Phenomenology of Strongly Coupled Heterotic String Theory

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This is the text of a talk given at the Inaugural Conference of the Asia Pacific Center for Theoretical Physics, Seoul, Korea, June 9, 1996. If nature is described by string theory, and if the compactification radius is large (as suggested by the unification of couplings), then the theory is in a regime best described by the low energy limit of $M$-theory. We discuss some phenomenological aspects of this view. The scale at which conventional quantum field theory breaks down is of order the unification scale and consequently (approximate) discrete symmetries are essential to prevent proton decay. There are one or more light axions, one of which solves the strong CP problem. Modular cosmology is still problematic but much more complex than in perturbative string vacua.
1. Introduction

Before the advent of string duality, weakly coupled heterotic string theory was the best string theory fit to low energy phenomenology. It gives an impressive account of the low energy gauge groups and matter fields, but does less well in quantitative predictions. Most quantitative issues depend on where the world sits in moduli space. More disturbingly, the theory gives a model independent prediction of the unification scale in terms of the unified fine structure constant and the Planck mass. This prediction is off by a factor of 20. Furthermore, in order to get the right value of the unification scale, one must choose the dimensionless string coupling to be of order at least $10^7$. The weak coupling theory does not give a consistent account of phenomenology.

Witten[1] has recently argued that the strong coupling limit of heterotic string theory, which is M theory on an interval[2] gives a better fit to the data. In the M theory regime, the dimensionless string coupling is interpreted as the size of the eleventh dimension, measured in eleven dimensional Planck units, $\lambda \sim (R_{11} M_{11})^{2/3}$. The $E_8$ gauge groups live on the two ten dimensional boundaries of the eleven dimensional manifold. When one group is broken by the standard imbedding of the spin connection of the Calabi Yau manifold in the gauge connection, the boundaries act like “capacitor plates” for the eleven dimensional massless fields. Witten shows that this leads to a linear growth of the inverse $E_8$ coupling with $R_{11}$. The coupling reaches infinity at a finite value of $R_{11}$ which is close to the value required to fit phenomenology.

Using formulas presented in [1], one finds the following connections between the 11 dimensional Planck mass, $M_{11}$ (defined in terms of the coefficient of the Einstein lagrangian in 11 dimensional supergravity, as $M_{11} = \kappa_{11}^{-2/9}$), the 11-dimensional radius, $R_{11}$, and the compactification radius, $R = V^{1/6}$, where $V$ is the volume of the Calabi-Yau space on the boundary with unbroken $E_6$ gauge group:

\[ R_{11}^2 = \frac{a_{GUT}^3 V}{512 \pi^4 G_N^2}, \quad (1.1) \]

where $G_N$ is the four dimensional Newton’s constant;

\[ M_{11} = R^{-1} \left(2(4\pi)^{-2/3} a_{GUT}\right)^{-1/6}. \quad (1.2) \]
Substituting $M_{GUT} = R^{-1} = 10^{16}$ GeV, $\alpha_{GUT} = \frac{1}{25}$ and the correct value for Newton’s constant, one finds that

\[ M_{11} R \sim 2 \quad (1.3) \]
\[ M_{11} R_{11} \sim 72 \quad (1.4) \]

In the paper on which this talk is based, we chose the unification scale to be a factor of three larger and thus had a smaller value of the size of the eleventh dimension. These values of the parameters are quite remarkable. They imply that the scale at which “quantum gravity” corrections to field theoretic predictions become important is the unification scale. The four dimensional Planck scale is a low energy artifact, and does not control the strength of these corrections. Furthermore, at a scale two orders of magnitude below the unification scale, physics becomes 5 dimensional. Gravitational physics is certainly more accessible to experiment in this regime than it is in weakly coupled string theory.

2. General Consequences of the Strong Coupling Limit

The paper was devoted to exploring further general consequences of the assumption that nature is described by strongly coupled heterotic string theory. The most striking of these is the emergence of a solution to the strong CP problem. String theory has a wide variety of axion candidates. However, in the weakly coupled regime there seem to be mechanisms which give all of them potentials much larger than that generated by QCD. In the strong coupling regime this is no longer the case. To see this it is most convenient to exploit the large size of the eleventh dimension and pass to a four dimensional effective theory via a five dimensional effective theory first worked out by Antoniadis et. al., following.

