Open string field theory without open strings

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Abstract

Witten’s cubic open string field theory is expanded around the perturbatively stable vacuum, including all scalar fields at levels 0, 2, 4 and 6. The (approximate) BRST cohomology of the theory is computed, giving strong evidence for the absence of physical open string states in this vacuum.

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1 Introduction

The 26-dimensional open bosonic string has a tachyon in its spectrum with \( M^2 = -1/\alpha' \). The presence of this tachyon indicates that the perturbative vacuum of the theory is unstable. While some early work \([1]\) indicated the possible existence of a more stable vacuum at lower energy (see also \([2, 3]\)), until fairly recently the significance of this other vacuum was not understood, and the tachyon was taken to be an indication of fundamental problems with the open bosonic string.

In 1999, Sen suggested that the open bosonic string should be interpreted as ending on an unstable space-filling D25-brane \([4]\). Sen argued that the condensation of the tachyon should correspond to the decay of the D25-brane, and that it should be possible to give an analytic description of this condensation process using the language of Witten’s cubic open string field theory \([5]\). In particular, Sen made three concrete conjectures:

a) The difference in the action between the unstable vacuum and the perturbatively stable vacuum should be \( \Delta E = V T_{25} \), where \( V \) is the volume of space-time and \( T_{25} \) is the tension of the D25-brane.

b) Lower-dimensional \( Dp \)-branes should be realized as soliton configurations of the tachyon and other string fields.

c) The perturbatively stable vacuum should correspond to the closed string vacuum. In particular, there should be no physical open string excitations around this vacuum.

Conjecture (a) has been verified to a high degree of precision in level-truncated cubic open string field theory \([6, 7]\) and has been shown exactly using background independent string field theory \([8, 9, 10]\). Conjecture (b) has been verified for a wide range of single and multiple \( Dp \)-brane configurations, using both the cubic and background independent formulations of SFT (see \([11]\) for a review and further references). To date, however, little concrete evidence has been put forth either for the decoupling of open strings in the perturbatively stable vacuum or for the interpretation of this state as the closed string vacuum. In this note we explicitly compute the scalar open string spectrum in the cubic open string field theory expanded around the perturbatively stable vacuum, using the level-truncation approximation. The results of this computation give strong evidence that there are no physical open string states in this vacuum, and that the open strings are removed from the spectrum by purely classical effects in the string field theory.

2 String Field Theory in the Stable Vacuum

We begin with a brief summary of Witten’s cubic formulation of open bosonic string field theory \([3]\) (see \([12, 13]\) for reviews). The string field \( \Phi \) contains an infinite family of space-time fields, one field being associated with each state in the open string Fock space. Physical
fields are associated with states in the Hilbert space of ghost number one. The string field may be formally written as

$$\Phi = \phi(p)|0; p\rangle + A_{\mu}(p)\alpha_{-1}^\mu|0; p\rangle + \cdots$$  \hspace{1cm} (1)

where $|0\rangle$ is the ghost number one vacuum related to the $SL(2, R)$-invariant vacuum $|0\rangle$ through $|0\rangle = c_1|0\rangle$. Witten’s cubic string field theory action is

$$S = -\frac{1}{2} \int \Phi \star Q\Phi - \frac{g}{3} \int \Phi \star \Phi \star \Phi$$  \hspace{1cm} (2)

where $Q$ is the BRST operator of the string theory and the “star product” $\star$ is defined by dividing each string evenly into two halves and “gluing” the right side of one string to the left side of the other through a delta function interaction. The action (2) is invariant under the stringy gauge transformations

$$\delta\Phi = Q\Lambda + g(\Phi \star \Lambda - \Lambda \star \Phi)$$  \hspace{1cm} (3)

where $\Lambda$ is a ghost number zero string field.

