String Theory, Unification and Supersymmetry

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Abstract

One cannot yet point to any firm string prediction. While many approximate string ground states are known with interesting properties, we do not have any argument that one or another describes what we observe around us, and for reasons which appear fundamental we do not know how to systematically determine even any rough quantitative properties. I argue here that we should examine large classes of string ground states, trying to determine whether features such as low energy supersymmetry, the pattern of supersymmetry breaking, the presence of axions, large dimensions, or others might be generic.
1 Introduction

We have spent about 17 years thinking seriously about string phenomenology. In one sense we have come quite far. We have seen that string theory can exhibit many of the intricate properties of the world we see: four dimensions, Standard Model gauge groups, repetitive generations, and the like. As described at this meeting, we know of string ground states which, in many of their features, look quite close to the Standard Model.

Despite this – indeed, partly because we have so many options for thinking about the connection between string theory and nature – we are hard pressed to name a string theory prediction. Does string theory predict low energy supersymmetry? Does it predict large extra dimensions with/without low energy supersymmetry? Does it predict gauge coupling unification? Neutrino masses of the sort observed? If we are honest, we must say we don’t know.

In fairness, there are good reasons for this. It has been clear almost from the beginning that the problem of determining the ground state of string theory and of making calculations in this state is almost certainly a strong coupling problem in a non-supersymmetric state.[1] Despite all of the progress in non-perturbative string theory, we still have no tools with which to approach such problems.

So it is worthwhile, at a meeting like this, to pause and to ask: how might string theory make contact with nature? One can imagine suggest several possibilities:

- We might hope to “solve” the theory and calculate everything we might wish to know. As I have indicated, this seems implausible, for the foreseeable future.

- We might conjecture that some string solution is the relevant one to describing nature, and manage to calculate some quantities. This is the subject of many of the talks at this meeting, and more generally of most of the work on string phenomenology. Whether successful or not, this is an important activity since it teaches us much about the underlying theory. Here the goal might be to predict, say, some ratio of fermion masses, or perhaps the existence of some additional massive gauge bosons at accessible energies.

- Finally, we might try to focus on some questions which have a generic character. We might try to argue that string theory predicts low en-
ergy supersymmetry, or that, given low energy supersymmetry, some pattern of symmetry breaking (anomaly mediation, gauge mediation, gaugino mediation, etc.) is a likely outcome. A strategy to approach such problems might be to examine broad classes of classical string ground states, trying to determine features which are, or are not, typical.

It is this last possibility which will be the focus of this talk. There is, of course, no guarantee of success. But the potential payoff is enormous. Today we will ask:

- Is it possible to establish that low energy supersymmetry is a prediction of string theory?
- Assuming that low energy supersymmetry is a prediction of string theory, what can we hope to say about the pattern of soft breaking?
- If the underlying structure is a string theory, what might a grand unified field theory look like? And related to this: what are the distinctions between string-theoretic and field-theoretic unification?

Our success today will be small but real. We will be able to give examples of phenomena which are not characteristic of typical string ground states. In addition, we will at least take steps towards defining the problem of determining if low energy supersymmetry is a prediction of string theory. We will describe an attempt to show that non-supersymmetric ground states do not make sense in string theory. We will give some indications of how, given low energy supersymmetry, predictions for the pattern of soft breaking might emerge. We will argue that string theory suggests a specific approach to conventional GUT model building.

In recent years, theoretical speculations about unification of forces have become more expansive, including large or very large extra dimensions, and localized gravity. I won’t talk about these ideas here, but note that none of these ideas can be explored without a theory like string theory, which incorporates gravity and is finite (“complete” might be a better expression). I also won’t talk about flavor, since it is harder to see how to make generic statements (but I would love to).

In the next section, I discuss what might be called “String inspired Grand Unification.” I give some reasons why grand unification is interesting, even in string theory, and argue that string theory suggests some rules for grand unified model building. In section 3, I discuss some attempts to predict
low energy supersymmetry from string theory. In section 4, I review an analysis that shows that anomaly mediation is not a generic outcome of string theory. In section 5, I discuss aspects of moduli in string theory, and their implications for phenomenology. In particular, I explain why some possible solutions of the cosmological moduli problem point to particular mechanisms for supersymmetry breaking.