In the weakly coupled theory, there are a set of $h_{1,1}$ complex moduli $T^a$ whose imaginary parts are potential axions. However, the associated Pececi-Quinn (PQ) symmetries are broken by world sheet instantons. The corresponding fields $Y^a$ in the strong coupling description, descend from five dimensional vector superfields. Their imaginary parts are the fifth components of vector fields and the four dimensional PQ symmetries can be thought of as arising from five dimensional “gauge transformations” with gauge functions that do
not vanish on the boundary of spacetime where the standard model gauge fields live. Thus all effects which break these symmetries must involve this boundary in some way. There are two distinct mechanisms of PQ symmetry breaking. The first involves effects localized in the standard model boundary. If QCD is the largest gauge group on the boundary then this will be the dominant effect here. We can also have membrane instantons, membranes stretched between the two boundaries and wrapped around two cycles in the Calabi Yau manifold. These are the strong coupling remnants of world sheet instantons. We refer to them as remnants, because the large value of $R_{11}$ gives an exponential suppression of these effects. They are totally negligible compared to QCD.

The strongly coupled region of heterotic moduli space thus gives a solution of the strong CP problem under fairly generic conditions. If $h_{1,1} > 1$ it also predicts at least one extremely light axion with a Compton wavelength of cosmological size. The approximate PQ symmetry which protects the mass of this axion also ensures that it has only very tiny coherent couplings to matter. Thus it is not ruled out by experiments on coherent long range forces. Probes of spin dependent long range forces can now be seen as detecting the topology of the internal Calabi Yau manifold.

It is possible that such light axions exist even when $h_{1,1} = 1$. The strongly coupled vacuum has boundary moduli which, in the large volume limit can be thought of as moduli of the $E_8$ gauge bundle on the standard model boundary. Explicit orbifold calculations suggest that these have axionlike couplings to gauge fields. Furthermore, since they live only on the standard model boundary their potential should arise only from effects that involve this boundary. Furthermore, we should expect that their couplings to ordinary matter are stronger by a factor of $R_{11}M_{11}$ than the couplings of the $Y^a$ fields described above. This is a consequence of the fact that the latter are defined as averages over fields which live in the bulk of the eleven dimensional spacetime. If such boundary axions exist, then the QCD axion will be a linear combination of them and of the $\text{Im } Y^a$, with the dominant component being a boundary field. The other linear combinations will be superlight axions.

For cosmological reasons, the decay constant of the axion is of considerable interest.  

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1 T.B. would like to thank K. Choi for a discussion of this point.
In the case that the axion is a bulk modulus, one would have imagined that, like the gravitational field, its couplings were of order \( m_4^{-1} \) where \( m_4 \sim 2 \times 10^{18} \) GeV, is the reduced Planck mass. However, in weakly coupled heterotic string theory, Kim and Choi [6], have shown that the decay constant of the model independent axion is smaller than the Planck mass by a factor \( 16\pi^2 \). We might anticipate similar factors in the strong coupling region, so axion decay constants as small as \( 10^{16} \) GeV do not seem unreasonable. Similar factors in the coupling of moduli whose mass comes from SUSY breaking interactions might substantially alleviate the cosmological moduli problem. In such a context a scenario in which an axion with decay constant \( \sim 10^{16} \) GeV is the dark matter in the universe may be viable[7]. Note further that if the axion originates as a boundary modulus, it will have an even smaller decay constant.

The strongly coupled region of heterotic moduli space contains a large number of different light scalars with a variety of masses and couplings. Early universe cosmology in this region is undoubtedly quite complex and rich. It is too early to say whether an acceptable cosmological scenario emerges.