While there are an infinite number of component fields in the string field $\Phi$, for any particular component fields the quadratic and cubic interactions in (2) and the related terms in the gauge transformations (3) can be computed in a straightforward fashion using a Fock space representation of the BRST operator $Q$ and the star product [14, 15, 16]. It has been found [1, 17] that truncating the theory by including only fields up to a fixed level $L$ is an effective approximation technique for many questions relevant to the tachyon condensation problem. (By convention the tachyon is taken to have level zero). At fixed level $L$, the theory can be further simplified by only considering interactions between fields whose levels total to some number $I < 3L$. Empirical evidence [1, 7] indicates that truncating at level $(L, I) = (L, 2L)$ is the most effective cutoff to maximize accuracy for a fixed number of computations and that calculations at truncation level $(L, 2L)$ give similar results to calculations at truncation level $(L, 3L)$.

Sen’s conjecture states that there is a Lorentz invariant solution $\Phi_0$ of the full string field theory equations of motion

$$Q\Phi_0 = -g\Phi_0 \star \Phi_0$$  \hspace{1cm} (4)

corresponding to the closed string vacuum without a D25-brane. The existence of a nontrivial solution to (4) has been analyzed in the level-truncated theory [1, 3, 4]. In the level (0, 0) truncation, the tachyon potential is simply $-\frac{1}{2}\phi^2 + g\kappa\phi^3$, where $\kappa$ is a numerical constant. This potential gives a locally stable vacuum at $\phi_0 = 1/(3\kappa)$. Evaluating the potential at this point gives 68% of Sen’s conjectured value $T_{25}$ for the energy gap between the unstable vacuum and the perturbatively stable vacuum. When other scalar fields are included in the string field by raising the level at which the theory is truncated, many of these fields couple to the tachyon $\phi$ and take expectation values when $\phi$ becomes nonzero, but similar solutions to the level-truncated string field theory equations of motion continue to exist. In the level (4, 8) truncation, the energy gap between the two vacua becomes 98.6% of the predicted
value, and in the level (10, 20) truncation the energy gap becomes 99.91% of the predicted value. As the level of truncation is increased, the vacuum expectation values of the scalar fields converge rapidly, so that the level (10, 20) values for the field values in the vacuum appear to be within less than 1% of their exact values for low-level fields. These results provide us with a close approximation to a field $\Phi_0$ satisfying (4), which we can use to study the perturbatively stable vacuum in the level truncated theory.

We can describe the physics around a nontrivial vacuum $\langle \Phi \rangle = \Phi_0$ satisfying the equation (4) by shifting the string field

$$\Phi = \Phi_0 + \tilde{\Phi}.$$ (5)

In terms of the new field $\tilde{\Phi}$, the action becomes

$$S = S_0 - \frac{1}{2} \int \tilde{\Phi} \star \tilde{Q} \tilde{\Phi} - \frac{g}{3} \int \tilde{\Phi} \star \tilde{\Phi} \star \tilde{\Phi}$$ (6)

where the new BRST operator $\tilde{Q}$ acts on a string field $\Psi$ of ghost number $n$ through

$$\tilde{Q} \Psi = Q \Psi + g (\Phi_0 \star \Psi - (-1)^n \Psi \star \Phi_0).$$ (7)

The identity

$$\tilde{Q}^2 = 0$$ (8)

for the new BRST operator follows from (4). The BRST invariance of the level-truncated approximation to the vacuum $\Phi_0$ was studied in [18].

We are interested in studying the physics of the new string field theory defined through (6, 7). According to Sen, the vacuum $\Phi_0$ should be the closed string vacuum, and should not admit open string excitations. To study the spectrum of excitations of the theory, we need to explicitly calculate the quadratic terms in the action, or equivalently to compute the action of the new BRST operator (7) on a general string field. This requires us to compute all cubic couplings in the original string field theory of the form

$$t_{ijk}(p) \phi_i(0) \phi_j(-p) \phi_k(p).$$ (9)

In this letter we restrict attention to scalar excitations, so we need to compute all terms of the form (9) where $\phi_i, \phi_j$ and $\phi_k$ are scalar fields. Because $\phi_j, \phi_k$ are momentum-dependent, we must include among these fields longitudinal polarizations of all higher-spin tensor fields as well as the zero-momentum scalars $\phi_i(0)$ which can take nonzero vacuum expectation values in $\Phi_0$. We restrict attention in this letter to scalars at even levels, which decouple from odd-level scalars at quadratic order due to the twist symmetry of the theory [1, 6].