2 String theoretic unification

There has, through the years, been much criticism directed at string theory and string theorists, to the effect that string theory is somehow not a scientific theory. In assessing these criticisms, it is useful to contrast the situation with grand unification. In the case of grand unification, one has an essentially infinite array of theories. Prior to the resurgence of string theory in the mid '80's, there were many ad hoc rules for writing down such models. To mention two, many models were postulated with global continuous symmetries and with axions. Many questions were raised about whether these two ideas made sense in a theory with gravity. String theory early on offered an answer to both questions:

- In string theory there are no continuous global symmetries. There are, on the other hand, often discrete symmetries. These symmetries are often, and likely always, gauge symmetries.

- There are axions associated with spontaneously broken global symmetries which are exactly conserved in perturbation theory, and broken by non-perturbative effects.

2.1 String Unification vs. Field Theory Unification

Coupling unification is one of the few solid pieces of evidence in favor of supersymmetry, as well as unification. While supersymmetric guts predict approximate unification of coupling constants, string theory offered from the beginning a way to think about coupling unification different than that of field theory. In string theory, unification can occur even if there is no scale at which physics can be described by an effective four dimensional field theory with a unified gauge group. For that matter, there need not even be any scale at which one sees a higher dimensional theory. This is illustrated by Calabi-Yau compactifications at a Gepner point. One of the
triumphs of weakly coupled heterotic strings was their generic prediction of unification of couplings at weak coupling. These theories also yielded another remarkable result: they could readily explain the splitting between doublets and triplets. No symmetry explanation was required; this is an example of a string miracle. Yet these ideas were have phenomenological limitations.

- In weakly coupled heterotic string theory, the unification scale is essentially equal to the Planck scale. This is not the case in the strongly coupled limit, but at strong coupling it is not clear that unification is a robust prediction. Similar statements apply to other regimes of the moduli space.

- Neutrino masses provide further evidence that there is another scale in nature well below the Planck scale. While this could be something like the scale of the strongly coupled heterotic theory, it is interesting to explore the possibility that these are connected with a purely four-dimensional scale.

- Leptogenesis suggests the existence of a scale well below the Planck scale. Baryogenesis through coherent scalar field oscillations might provide an alternative, but the existence of substantial neutrino masses makes the leptogensis scenario seem a promising one.

2.2 The Unification Scale as a Modulus

Many papers have been written on the possibility of obtaining conventional unification in string theory. By this one means finding states with adjoints of a group like $SU(5)$ in some limit of string theory (e.g. weakly coupled heterotic strings). In order that there be a separation of scales, it is generally necessary that the adjoints be massless in some approximation. But this is not all one needs to build a successful unified model. One needs, as well

- A flat or nearly flat potential for the adjoint, in order that this field can obtain a very large vev.

- No extra massless octets and triplets of $SU(3) \times SU(2)$ in this direction.

Obtaining flat directions naturally in a supersymmetric field theory is easy. Suppose one has a discrete $R$-symmetry under which the superpotential transforms as

$$W \rightarrow \alpha W \quad \alpha = e^{2\pi i \frac{N}{N}}$$

(1)
while the adjoint, $A$, is invariant, $A \rightarrow A$. Then $W = A^n$ is forbidden, for all $n$. Such discrete $R$ symmetries are common in string theory. We will exploit such symmetries throughout our discussion. One should keep in mind, though, that conventional notions of naturalness are not always applicable in string theory and flat directions often arise for which there is no obvious field-theoretic explanation.

This simple model above has a serious difficulty. While there is a flat direction, there are also a massless octet and triplet of $SU(3) \times SU(2)$ in the low energy theory, which completely spoil the prediction of unification.

It is not easy to fix this in $SU(5)$ or $O(10)$ with only discrete symmetries, even if one adds additional fields.\textsuperscript{1} As we will see, however, it is not difficult in the context of the models which Witten has recently described to attempt to address the doublet-triplet problem.\textsuperscript{10}

Witten has proposed that one should understand the lightness of Higgs doublets by supposing that there is a discrete symmetry which distinguishes doublets and triplets;\textsuperscript{10} ideas along these lines are implicit in earlier work of Barr.\textsuperscript{11} The basic model-building strategy can be summarized by taking the group to be $SU(5) \times SU(5)$, with two pairs of bifundamentals, $\Phi_i, \bar{\Phi}_i$, with expectation values:

$$
\Phi_1 = \bar{\Phi}_1 = \begin{pmatrix} v_1 & 0 \\ v_1 & \alpha^N \\ 0 & 0 \end{pmatrix} \quad \Phi_2 = \bar{\Phi}_2 = \begin{pmatrix} 0 & 0 \\ v_2 & v_2 \end{pmatrix}
$$

One can imagine\textsuperscript{12} then taking the Higgs fields to be a 5 and $\bar{5}$ of one or the other $SU(5)$, and coupling them only to $\Phi_1$.