3. Holomorphy as a Calculational Tool

As mentioned above, Witten found a diverging gauge coupling at finite \( R_{11} \) by performing a classical calculation in eleven dimensional supergravity. In [3] we pointed out that this result could be reproduced by extrapolating existing weak coupling calculations[8]. The gauge coupling function is a holomorphic function of the conventional chiral superfields \( S \) and \( T^a \). The action is invariant under shifts of the imaginary part of these fields by multiples of \( 2\pi \). This means that up to corrections which are exponentially small when the real parts of these fields are large (which is the case in the strong coupling regime), the gauge coupling function is a linear function of \( S \) and \( T^a \) and is therefore exactly computed by the tree and one loop contributions in weak coupling perturbation theory. This computation gives

\[
\frac{f_{6/8}}{8} = S \pm T^a \int \frac{b_a \wedge F \wedge F}{8\pi^2} \tag{3.1}
\]

for the \( E_6 \) and \( E_8 \) couplings. Here \( b_a \) is a harmonic \((1,1)\) form and \( T^a \) the associated chiral
superfield. We see the blowup of the $E_8$ coupling when $S$ and $T^a$ are comparable. Apart from this sign, the calculation primarily determines the relation between the natural basis of chiral superfields in the weak and strong coupling descriptions. At strong coupling, the $E_8$ function is given simply by $S$ a chiral superfield whose real part is just the volume of the Calabi Yau manifold on the $E_8$ boundary, measured in terms of eleven dimensional Planck units. The difference of the two couplings determines that $T^a$ is $Y^a$, the chiral superfield which descends from one of the $h_{1,1}$ vector multiplets of the five dimensional theory. It is proportional to $R_{11}$ when written in eleven dimensional Planck units.

The holomorphic calculation breaks down as we enter the strong gauge coupling regime $S \sim 0$. We can no longer neglect exponentials of $S$ and the coupling may not really go to infinity.

Finally, we note that the calculation of PQ symmetry breaking referred to above can also be performed by analytic extrapolation of the weak coupling formula for world sheet instanton effects.

4. Supersymmetry Breaking and Modular Stabilization

The most important phenomenological problem of string theory is to understand the mechanism which stabilizes the moduli at fixed values. This is true both because these values will determine the nature of low energy physics and because unstabilized moduli are massless fields whose properties are incompatible with a variety of astrophysical and terrestrial observations. The M theory regime sheds new light on the stabilization problem, but does not solve it.

First of all, the region of large Calabi Yau volume and large $R_{11}$ is a region of instability. Once the moduli enter into this region they tend to flow to infinity. This was inevitable given the generality of the analysis of [9]. The phenomenological values of the parameters and the analysis of [1] suggest some new possibilities for stabilization at finite volume. The linear size of the Calabi Yau manifold appears to be of order the eleven dimensional Planck scale. Thus, we should not trust a semiclassical calculation of its Kahler potential. Furthermore, the five dimensional analysis of [1] shows that the Calabi Yau volume is part
of a five dimensional hypermultiplet. Thus, even if $R_{11}$ is large, five dimensional symmetries will not fix its Kahler potential. These observations suggest that Kahler stabilization of the volume modulus (and all others which come from five dimensional hypermultiplets), which was advocated in [10], may be operative here.

In addition, Witten\textsuperscript{1} finds that the phenomenological values of the coupling are close to the point where the $E_8$ coupling seems to blow up. In this region one can no longer argue that the superpotential generated by gaugino condensation is a pure exponential, or indeed that the mechanism which generates the superpotential can be understood on the basis of low energy physics. The superpotential is a complicated function of the moduli subject to only mild symmetry constraints.\textsuperscript{2} It is then reasonable to assume that all hypermultiplet moduli are frozen at discrete values determined by nontrivial solutions of the F-flatness conditions. Note however that the nontrivial superpotential cannot depend on the vector moduli $Y^a$. Such a dependence is forbidden by the approximate PQ symmetries, which are not broken by strong coupling dynamics on the $E_8$ boundary.

These assumptions lead immediately to an approximate no-scale model for SUSY breaking at large $Y$. Indeed, at large $Y$, five dimensional SUSY fixes the Kahler potential of the $Y^a$, and the superpotential is nonzero but does not depend on them. The SUSY breaking scale is $F \sim Y^{-3/2}W$. Presumably, since it contains no small coupling parameters, the superpotential is of order the eleven dimensional Planck scale. Thus, for phenomenologically reasonable values of $Y$, the scale of SUSY breaking is much too large.