With the assistance of the symbolic manipulation program Mathematica we have computed all 58,481 scalar interactions of the form (9) in the level (6, 12) truncation of the theory. There are 160 scalar fields $\phi_j(p)$ at even levels $\leq 6$, including longitudinal polarizations of tensor fields, and 31 momentum-independent scalar fields $\phi_i(0)$, each of which takes a nonzero value in the vacuum $\Phi_0$. (Actually, the vacuum lies in a subspace $\mathcal{H}_1$ of the full scalar field space [4], but we do not use this decomposition in our analysis). As a check on
our calculations we have also computed all the coefficients associated with gauge transfor-
mations (3) where one of the three fields involved has vanishing momentum. We have verified
that our terms of the form (9) give rise to an action (in the perturbative vacuum) which is
invariant at order $g^1$ under arbitrary momentum-independent gauge transformations and a
random sampling of momentum-dependent gauge transformations.

Using the complete set of terms of the form (9) in the level $(6, 12)$ truncation, we
have calculated all the quadratic terms for even-level scalars in the action (6) around the
perturbatively stable vacuum. The details of this action are far too lengthy to appear in
print, but will be made available in the future in electronic form. In the remainder of this
note we summarize the results of using this quadratic action to study the spectrum of open
string states in the theory (6). Earlier attempts to study the spectrum of physical states in
a subset of the level $(2, 6)$ truncation appeared in [1, 19].

3 BRST Cohomology

The spectrum of physical states in the theory (6) is given by the BRST cohomology

$$\text{Ker} \, \tilde{Q}_1/\text{Im} \, \tilde{Q}_0,$$

where $\tilde{Q}_n$ describes the action of the BRST operator $\tilde{Q}$ on a string field of ghost number $n$.
From (8), it follows that $\tilde{Q}_1 \tilde{Q}_0 = 0$ in the full string field theory. The states associated with
vanishing eigenvalues of the kinetic operator $\tilde{Q}_1$ at a fixed value of $p^2$ are the $\tilde{Q}$-closed states
in the theory. Two $\tilde{Q}$-closed states are physically equivalent if they differ by a $\tilde{Q}$-exact state
$\tilde{Q}_0 \Lambda$ where $\Lambda$ is a string field of ghost number 0.

Level truncation of the open string field theory breaks the general gauge invariance (3)
at order $g^2$, although gauge invariance is preserved at order $g^0$ and $g^1$. This breaking of
gauge invariance means that the level-truncated BRST operator no longer squares to zero.
In other words,

$$\tilde{Q}_1^{(L,I)} \tilde{Q}_0^{(L,I)} \neq 0$$

where $\tilde{Q}_n^{(L,I)}$ is the level $(L, I)$ truncated approximation to $\tilde{Q}_n$. The inequality (11) means
that $\tilde{Q}$-closed states which are also $\tilde{Q}$-exact in the full string field theory (6) will be approxi-
mated in the level truncated theory by $\tilde{Q}$-closed states which are not precisely $\tilde{Q}$-exact. This
fact makes the identification of physical states in the theory only possible in an approximate
sense.

We have systematically computed $\tilde{Q}$-closed states in the level-truncated theory by finding
values of $M^2 = -p^2$ where

$$\det \tilde{Q}_1^{(L,I)} = 0$$

and then computing the eigenvectors associated with the vanishing eigenvalues.

As an example of this computation, consider the level $(0, 0)$ truncation of the theory,
which includes only the tachyon field $\phi$. The quadratic term for the tachyon field in the
The nontrivial vacuum is
\[ \phi(p) \left[ \frac{p^2 - 1}{2} + g\kappa \left( \frac{16}{27} \right)^{p^2} \cdot 3\langle \phi \rangle \right] \phi(p). \] (13)

The determinant of \( \tilde{Q}^{(0,0)}_1 \) is simply the quantity in square brackets. This quantity does not vanish for any real value of \( p^2 \), so there are no \( \tilde{Q} \)-closed states in the spectrum at this level.