This structure of expectation values is natural if it preserves a symmetry. This symmetry must be a combination of an ordinary discrete symmetry and a gauge symmetry, say in the first $SU(5)$:

$$
g_1 = \text{diag} \left( \alpha^{-1}, \alpha^{-1}, \alpha^{-1}, \alpha^{-\frac{N+3}{2}}, \alpha^{-\frac{N+3}{2}} \right)
$$

Then if the $\Phi$'s transform under a $Z_N$ as:

$$
\Phi_1 \rightarrow \alpha \Phi_1 \quad \bar{\Phi}_1 \rightarrow \alpha^{-1} \bar{\Phi}_1 \quad \Phi_2 \rightarrow \alpha^{-\frac{N+3}{2}} \Phi_2 \quad \bar{\Phi}_2 \rightarrow \alpha^{-\frac{N+3}{2}} \bar{\Phi}_2
$$

\textsuperscript{1}In O(10), Hall and Raby have written a model with continuous global $R$ symmetries without this problem; for future reference, this model contains six adjoints, two symmetric tensors and two spinor representations just in order to obtain the first stage of symmetry breaking.\textsuperscript{9}
the symmetry is preserved by the expectation values, and this structure is natural.

A superpotential which respects this symmetry has been discussed by Barr:

\[
W = M_{\text{gut}}(r_1\Phi_1\Phi_1 + r_2\Phi_2\Phi_2) + \frac{1}{M_{\text{gut}}}(a\Phi_1\Phi_1\Phi_1 + b\Phi_1\Phi_1\Phi_2 + c\Phi_2\Phi_2\Phi_2 + d\Phi_2\Phi_2\Phi_2 + e\Phi_2\Phi_2\Phi_2 + f\Phi_2\Phi_2\Phi_2 + \ldots) \tag{5}
\]

In this model, the GUT scale is put in explicitly. There are no extra states beyond those of the MSSM below this scale.

### 2.3 Turning the GUT scale into a modulus

To turn the GUT scale into an exact modulus in these theories is not difficult; we can simply add a discrete R symmetry as for the SU(5) model. To also give masses to all fields is more challenging (but not nearly as challenging as in conventional SU(5) and O(10) models). We can obtain approximate moduli which accomplish this without great difficulty. Giving mass to all fields requires, at a minimum, three adjoints and two singlets. The fields and their transformation laws under the symmetries are indicated in Table 1.

The renormalizable terms in the superpotential permitted by the symmetries are:

\[
W = \lambda_{12}\Phi_1A_1\Phi_2 + \lambda_{21}\Phi_2A_2\Phi_1 + \lambda_{11}\Phi_1A_3\Phi_1 + \lambda_{22}\Phi_2\Phi_2 + \eta_{12}SA_1A_2 + \eta_{33}\lambda S^A A_3^2 + X_1\text{tr}(A_1) + X_2\text{tr}(A_2) + X_3\text{tr}(B) \tag{6}
\]

In determining whether or not there are exact or nearly exact flat directions, it is necessary to look beyond the renormalizable terms. An analysis of these shows that:

- There are exact flat directions with \(\Phi_i\)'s non-zero, or \(S\) non-zero, but not both; there are approximate flat directions with both non-zero. Phenomenologically, this can easily be good enough.

- There are no extra states below the GUT scale. Three adjoints constitute the smallest representation which can achieve this.
### Table 1: Field content of model I.

| Field | $G_h$               |
|-------|--------------------|
| $h$   | $(5, 1, \alpha, \beta)$ |
| $\bar{h}$ | $(5, 1, 1, 1)$   |
| $h'$  | $(1, 5, \alpha^{-1}, \beta)$ |
| $\bar{h}'$ | $(1, 5, 1, 1)$  |
| $\Phi_1$ | $(5, 5, \alpha, 1)$ |
| $\Phi_1$ | $(5, 5, \alpha^{-1}, 1)$ |
| $\Phi_2$ | $(5, 5, \alpha^{(N-3)/2}, 1)$ |
| $\Phi_2$ | $(5, 5, \alpha^{(N+3)/2}, 1)$ |
| $A_1$ | $(24, 1, \alpha^{(N-5)/2}, \beta)$ |
| $A_2$ | $(24, 1, \alpha^{(N+5)/2}, \beta)$ |
| $A_3$ | $(24, 1, 1, \beta)$ |
| $S$   | $(1, 1, 1, \beta^{-1})$ |

