alpha_i$. Using the correlator (3.6) and plugging the identity (3.7) into (3.5), we get

$$
\frac{1}{2\pi^2} \int_0^\infty d\alpha_1 d\alpha_2 d\alpha_3 d\alpha_4 f_1(\alpha_1) \alpha_2 f_2(\alpha_2) f_3(\alpha_3) f_4(\alpha_4) \int_0^\infty ds \int_-i\infty^{+i\infty} \frac{dz}{2\pi i} s e^{sz} e^{-z \sum_{i=1}^4 \alpha_i}. \quad (3.8)
$$

Performing the integral over the variables $\alpha_i$ and reexpressing the result in terms of the original functions $F_i(z)$, we obtain

$$
\left\langle F_1, F_2, F_3, F_4 \right\rangle = -\frac{1}{2\pi^2} \int_0^\infty ds \int_-i\infty^{+i\infty} \frac{dz}{2\pi i} s e^{sz} F'_2(z) F_1(z) F_3(z) F_4(z). \quad (3.9)
$$

With the help of this formula (3.9), we are ready to evaluate the kinetic energy $\langle \Psi Q \Psi \rangle$. For instance, for the first term on the right-hand side of equation (3.1) the functions $F_i$’s are given by $F_1 = K/G$, $F_2 = (1 - G)$, $F_3 = K$ and $F_4 = (1 - G)$, so that using (3.9), we arrive at the following result

$$
\left\langle \frac{K}{G}, (1 - G), K, (1 - G) \right\rangle = -\frac{1}{2\pi^2} \int_0^\infty ds \int_-i\infty^{+i\infty} \frac{dz}{2\pi i} s e^{sz} \left[ G'(z) - \frac{G'(z)}{G(z)} \right]. \quad (3.10)
$$
Performing a similar computation for the rest of terms on the right-hand side of equation (3.1), and adding up the results, we derive an expression for the kinetic energy given by

\[
\langle \Psi Q \Psi \rangle = -\frac{1}{2\pi^2} \int_0^\infty ds \int_{-i\infty}^{+i\infty} \frac{dz}{2\pi i} e^{sz^2} \left[ -\frac{6G'(z)}{G(z)} + \frac{3G''(z)}{G(z)^2} + 3G'(z) \right].
\]  

(3.11)

Evaluating the integral over the variable \( s \), which is well defined for \( \text{Re}(z) < 0 \), we obtain

\[
\langle \Psi Q \Psi \rangle = -\frac{1}{2\pi^2} \lim_{\epsilon \to 0^+} \int_{-i\infty-\epsilon}^{+i\infty-\epsilon} \frac{dz}{2\pi i} \left[ -\frac{6G'(z)}{G(z)} + \frac{3G''(z)}{G(z)^2} + 3G'(z) \right].
\]  

(3.12)

Let us suppose that the function \( G \) can be expanded as \( G(z) = 1 + \sum_{n=1}^{\infty} a_n z^{-n} \), i.e., \( G \) is holomorphic at the point at infinity \( z = \infty \) and has a limit \( G(\infty) = 1 \). Using this condition, we can make the integral along the imaginary axis into a sufficiently large closed contour \( C \) running in the counterclockwise direction by adding a large non-contributing half-circle in the left half plane \( \text{Re}(z) < 0 \). Therefore under this assumption, the kinetic energy (3.12) can be written as

\[
\langle \Psi Q \Psi \rangle = -\frac{1}{2\pi^2} \oint_C \frac{dz}{2\pi i} \left[ -\frac{6G'(z)}{G(z)} + \frac{3G''(z)}{G(z)^2} + 3G'(z) \right].
\]  

(3.13)

Additionally by assuming two more conditions for the functions \( G \) and \( 1/G \),

- \( G \) and \( 1/G \) are holomorphic in \( \text{Re}(z) \geq 0 \) except at \( z = 0 \).
- \( G \) or \( 1/G \) are meromorphic at \( z = 0 \).

We can shrink the \( C \) contour around infinity, picking up only a possible contribution from the origin,

\[
\langle \Psi Q \Psi \rangle = -\frac{1}{2\pi^2} \oint_{C_0} \frac{dz}{2\pi i} \left[ -\frac{6G'(z)}{G(z)} + \frac{3G''(z)}{G(z)^2} + 3G'(z) \right],
\]  

(3.14)

where \( C_0 \) is a contour encircling the origin in the clockwise direction. The second and third term in the integrand given on the right hand side of (3.14) are total derivative terms with respect to \( z \) such that the contour integral of them usually vanishes. In fact, since we assume the meromorphicity of \( G(z) \) at the origin, these total derivative terms vanish. Now inverting the direction of the contour \( C_0 \), we finally obtain

\[
\langle \Psi Q \Psi \rangle = -\frac{3}{\pi^2} \oint \frac{dz}{2\pi i} \frac{G'(z)}{G(z)}.
\]  

(3.15)

Note that to compute this integral (3.15), we need to consider a closed contour encircling the origin in the counterclockwise direction.
4 The multibrane solution