In the level (2, 6) truncation there are seven scalar fields to be considered, associated with the Fock space states
\[
\begin{align*}
|0; p\rangle, & \quad (\alpha_{-1} \cdot \alpha_{-1}) |0; p\rangle, \\
(\alpha_0 \cdot \alpha_{-2}) |0; p\rangle, & \quad (\alpha_0 \cdot \alpha_{-1})^2 |0; p\rangle, \\
b_{-1}c_{-1} |0; p\rangle, & \quad (\alpha_0 \cdot \alpha_{-1}) b_{-1}c_{0} |0; p\rangle, \\
b_{-2}c_{-0} |0; p\rangle
\end{align*}
\] (14)

At this level of truncation, using the vacuum expectation values determined in [7] with the level (10, 20) truncation, we found five values of \( p^2 \) where \( \det \tilde{Q}^{(2,6)}_1 = 0 \), associated with states having \( M^2 = 0.9067, 2.0032, 12.8566, 13.5478, 16.5998 \) in units where \( M^2 = -1 \) for the tachyon. At level (4, 12) we found 18 \( \tilde{Q} \)-closed states with \( M^2 < 20 \), of which the lightest has \( M^2 = 0.58817 \). At level (6, 12) we found 33 \( \tilde{Q} \)-closed states with \( M^2 < 20 \), of which the lightest has \( M^2 = 0.85562 \). The complete set of \( \tilde{Q} \)-closed states we found is graphed in Figure 1.

To test the \( \tilde{Q} \)-exactness of a given \( \tilde{Q} \)-closed state at level \((L, I)\), we computed \( \tilde{Q}^{(L,I)}_0 \Lambda_i \) for each ghost number zero field \( \Lambda_i \) with level \( \leq L \). The span of the fields \( \tilde{Q}^{(L,I)}_0 \Lambda_i \) gives an approximation to the subspace of \( \tilde{Q} \)-exact states at each level. Suppose that \( \{e_i\} \) is an orthonormal basis for this subspace and \( s \) is one of the \( \tilde{Q} \)-closed states we found. We can then measure the extent to which a state is \( \tilde{Q} \)-exact by the norm squared of its projection onto the \( \tilde{Q} \)-exact subspace. Explicitly,
\[
\text{fraction in exact subspace} = \frac{\sum_i (s \cdot e_i)^2}{s \cdot s}.
\] (16)

There is no natural positive definite inner product defined on the single string Hilbert space \( \mathcal{H} \), so to compute (16) we had to make an ad hoc choice of such an inner product. We did

\[ ^5 \text{Note: a similar calculation was done at level (2, 6) in Feynman-Siegel gauge by Kostelecky and Samuel.} \]

\[ ^6 \text{Our algorithm for locating momenta associated with \( \tilde{Q} \)-closed states proceeded by calculating the determinant of \( \tilde{Q}^{(L,I)}_1 \) at equally spaced values of \( p \) (with \( \Delta p = 0.0001 \)) and looking for changes of sign in the determinant. The spacing of our \( p \) values was significantly less than the smallest distance we observed between \( \tilde{Q} \)-closed states (0.0039), so we believe that we have found all the \( \tilde{Q} \)-closed states at \( M^2 < 20 \). Some possibility remains that we have missed pairs of \( \tilde{Q} \)-closed states which are very close in momentum. It is remotely possible that physical states are hiding in such closely spaced pairs of \( \tilde{Q} \)-closed states.} \]
Figure 1: Spectrum of $\tilde{Q}$-closed states in level truncations $(0, 0)$, $(2, 6)$, $(4, 12)$ and $(6, 12)$. States below the cutoff $M^2 = L - 1$ lie mostly in the exact subspace, confirming Sen's conjecture.
the calculation using two choices for this inner product, and found similar results in both cases. The first choice, which seems most natural, is to take the inner product $\langle s|s \rangle$ with $p \rightarrow |p|$ in the matter sector and a Kronecker delta function in the ghost sector. The second inner product we tried was simply defined by a Kronecker delta function on a basis of states spanned by all possible scalar products of matter and ghost operators (such as $(14)$ at level $(2, 6)$, giving a unit normalization to each of these states). Using these two definitions of the inner product, we find for example that the $\tilde{Q}$-closed state at $M^2 = 0.9067$ found in the $(2, 6)$ truncation lies $97.90\%$ in the exact subspace using the first inner product, and $95.24\%$ in the exact subspace using the second inner product. In the remainder of this note all calculations use the first definition of the inner product.