- It is difficult to build models with exact flat directions for both $S$ and $\Phi$ and this low energy particle content.
- It is not difficult to build models with “baryonic” flat directions, with $\Phi_1, \Phi_2 \neq 0, \Phi_1, \Phi_2 = 0$, but this leaves a set of light fields with the quantum numbers of a full $SU(5)$ adjoint, and the gauge couplings become strong near the unification scale.

To summarize: we have proposed a set of rules for grand unified model building. It is possible to build models which satisfy them, but the rules are very restrictive. This is an appealing feature of this viewpoint.

#### 2.4 Distinctions Between String Theory and Field Theory Unification

We have given above a definition of a grand unified field theory (within the framework of a more fundamental theory like string theory): a theory in which, for a range of scales, the standard model group is unified into a larger group, with a finite number of fields. We can use the phrase “string unification” to refer to theories in which couplings are unified, but there is no range of scales in which the gauge interactions are unified with a
finite number of fields. It is natural to ask: are there qualitative differences between string and field theory unification? Witten\cite{10} has pointed out two:

- String unification typically leads to superheavy fractionally charged particles.
- Discrete symmetries in string theory are typically subject to anomaly constraints. In weakly coupled heterotic strings, there is only one modulus which can cancel anomalies, so discrete anomalies must be universal. M. Graesser and I, however, have recently shown that in other limits of string/M theory, discrete anomalies are cancelled in by several different axion-like fields, so there are no generic constraints.\cite{14}

In addition, we have seen that, if field theoretic unification arises within the framework of string theory, the GUT scale is likely to be a modulus. This has implications for cosmology.

3 Predicting Low Energy Supersymmetry?

It is often said that supersymmetry is an integral part of string theory, as if this somehow implies that low energy supersymmetry is a feature of the theory. But supersymmetry is a gauge symmetry. Just as for ordinary bosonic symmetries, if supersymmetry is badly broken, there is no low energy remnant. How might we argue that low energy supersymmetry is a prediction of string theory?

Clearly we should first ask: what would it mean to predict low energy supersymmetry in string theory? In practice, what we have all understood by this, and what I will understand in what follows, is that the ground state of string theory which describes the world we observe lies on an approximate $N = 1$ supersymmetric moduli space. More precisely, it lives on a moduli space which has the property that in various asymptotic regions, the theory becomes four dimensional with approximate $N = 1$ supersymmetry. For example, for the heterotic string on a Calabi-Yau manifold, the region where the dilaton is large, with other moduli fixed, is an example; for the strongly coupled theory, one must take a different limit. In both cases, the potential energy is generically non-zero throughout the moduli space, but tends to zero in this limit. This hypothesis is consistent with experimental facts: the gauge couplings, for example, are small (corresponding to a large value of the dilaton, perhaps) and there is a large hierarchy, presumably related to some quantity like $e^{-8\pi^2 g s^2}$.
One of the most difficult aspects of string phenomenology lies in understanding the smallness of the gauge coupling and the large size of the hierarchy. String theory does not possess a small parameter, in the sense of a quantity which can be taken arbitrarily small. So it would seem that, if the theory describes nature, it must be strongly coupled. Various scenarios for understanding how a theory which is strongly coupled might yet produce a small gauge coupling, or how the theory might ultimately be weakly coupled, have been put forward. To date, no complete string implementation of any of these has been exhibited (several models of these phenomena were discussed in the parallel sessions). [15]

One might even have wondered whether it made sense to speak of such approximate moduli spaces. Indeed, it has always been distressing that one can give arguments that moduli spaces of string vacua with more than four supersymmetries exist, not only perturbatively but non-perturbatively as well, whereas states with less supersymmetry hold a more questionable status. Most of the recent progress in string theory has been based on the study of states with a high degree of supersymmetry, and, incidentally has provided further evidence that such states exist and make sense. But the developments in duality have also provided evidence that moduli spaces with approximate N=1 supersymmetry exist.

