A Proposal for Altering the Unification Scale in String Theory

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Abstract

An ensemble of short open strings in equilibrium with the heat bath provided by the Euclidean worldvolume of a stack of Dbranes undergoes a thermal phase transition to a long string phase. The transition temperature is just below the string scale. We point out that this phenomenon provides a simple mechanism within open and closed string theories for altering the strong-electro-weak coupling unification scale relative to the fundamental closed string mass scale in spacetimes with external electromagnetic background.
1 Introduction

There have been many attempts to explore the viability of weakly coupled supersymmetric string theory ground states with particle content roughly that of the minimal supersymmetric standard model [1, 2, 3, 4, 5, 6]. On the one hand, as reiterated in many recent precision phenomenological analyses, the trend in experimental data over many years overwhelmingly continues to favour theoretical particle-cosmology models that are close to minimal [7]. Such models traditionally assumed a grand desert between the weak, or TeV, scale and the coupling unification scale, which is of order $10^{16}$ GeV. Moreover, the weak scale can be generated radiatively from the unification scale in good agreement with precision RG analysis of the flow of couplings in the minimal supersymmetric standard model with three generations and a heavy top quark. On the other hand, recent directions in braneworld phenomenology have explored the implications of large spatial dimensions [9], of warped spacetime metrics [10], of hierarchies from fluxes [6], and of split supersymmetry breaking [11, 5]: a wide variety of phenomenological scenarios, and where the string scale has been assumed to range anywhere from the GUT scale down to the TeV scale [8]. The detailed analyses are far from conclusive and the debate is likely to remain controversial for some time to come. In this paper, we wish to simply point out that there is a mechanism within open and closed string theory that can alter the gauge coupling unification scale significantly relative to the fundamental closed string scale, $m_s = \alpha'^{-1/2}$.

The key point is that open and closed string theories can couple to external electromagnetic background fields [12]. Thus, the effective string tension in a vacuum with external electromagnetic background field is altered relative to its value in empty space [13]. While this phenomenon is well-known in intersecting brane models [3, 4, 5], we wish to focus on its possible significance in the broader context of early Universe phenomenology. Consider the following generic setting for a 4D braneworld model describing our early Universe: a stack of intersecting Dbranes in the type IB string with standard model gauge group and particle spectrum realized on the worldvolume of the intersecting branes [3]. We will examine such a braneworld model at finite temperature in the Euclidean time prescription [23]. It is helpful to think of the gravitational sector of the thermal type IB string as providing a heat bath with which the ensemble of short open strings on the branevolume is in thermal equilibrium. We work with the canonical ensemble, in a fixed spatial volume $V$, and at fixed temperature $1/\beta$.

As shown in [16, 23], the free open and closed string gas undergoes a continuous phase transition of the Kosterlitz-Thouless type at a temperature of order the string scale. At low temperatures, we have a gas of short open strings whose free energy scales as $T^{p+1}$. This is as expected, since the low energy field theory isolated in the short open string limit is a $p+1$-dimensional finite temperature gauge theory. The order parameter for the phase transition in the low energy finite temperature supersymmetric gauge theory is the coincidence limit, $r \to 0$, of the expectation value of a pair of timelike Wilson loops at fixed spatial separation $r$ which, as shown in [16] and more recently in [23], has a first-principles derivation from the worldsheet representation. The leading contribution is independent of string coupling and is given by a sum over oriented world-surfaces of cylindrical topology with boundaries mapped to a pair of fixed curves winding the Euclidean time direction. The leading contribution to the free energy, on the other hand, comes from both oriented and unoriented surfaces— with topology of the cylinder, Mobius strip, or Klein bottle, and it is independent
of string coupling. The contribution from the tours vanishes [16], as shown in detail more recently in [22]. In [16, 23], we calculate the one-loop contributions to the free energy as well as to the short distance correlation function of a pair of timelike Wilson-Polyakov loops. The one-loop free energy turns out to vanish identically as a consequence of tadpole cancellation for the unphysical massless state in the Ramond-Ramond sector; a vanishing dilaton tadpole is another remarkable consequence. The remaining thermodynamic potentials are nonvanishing.