In the full string field theory, there are continuous families of $\tilde{Q}$-closed states which are also $\tilde{Q}$-exact at all $p$, given by states of the form $\tilde{Q}_0|s;p\rangle$. In the level truncation approximation we expect these continuous families to be replaced by a discrete spectrum of almost-exact states, approaching a continuous distribution as the level of truncation is increased. The extent to which we see a continuous distribution of $\tilde{Q}$-exact states arising in the level-truncation approximation to the theory around the vacuum $\Phi_0$ is a measure of how well level truncation works in the new vacuum, and how close the level-truncation approximation comes to giving a BRST operator satisfying $\tilde{Q}_1\tilde{Q}_0 = 0$. A complete list of $\tilde{Q}$-closed states at $M^2 < 20$ and the exactness of these states is given in Table 1; qualitative results for the exactness of all $\tilde{Q}$-closed states are depicted in Figure 1. As we would hope, as the level of truncation is increased we see a discrete distribution of almost-exact states which become both more exact and more closely spaced as the level of truncation is lifted. We interpret these almost-exact states as the remnant in the level-truncated theory of the continuous families of $\tilde{Q}$-exact states in the full theory.

Physical states in the theory correspond to $\tilde{Q}$-closed states satisfying $\tilde{Q}_1|s;p\rangle = 0$ which are not $\tilde{Q}$-exact. Because states in the cohomology of $\tilde{Q}$ will not be removed by a generic small perturbation, all physical states in the theory should appear in the level truncation as $\tilde{Q}$-closed states with $-p^2$ approaching some fixed value $M^2$ as the level of truncation is increased. To verify Sen’s conjecture, we would hope to find that the states lying below the cutoff $M^2 = L − 1$ are all approximately $\tilde{Q}$-exact, to the precision allowed by the level-truncation approximation, so that no physical states appear in the limiting theory. Indeed, we find that beyond the level $(2, 6)$ truncation all states below the cutoff lie more than $99\%$ in the exact subspace, using either choice of inner product described above. For example, the lowest lying states mentioned above in the level truncations $(2, 6)$, $(4, 12)$ and $(6, 12)$ lie $97.90\%, 99.990\%$ and $99.997\%$ in the exact subspace. We would expect physical states in the theory to appear consistently in each level truncation as states with significant components outside the exact subspace, since the average state in the level-truncated space lies less than $35\%$ in the exact space. We see no sign in our data of such physical open string excitations around the vacuum $\Phi_0$, and that this string field configuration should be identified with the
closed string vacuum.

It may seem surprising that we expect to see the physical states in the cohomology of $\tilde{Q}$, which form a set of measure zero in the full space of $\tilde{Q}$-closed states, through this approach. The difference between the behavior of physical and exact states under level truncation of $\tilde{Q}$ can be understood by considering the behavior of the zeros of the functions $f(x) = x - 1$ and $g(x) = 0$ under a small perturbation by a noise function $\eta(x)$. In the first case, generically $f(x) + \eta(x)$ will have a single zero near $x = 1$. In the second case, $g(x) + \eta(x)$ will develop a discrete spectrum of randomly spaced zeros. The physical states in the cohomology of $\tilde{Q}$ are controlled by functions like $f(x)$, while the continuous families of exact states are controlled by functions like $g(x)$. While this argument suggests that physical states should indeed continue to be present in the level-truncation approximation, as a check on our methodology we have used the same method we used to compute the approximate cohomology of $\tilde{Q}$ to compute the approximate cohomology of the BRST operator $Q$ in the perturbative vacuum, after adding a small random perturbation $\hat{Q} = Q + \eta$. We find that unless the perturbation $\eta$ is large enough to dominate the system (e.g., by pushing the exactness of a generic $\hat{Q}$-closed state below 90%), the physical states at $M^2 = -1$ and $M^2 = 3$ are easily distinguishable in a level (4, 12) truncation of the theory.