Much less is known about approximate moduli spaces without supersymmetry. In weak coupling, they often exhibit pathologies. Typically there are tachyons in some region of the moduli space. They are also often subject to catastrophic instabilities. [16]

Apart from simply “solving” the theory, one might imagine arguing that supersymmetric approximate moduli spaces – and local minima which might sometimes appear in them – enjoy some special status. In this way one might argue that low energy supersymmetry is an outcome of string theory.

In order to accomplish this, one must argue that moduli spaces with more supersymmetry are, despite their apparent consistency, irrelevant to describing what we see in nature. Such an argument might involve the connectivity of the moduli space; more likely, it will involve cosmological considerations. These might be connected with some of the deep issues which have been raised recently concerning the number of states in De Sitter space, or they might be associated with some very weak anthropic considerations. One might hope to argue that non-supersymmetric moduli spaces are somehow inconsistent, or perhaps disconnected from the supersymmetric ones.

This program also requires that non-supersymmetric moduli spaces are somehow inconsistent. We have alluded to some evidence above. The
tachyon problem, naively, seems quite serious. For example, in weakly coupled, closed string theories, even if there is a minimum for the tachyon potential, for fixed string coupling, the energy of this minimum (the value of the dilaton potential) will behave, parameterically, as

$$V = -\frac{1}{g^2} M^4$$

for some mass scale $M$. So it would appear that the energy is unbounded below. However, the situation is not so clear. We do not know how to describe these systems as Hamiltonian systems. So it is best to examine their behavior in a cosmological setting. The full set of dynamical equations are best studied by first integrating out the tachyon, then performing a Weyl rescaling of the fields to the Einstein frame. In this way, one sees that the system is simply driven to strong coupling, where one loses control of any analysis, so it is difficult to give a decisive argument that tachyons in a moduli space are problematic. The problem of catastrophic vacuum decay first arose many years ago in work of Witten, and has been the subject of more recent analyses. Still another possibility is to look for non-perturbative inconsistencies. Michael Graesser and I have spent some time looking for anomalies in discrete symmetries. Because discrete symmetries are believed to be gauge symmetries in string theory, such anomalies would signal inconsistencies. Previous searches have been limited to supersymmetric models. There is no simple argument that such anomalies cannot arise in non-supersymmetric theories. We have examined a variety of models, including asymmetric orbifolds and various brane constructions. So far, however, this search has not yielded any positive results.

So, while there is some evidence that generic non-supersymmetric string theories suffer from a variety of difficulties, we don’t have a solid, compelling argument that non-supersymmetric theories do not make sense. I have not given up on the possibility that other sorts of anomalies might lurk in the non-supersymmetric (approximate) moduli spaces. It would be a triumph if string theory were to successfully predict (or not) low energy supersymmetry before its discovery (or not). If we fail to make such a prediction, the discovery of supersymmetry (or not) should give us significant insight into the theory.

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2This point was mentioned to me a few years ago by L. Susskind.

3If it happens that the tachyon potential is only stabilized quantum mechanically, then the system is driven to ever lower energy at weak coupling. In some cases, however, one can show that the tachyon is stabilized classically.
4 String Theory in a Supersymmetric World

If supersymmetry is discovered, whether or not string theory has succeeded in predicting it, we will enter a very exciting era. It is often said that string theory requires a Planck scale accelerator, and that this is impossible. But in most conjectures for supersymmetry breaking, the 105 or more soft breaking parameters are related to Planck scale physics. So there is potentially a huge amount of information accessible to TeV scale accelerators.

4.1 Generalities about Supersymmetry Breaking

At first sight, sorting this out may seem a daunting task, no easier than understanding the quark and lepton masses. But we expect that the squark and slepton mass spectrum will exhibit striking regularities, to account for the absence of flavor-changing processes. Most proposals to understand approximate flavor conservation involve a high degree of degeneracy or alignment among the squarks and sleptons.

Only a few proposals have been put forward through the years to understand degeneracy. This could, of course, be due to our lack of inventiveness. But it is interesting to review them and ask how they might fit into string theory.

- Dilaton domination: If the dilaton $F$-term dominates susy breaking, this gives a degenerate spectrum classically,\cite{20} with degeneracy (optimistically) of order $\frac{\alpha_{\text{gut}}}{\pi}$. This is the only proposed realization of “gravity mediation” in string theory. One difficulty with this idea is that it requires that a weak coupling approximation be valid for the Kahler potential, which is difficult to understand.