The vacuum energy predicted by this model is, barring unexplained cancellations, of order $Y^{-2}$ times the square of the SUSY breaking order parameter. Thus, even if we retreat from the assumption of strong coupling stabilization, and choose a weak coupling scenario in which an exponentially small superpotential is stabilized at the proper scale of SUSY breaking by the Kahler potential, the vacuum energy is too large to be compatible with observation. Of course, we did not really expect to solve the cosmological constant problem this easily.

\textsuperscript{2} There may be some sophisticated argument which in fact determines this complicated function. However, any such argument would depend on a knowledge of the singularities of the function at finite values of its argument, and we are presently unaware of any information about this.
Another generic prediction in this regime is that the leading order squark mass matrix is of the same order as gaugino masses and is flavor independent. This follows from homogeneity of the leading order terms in $Y$, for large $Y$. It is unclear whether the corrections to this result are small enough to account for the absence of flavor changing neutral currents. The real problem is that to leading order in $Y$ there is no stable minimum for the potential of $Y$ itself. This is another example of the general difficulty exposed in [3]. Thus in order to find a satisfactory vacuum state we must contemplate competition between different orders in the $Y$ expansion. This is somewhat less plausible for the parameter values ($R_{11} M_{11} \sim 200$) that we have chosen in this lecture than for those used in [3]. But even if we find a stable vacuum at a large value of $Y$, its very existence leads us to doubt the reliability of the expansion. Thus, we can have little confidence in our prediction of squark degeneracy.

5. Conclusions

Strongly coupled heterotic string theory is a better fit to the parameters of nature than the weakly coupled version. If correct, it implies potentially dramatic gravitational physics at energy scales well below the Planck scale. Conventional approaches to grand unification and to inflation may have difficulty surviving in this environment. The nominal scale at which quantum gravitational corrections become important is of order both the unification scale and the scale of energy density in the simplest inflationary models. Moreover, the strongly coupled heterotic theory implies that the radius of the fifth dimension is one or two orders of magnitude larger than the inverse unification mass.

In the strongly coupled regime, string theory provides a solution of the strong CP problem and may also predict one or more superlight axion fields. The value of the axion decay constant and the cosmological implications of the theory are under investigation.

There is also an interesting new slant on the problems of modular stabilization and supersymmetry breaking. Strong coupling physics on the “hidden boundary” can lead to stabilization of many of the moduli. However, an approximate five dimensional supersymmetry then implies too large a scale of $N = 1$ SUSY breaking in the four dimensional
effective theory, via the no scale mechanism. This can be avoided by invoking Kahler stabilization of the moduli at a point where the hidden sector gauge theory is weakly coupled. One then obtains a no scale model of SUSY breaking with approximately degenerate squarks. However, in the same approximation it is impossible to stabilize the moduli fields which are remnants of five dimensional vector multiplets. This observation puts the entire scheme of SUSY breaking under a cloud of suspicion.

Although the strong coupling theory is by no means ruled out by these considerations, it clearly has many problems. One is led to ask whether its attractive features might be found in a wider class of string vacua. The key feature which enabled Witten to obtain the required discrepancy between the four dimensional Planck scale and the unification scale was that the gauge sector of the low energy theory lives on a lower dimensional submanifold of spacetime, while gravity propagates in bulk. Recent work on string duality has shown that it is quite typical to have gauge fields living on low dimensional manifolds called D-branes. Thus, there may be many classical string vacua which will naturally explain the ratio of the Planck and unification scales. Notice that it will always be the case in such a vacuum that quantum gravity effects become important below the Planck scale. It is also fairly common to find distortions of bulk gauge symmetries on D-branes. In an effective four dimensional theory, these will show up as PQ symmetries broken by nonperturbative physics attached to the brane. Thus our observation that the strong CP problem is solved in the strongly coupled heterotic vacuum may generalize as well.

We are thus motivated to search for general realizations of the field content of the standard model in D-brane physics. Given a list of such constructions one could then try to embed them into full string compactifications in which all tadpoles/anomalies are cancelled, and search for examples with sensible dynamics for stabilizing the moduli and breaking SUSY.
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