4 Discussion

We have explicitly calculated the quadratic terms in the open string field theory action around the nonperturbative vacuum $\Phi_0$ in the (6, 12) level truncation. We computed the BRST cohomology by computing all closed states under the truncated BRST operator $\tilde{Q}_1^{(L,I)}$, and comparing with the subspace of exact states formed by the operator $\tilde{Q}_0^{(L,I)}$. We found evidence that all $\tilde{Q}$-closed states in the theory become $\tilde{Q}$-exact in the limit when fields of all levels are included.

There are several directions in which it would be interesting to proceed, given the results in this letter. For one thing, it would be very nice to have a better conceptual understanding of the decoupling of open string states in the perturbatively stable vacuum. While some interesting perspectives on this phenomenon have been given [20, 21, 22, 23, 3, 24, 25, 26], a convincing picture which explains the classical decoupling of open strings in the cubic string field theory picture has yet to be given. An intriguing suggestion for the form of the string field theory in the nontrivial vacuum was made in [27, 28], where it was suggested that the new BRST operator $\tilde{Q}$ can be related through a field definition to a pure ghost operator such as $c_0$ or more generally $\sum a_n (c_n + (-1)^{n}c_{-n})$. It would be very interesting to use the explicit form of $\tilde{Q}$ which we have computed in level truncation to prove or disprove this conjecture. Finally, a question of fundamental importance is to what extent the cubic open string field theory in the perturbatively stable vacuum contains closed string excitations. Sen’s conjectures suggest that it might be possible to give a direct description of asymptotic closed string states in terms of the open string field theory degrees of freedom in the vacuum $\Phi_0$. If such a description could be made explicit, it would lead to new insight into the nature of the theory.
| $(L, I)$ | $M^2$ | % exact | $M^2$ | % exact | $M^2$ | % exact |
|---------|--------|---------|--------|---------|--------|---------|
| (2, 6)  | 0.9067 | 97.90%  | 2.0032 | 93.79%  | 12.8566| 64.17%  |
|         | 13.5478| 5.50%   | 16.5998| 2.56%   |        |         |
| (4, 12) | 0.5882 | 99.99%  | 2.9412 | 99.94%  | 3.1163 | 99.97%  |
|         | 3.9757 | 98.51%  | 4.3462 | 98.92%  | 4.5429 | 99.07%  |
|         | 5.7318 | 98.28%  | 10.1466| 80.96%  | 10.6907| 98.06%  |
|         | 12.7265| 73.42%  | 13.0284| 52.71%  | 13.4834| 37.09%  |
|         | 13.9911| 12.86%  | 15.2853| 58.25%  | 16.2490| 66.20%  |
|         | 17.0407| 13.88%  | 17.7912| 14.72%  | 19.2337| 35.80%  |
| (6, 12) | 0.8632 | 99.997% | 2.0525 | 99.982% | 2.3355 | 99.976% |
|         | 2.9664 | 99.997% | 3.1800 | 99.998% | 4.0961 | 99.999% |
|         | 4.2023 | 99.999% | 4.5645 | 99.999% | 4.5869 | 99.999% |
|         | 4.7265 | 99.999% | 4.7841 | 99.993% | 4.9703 | 99.994% |
|         | 5.4552 | 99.984% | 5.5382 | 99.976% | 5.6285 | 99.992% |
|         | 5.8999 | 99.988% | 6.3008 | 99.986% | 6.3204 | 99.265% |
|         | 6.5285 | 99.986% | 6.7381 | 98.328% | 7.6480 | 97.672% |
|         | 8.2205 | 99.936% | 8.2441 | 98.748% | 8.6604 | 96.683% |
|         | 11.5289| 98.958% | 11.7778| 99.652% | 12.1027| 99.529% |
|         | 13.3346| 88.497% | 14.5313| 94.919% | 16.3295| 52.298% |
|         | 16.9177| 90.786% | 16.9991| 79.305% | 18.2649| 86.453% |

Table 1: Masses and exactness of all $\tilde{Q}$-closed states found in level truncations $(2, 6), (4, 12), \text{ and } (6, 12)$ with $M^2 < 20$. 

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of closed string field theory and the structure of D-branes as closed string solitons.

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