- Gaugino domination: If the gaugino masses are much larger than scalar masses at the high scale, then one obtains approximate degeneracy through renormalization group evolution.

- Brane World Susy Breaking (Anomaly Mediation,\cite{22} Gaugino Mediation\cite{23}). These hypotheses give a predictive form for spectrum with a high degree of degeneracy.

- Non-abelian flavor symmetries: These give degeneracy, correlations between soft breakings, quark and lepton masses and mixings.
• Gauge mediation predicts a high degree of degeneracy between squarks, sleptons with same gauge quantum numbers. More detailed predictions are possible if the dynamics of supersymmetry breaking are known.

How might these emerge as predictions from string theory, or what might they tell us about string theory? Might any of these have a generic quality, e.g. true of a large set of string states? We have indicated how dilaton domination might arise. Discrete symmetries, both abelian and non-abelian, are common in string theory. As we will see later, gauge mediation is a natural possibility to consider in string theory, and might be a plausible outcome of one solution of the moduli problem. I am not aware of any compelling picture of how gaugino domination might arise in a generic way. In the next subsection, we will explain why one item in this list, anomaly mediation (and gaugino mediation) does not seem to arise in string theory in any generic sense.

4.2 Almost a prediction (“unprediction”?)

The basic idea of brane world susy breaking is to suppose that the standard model localized on a brane, while susy is broken on another brane. Locality, it is argued, strongly constrains the interactions between the fields on different branes, and the form of supersymmetry breaking. This leads to vanishing scalar masses at low order, the leading contributions being certain “anomaly mediated” ones. Alternatively, if there are bulk gauge fields, the leading contributions come from the interactions of these fields.

More precisely, crucial to anomaly mediated supersymmetry breaking is the assumption that the Kahler potential takes a particular form, which has been dubbed “sequestered.” This form would seem to follow from higher dimensional locality. Because the hypothesis does not make reference to the strength of the coupling, this is a question which one can study in a variety of string and M theory setups in controlled approximations. In all of these cases, one finds that the Kahler potential does not have the sequestered form. As a result, there are typically tree level masses, so the anomalous and/or gaugino contributions do not dominate. In fact, one has problems with flavor changing currents unless there are additional flavor symmetries. So anomaly mediation is not generic to string theory.

This is not to say that anomaly mediation could not emerge in string theory. A plausible argument has been given that the required sequestered Kahler potential might arise in special cases.
While we have shown how one might rule out one possible form of supersymmetry breaking, and suggested how others might arise from string theory, we are clearly a way from making a definitive prediction. But I believe this discussion suggests that there is some real hope. These different possibilities make distinct and in some cases very dramatic predictions for accelerators.

Apart from making predictions, these sorts of ideas suggest how data we can expect over the next decade could provide important information about string theory. Imagine that supersymmetry has been discovered, and that we know something about the spectrum. If the spectrum is gauge-mediated, this would suggest possible mechanisms for fixing the moduli. If it is like gravity mediation, but with percentish deviations and dramatic flavor violation, this would be suggestive of dilaton dominance.

5 The Cosmological Moduli Problem, The Strong CP Problem And Other Issues

The cosmological moduli problem is usually described by saying that, in string theory (in this section, we will take low energy supersymmetry as a given), one might expect moduli to have a potential of the form:

$$V = m_{3/2}^2 M^2 f\left(\frac{\phi}{M}\right).$$ (8)

Here $M$ is typically thought of as the Planck scale (within an order of magnitude or two). The field $\phi$ then has a mass of order $m_{3/2}$, and starts to oscillate when $H \sim m_{3/2}$. At this time, this field carries a fraction of order 1 of the energy density. Even if there is radiation at this time, $\phi$ quickly comes to dominate the energy density of the universe. The lifetime of $\phi$ is expected to be long, of order

$$\Gamma = \frac{1}{2\pi} \frac{m_{3/2}^3}{M^2}$$ (9)

or smaller.