It should be stressed at the outset that the worldsheet analysis in [22, 23] is restricted to the thermal behavior of the canonical ensemble of open and closed strings. All of our considerations are based on the one-loop vacuum amplitude at finite temperature which is independent of dependence on the string coupling. Thus, our results are expected to dovetail neatly with any nonperturbative analyses that may follow in the future. Although the phase transition itself lies well within the regime of validity for our one-loop calculation, we cannot follow the behavior of the long string phase to indefinitely high temperatures since string loop corrections, and consequently, gravitational interactions have not been examined thus far. Such interactions may, for example, indicate a further phase transition into a Schwarzschild black hole, but such phases are beyond the realm of our worldsheet analysis. They necessarily require an understanding of strong coupling effects. In addition, a formalism for the microcanonical string ensemble seems necessary for a fully convincing discussion [23]. We emphasize that our analysis of the free energy of the string canonical ensemble in [23] is fully compatible with the analyticity of perturbative string amplitudes as a function of temperature; this property is simply a special case of the well-known analytic dependence on the moduli in any braneworld or string compactification. On the other hand, a description of a first-order phase transition in the low energy finite temperature supersymmetric gauge theory can be achieved if we combine the low energy limits of a pair of string theories linked by a thermal T-duality transformation, namely, type IB and type $I'$. This phenomenon is elaborated in much more detail in our recent papers [23, 22]. Note that this provides an analytic description of either side of the phase boundary at a temperature of order the string scale.

In recent years it has become well-known that sub-string-scale short distance phenomena can be probed in an open and closed string theory with D0branes—pointlike topological string solitons whose mass scales as $1/g$, in the presence of a background electromagnetic field [18, 19]. The key point is the altered effective string mass scale in a vacuum with two-form background field. Notice that the pointlike D0branes behave like analogs of the infinitely massive heavy quarks of QCD. Guided by this analogy, we consider parallel timelike Wilson loops at fixed spatial separation $r$, lying in the worldvolume of intersecting Dbranes wrapped about the Euclidean coordinate $X^0$. The loops represent the Euclidean time world-histories of a pair of static, semiclassical heavy quarks: the endpoints of open string belong in the fundamental representation of the Yang-Mills gauge group. As shown in [20, 21, 16, 23], in the simplest case of loops lying within the D9brane stacks of the $O(16) \times O(16)$ type IB ground state at finite temperature, an expression for this macroscopic loop amplitude can be derived from an extension of the usual Polyakov path integral over connected worldsheets. Thus, $W^{(2)}$ is also computed from first principles using Riemann surface methodology, and it is obtained by summing worldsheets with the topology of an annulus, but with boundaries mapped to a pair of closed timelike loops, $C_i, C_f$, at fixed spatial separation $r$ in the
embedding, target-space worldvolume of Dbranes [20, 21, 23]. The result takes the form:

\[ W_2(\beta, r) = \lim_{r \to 0} \int_0^\infty dt \frac{e^{-r^2 t/2\pi\alpha'}}{\eta(it)^8} \sum_{n \in \mathbb{Z}} q^{\pi^2 n^2 \alpha' / \beta^2} \]

\[ \times \left[ \left( \frac{\Theta_{00}(it; 0)}{\eta(it)} \right)^4 - \left( \frac{\Theta_{10}(it; 0)}{\eta(it)} \right)^4 \right] - e^{i\pi n} \left( \frac{\Theta_{01}(it; 0)}{\eta(it)} \right)^4 - \left( \frac{\Theta_{11}(it; 0)}{\eta(it)} \right)^4 \right]. \]  

More generally, in the generic braneworld model, the sum within square brackets will take a more complicated form, in general incorporating a dependence on moduli other than \( \beta \) characterizing the compact spatial coordinates. But the contribution from thermal modes will remain unchanged. The leading \( r \) dependence of the short distance pair potential is extracted from the dimensionless amplitude \( W_2 \) as follows. We set \( W_2 = \lim_{r \to \infty} \int_0^\infty dt V[r(\tau), \beta] \), inverting this relation to express \( V[r, \beta] \) as an integral over the modular parameter \( t \). Consider a \( q \) expansion of the integrand, valid for \( t \to \infty \) where the shortest open strings dominate the modular integral. Retaining the leading terms in the \( q \) expansion and performing explicit term-by-term integration over the worldsheet modulus, \( t \), [21], isolates the following short-distance pairwise interaction [16]:

\[ V(r, \beta) = (8\pi^2 \alpha')^{-1/2} \int_0^\infty dt e^{-r^2 t/2\pi\alpha'} t^{1/2} \]

\[ \times \sum_{n \in \mathbb{Z}} (16 - 16e^{i\pi n}) q^{\alpha' \pi n^2 / \beta^2} + \ldots \]

\[ = (8\pi^2 \alpha')^{-1/2} \Gamma(3/2) r^{3 \min} \frac{2^5}{r^3} \left[ 1 - \frac{3}{2} \sum_{n=0}^{\infty} \frac{\beta_C^2 (n + 1/2)^2}{\beta^2 r^2} \right] + \ldots. \]  