It is well known that the spectrum of open string theory contains tachyons. The presence of these tachyons is a perturbative consequence of the instability of the D-brane (the space filling brane) to which open strings are attached [34]. According to Sen’s conjecture [14, 15], there is a solution of the string field equation of motion, called the tachyon vacuum solution $\Psi_0$, such that at this vacuum there is no brane left on which open strings could end. As one consequence of this statement, the energy computed using the tachyon vacuum solution $\Psi_0$

$$U(\Psi_0) = \frac{1}{2} \langle \Psi_0 Q \Psi_0 \rangle + \frac{1}{3} \langle \Psi_0 \Psi_0 \Psi_0 \rangle$$

must cancel the tension of the D-brane

$$U(\Psi_0) + T_D = 0,$$

where in some appropriate units ($g_0 = 1$) the tension of the D-brane is given by

$$T_D = \frac{1}{2\pi^2}.$$  

Therefore at the tachyon vacuum solution $\Psi_0$, the energy (4.1) must have the value

$$U(\Psi_0) = -\frac{1}{2\pi^2}.$$  

Suppose that instead of having one D-brane, we have a stack of $n$ coincident D-branes, so that the total energy of this configuration should be $nT_D$. Now we should ask if there is a solution $\Psi$ of the string field equation of motion such that

$$U(\Psi) + nT_D = 0.$$  

Plugging the value of the tension of one D-brane (4.3) into this last equation (4.5), we obtain

$$U(\Psi) = -\frac{n}{2\pi^2}.$$  

The solution $\Psi$ which satisfies this condition is known in the literature as the multibrane solution [23, 24].

Let us derive the energy $U(\Phi)$ in terms of the kinetic energy evaluated at any general solution $\Phi$. The energy is given by the sum of the kinetic with the cubic term

$$U(\Phi) = \frac{1}{2} \langle \Phi Q \Phi \rangle + \frac{1}{3} \langle \Phi \Phi \Phi \rangle.$$  

$g_0$ is the open string coupling constant. For a more detailed discussion about these units, we refer to the paper by K. Ohmori [35].
If we assume the validity of the string field equation of motion when contracted with the solution itself \( \langle \Phi Q \Phi \rangle + \langle \Phi \Phi \Phi \rangle = 0 \), we can write the energy (4.17) in terms of the kinetic energy

\[
U(\Phi) = \frac{1}{6} \langle \Phi Q \Phi \rangle. \tag{4.8}
\]

At this point we are ready to evaluate the energy for a class of analytic solutions of the form given by equation (2.6). Clearly for this solution, using equations (3.15) and (4.8), we obtain

\[
U(\Psi) = -\frac{1}{2\pi^2} \oint \frac{dz}{2\pi i} \frac{G'(z)}{G(z)}. \tag{4.9}
\]

A function \( G(K) \), which satisfies the holomorphicity conditions stated in the previous section, is given by

\[
G(K) = \left( \frac{K}{1 + K} \right)^n. \tag{4.10}
\]

Since the contour integral (4.9) is performed around a closed curve encircling the origin, to compute this integral we need to write the Laurent series of the integrand around \( z = 0 \) and pick up the coefficient in front of the term \( 1/z \). For a function \( G \) defined by equation (4.10), it turns out that

\[
\frac{G'(z)}{G(z)} = \frac{n}{z} + \sum_{m \neq -1} b_m z^m, \tag{4.11}
\]

and consequently the contour integral (4.9) for this function (4.10) gives the following result

\[
U(\Psi) = -\frac{n}{2\pi^2}, \tag{4.12}
\]

which is the expected result for a multibran e solution. Therefore, in the context of the modified cubic superstring field theory, as in the case of open bosonic string field theory, we should also expect a solution which describes the so-called multibran e configuration [23, 24].

### 5 Summary and discussion

We have studied a class of analytic solutions of the string field equation of motion in the modified cubic superstring field theory. As in the case of open bosonic string field theory [23, 24], these solutions were characterized in terms of a single function \( F(K) \). We
have shown that this family of solutions can be derived by performing a suitable gauge transformation over an identity based solution constructed out of elements in the $KBc\gamma$ subalgebra.

We have analytically evaluated the energy associated to the solutions characterized by the function $F(K)$. We have shown that, under certain holomorphicity conditions on the function $G(K) = 1 - F^2(K)$, the energy is given in terms of a contour integral. We have written an explicit form for this function $G(K)$ and computed the energy associated to this solution. The result was given by integer multiples of a single D-brane tension. Therefore, in the context of the modified cubic superstring field theory, as in the case of open bosonic string field theory, we should also expect a solution which describes the so-called multibrane configuration.

Although we have performed analytic computations for evaluating the energy associated to the class of solutions considered in this work, it would be nice to confirm our results by employing numerical techniques such as the curly $L_0$ level expansion [36, 37] or the usual Virasoro $L_0$ level expansion scheme [38, 39]. The numerical analysis should be important, for instance, to check if the solution behaves as a regular element in the state space constructed out of Fock states. Specifically the examination of the coefficients appearing in the $L_0$ level expansion provides one criterion for the solution being well defined [7, 40, 41].

Finally, regarding the Berkovits non-polynomial open superstring field theory [42], since this theory is based on Witten’s associative star product, its algebraic structure is mainly similar to both the open bosonic string field theory and the modified cubic superstring field theory, and hence the strategy and prescriptions studied in this work should be directly extended to that theory. However, the construction of analytic solutions in Berkovits superstring field theory based on elements in the $KBc\gamma$ subalgebra or extensions of this subalgebra, remains an unsolved problem.

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