This is a long time after conventional nucleosynthesis. The decays of the moduli lead to some reheating: $T_R^4 = \Gamma^2 M^2$. For $m_{3/2} \approx 1$ TeV, this gives a reheating temperature of order 10 KeV. Restarting nucleosynthesis requires 10 MeV, which requires that the mass of the modulus be of order 100 TeV.
This is troubling from the perspective of fine tuning. But even if we accept this, there is another difficulty. In most discussions of the moduli multiplet, one speaks as if there is one scalar. But, of course, there are two. In general, one of these is an “axion.” The defining property of this field, in many cases, is that it is periodic. We can take this period, with some suitable normalization of the field, to be $2\pi$. In most pictures of supersymmetry breaking in string theory, this field is light. Most focus on supersymmetry breaking is on the superpotential. Holomorphy plus $2\pi$ periodicity strongly restrict the form of the moduli superpotential:

$$W = e^{-aM} + e^{-bM} + \ldots$$

(10)

for some constants $a$ and $b$. So the full, supergravity potential will be of order $e^{-2aM}$, but the leading terms which violate the Peccei-Quinn symmetry will be suppressed by a further exponential, $e^{-(b-a)M}$. This means that the axion in any given multiplet is light compared to the scalar. Yet this axion suffers from the same alignment problems as the scalar. If it is to give sufficient reheating, the scale of supersymmetry breaking must be very large.

To be more quantitative, there are several models for stabilization of moduli in string theory. One of these, which has been mentioned in several talks at this meeting, is known as Kahler stabilization. This assumes that $W$ is given by some weak coupling form, but order one corrections to the Kahler potential are responsible for stabilization of the moduli. For example, if gaugino condensation is the origin of $W$,

$$m_{3/2} = e^{-3S/b_0}M$$

(11)

giving $e^{-S/b_0} = 10^{-5}$. Corrections to $W$ from, e.g.,

$$< W^2 \alpha W^2 \beta > \sim e^{-6S/b_0}$$

(12)

give an axion mass seven orders of magnitude smaller than the scalar mass (10 KeV?). This is enough to cause cosmological troubles, and far too large to be the QCD axion.

This problem would be solved if there were big corrections to the Kahler potential which broke the symmetry, e.g.

$$\delta K = e^{-(M-M^\dagger)} f(M + M^\dagger)$$

(13)

(these respect the discrete shift symmetry, but badly violate the PQ symmetry). But if such corrections exist in string theory, it will not be possible for
such axions to solve the strong CP problem. One can consider many variations on this. E.g. discrete symmetries could suppress the PQ-violating terms in the superpotential, and the Kahler potential corrections might be small, allowing a small mass.

More generally, this discussion raises questions about the strong CP problem in string theory – and generally within supersymmetric theories. E.g. it is usually said that there is an upper limit on the axion decay constant of about $10^{11}$ GeV. This assumes that the universe is radiation dominated, for example, at the time of the QCD phase transition. But supersymmetry alone implies that the axion is accompanied by a scalar modulus. For a decay constant of order $10^{15}$ GeV, for example, the cosmological problems associated with the saxion are far more serious than those associated with the axion. Any sensible cosmology must address these, before claiming any limit on the axion. Results depend on model and cosmological assumptions, but rather generally the limits on the axion decay constant are significantly relaxed by these considerations. $10^{15}$ GeV seems a rather robust upper limit.

6 A Unified Picture

In focusing on the sorts of general questions I have discussed here, we can all develop our own speculations on what sorts of predictions we might hope to extract from string theory. I would propose one outline of a generic string phenomenology. No piece of this can be viewed as firmly established, but I hope I have indicated how such a picture might reliably emerge, using tools we already have at hand:

- Low energy supersymmetry
- No very light ($= m_{\text{susy}}$) moduli (uncharged under symmetries; there may be charged moduli).
- One light ($m_{\text{susy}} \ll m \ll M$) modulus, determines the value of the gauge couplings (one for unification). Its value might be determined as in racetrack models.
- Because there are no light neutral fields, susy breaking arises through gauge mediation at low energies.

Such a picture would be highly predictive, but by itself it would not predict everything we might ultimately want to know. For example, the soft
breaking spectrum would probably depend on a small number of unknown parameters. But this picture would have other interesting features:

- No cosmological moduli problem
- No axion to solve the strong CP problem. But in gauge mediation, it is not difficult to solve strong CP problem through, e.g., the Nelson-Barr mechanism.\[31, 32\]
- More speculatively: such a picture might be compatible with ideas of Banks to understand the cosmological constant and supersymmetry breaking in de Sitter space.\[33\]

I think this is a picture which might be correct and which we might establish in string theory. I am optimistic that investigations of the sort I have outlined here will teach us lessons about the theory, even if my own prejudices are incorrect. I encourage you to explore this and other points of view.

References

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