We have expressed the result in terms of the characteristic minimum distance scale probed in the absence of external fields, \( r_{\min} = 2\pi\alpha'^{1/2} \) [19], and the bosonic closed string’s self-dual inverse temperature, \( \beta_C = 2\pi\alpha'^{1/2} \) [14, 1]. At low temperatures, with \( \beta >> \beta_C \), we can expand in a power series, and the leading correction to the inverse power law is \( O(\beta_C^4 / \beta^2 r^5) \). At high temperatures with \( \beta << \beta_C \), the potential takes the form obtained by a thermal duality transformation, a plausible signal indicating the onset of the the expected long string phase. This hint is investigated more carefully in the recent works [22, 23, 29]. We give evidence of a first order deconfining phase transition in the low energy finite temperature supersymmetric gauge theory, extracting the high temperature behavior at temperatures far above the string scale from the low energy limit of the Euclidean T-dual, type I’ string theory. The transition temperature is string scale.\(^2\)

We now come to the main observation of this paper. In the presence of an external electromagnetic field, the result given above is modified by the simple replacements: \( r_{\min} \to 2\pi\alpha'^{1/2} u \), \( \beta_C \to u \beta_C \), where \( F^0 = \tanh^{-1} u \) is the electromagnetic field strength, assumed to be constant for simplicity of calculation. The transition temperature, \( T_d = T_H / u \), in the presence of an electromagnetic background is consequently shifted relative to the phase transition temperature in empty space, \( T_H = m_s / 2\sqrt{2}\pi \). Since we do not as yet have an understanding of the mechanism that might generate such an electromagnetic field at the string mass scale, the Wilsonian perspective suggests that we parameterize our ignorance by interpreting this as a generic consequence of an “effective”

\(^2\)The precise normalization of the potential, and the transition temperature, is given in the recent work [29].
string mass scale, $m_s/u$, in spacetimes with a two-form background field [13]. Clearly, whether one observes a lowering, or raising, of the string mass scale depends on the strength of the electromagnetic field. We should clarify that the statements above only invoke the leading correction to the effective string scale due to the background field as in [19]. But it is, in fact, easy to obtain the exact electromagnetic field dependence of both the macroscopic string amplitude, and generic one-loop string scattering amplitudes, in a two-form background field of arbitrary strength, as has been shown in the papers [12, 13, 21].

**Note Added (Dec 2004):** Since the first appearance of this work, we have further clarified the nature of the deconfining thermal phase transition in the string canonical ensemble in our papers hep-th/0409301, and hep-th/0408206. Notice that the ensemble of short open strings in our scenario is in a state of thermal equilibrium at the effective string scale. The idea that a deconfining thermal phase transition might have occurred in the early Universe, accompanied by the formation of a cosmic string which is tentatively identified with a long winding mode in the theory of fundamental superstrings, appears in a 1988 paper by Englert, Orloff, and Piran [24].

An interesting point made in [24] is the apparent clash between the necessary conditions that must be met by cosmic string dynamics as required by galactic structure formation vs those required by a viable beyond-the-Standard-Model particle phenomenology. Our observation that an electromagnetic background impacts the constraints on the latter analysis in open and closed string theories may help in mitigating this clash, although we do not have anything remotely close to a satisfactory proposal for early Universe phenomenology at the moment. There has been considerable recent activity in exploring cosmic string dynamics in String/M theory [25], although within a different phenomenological framework that has focussed on the important issue of moduli stabilization [6]. We should note that there is significant evidence for a micro-Gauss strength magnetic field in our Universe at the super-cluster distance scale, generally assumed by astrophysicists to be of primordial origin [27, 28]: can this be exploited to build a viable phenomenological model for the early Universe? The generation of primordial magnetic fields as seeds of galaxy formation has already played a significant role in the pre-Big-Bang Model scenarios of Veneziano and collaborators [28]. We leave these as tantalizing, disparate, hints that may point to a more complete picture of the Early Universe within String/M theory in the future.

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