Phenomenological survey of free fermionic models

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Introduction

The standard model of particle physics passes all experimental observations with flying colors. The gauge charges of the standard model matter states are strongly suggestive of the embedding of the standard model in larger grand unified groups. This is particularly striking in the context of $SO(10)$ grand unification in which each of the standard model matter generation is embedded in a single 16 spinorial representation of $SO(10)$. We recall that the standard model gauge charges were experimentally discovered and therefore are experimental observables. To account for these charges in the framework of the standard model requires $3 \times 3 \times 6 = 54$ distinct parameters, taking into account the three group factors, the three generations and the six multiplets (including the right–handed neutrino) within each generation. The embedding of the standard model reduces this number to one, being the number of spinorial representations needed to accommodate the three generations of the standard model, namely three. The evidence for the realisation of grand unification structures in nature is therefore striking indeed.

The standard model and grand unification in themselves cannot, however, be the end of the story. The first apparent question that pops to mind is how three generations came to be and not two, four or five. Next, there are the various mass and flavor mixing parameters of the standard model. The origin of these parameters is not explained in the context of the standard model, nor in grand unified theories.

It is plausible therefore that to seek answers to these questions one must explore the origins of the Standard Model at a more basic level. In modern parlance this means at an energy scale, which is above the the GUT energy scale, *i.e.* the Planck scale, where the strength of the gravitational interaction is comparable to that of the gauge interactions. We are lead to this conclusion by the structure of the standard model itself.

String theory provide a self consistent framework for the synthesis of quantum mechanics and gravity. It is a natural extension of point quantum field theories. It admits a quantised particle interpretation, which in is a highly non–trivial result. Furthermore, the internal particle attributes, which in point particle gauge theories are ad hoc, arise in string theory from the internal consistency conditions. We can interpret these internal degrees of freedom as extra space time dimensions. The important feature of string theory is precisely in that while providing a consistent approach to quantum gravity it gives rise to the gauge and matter structures that are used in contemporary quantum field theories and the standard model. This enables the development of a phenomenological approach to quantum gravity by constructing string models that aim to reproduce the standard model and in turn can be used to explore the dynamics of string theory and its fundamental properties from a phenomenological point of view.

The five ten dimensional string theories, as well as eleven supergravity are believed to be limits of a more fundamental theory. Any one of this limits can be used to construct phenomenological string models. As limits of a more fundamental theory we should not expect any of the limits to provide a complete description of the true vacuum but merely to probe some of its properties. As the standard model data favor its embedding in $SO(10)$, the two pivotal requirements from a phenomenological string vacuum is the existence of three generations and their embedding into $SO(10)$ multiplets. The perturbative string limit that facilitates the embedding in $SO(10)$ is the heterotic–string as it is the limit that produces spinorial representations in the perturbative spectrum. Thus, to preserve these two key properties of the standard model spectrum the perturbative string limit that should be used is the heterotic string. It is likely that to obtain insight into other properties of the true vacuum other limits other perturbative string limits should be used. For example, the dilaton exhibits a run away behaviour in the perturbative heterotic limit and its stabilisation requires moving away from that limit.

The study of phenomenological string vacua proceeds with the compactification of the heterotic–string from ten to four dimensions. A class string compactifications that preserve the $SO(10)$ embedding of the Standard Model spectrum are those that are based on the $Z_2 \times Z_2$ orbifold and have been extensively studied by utilizing the so–called free fermionic formulation [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13].

There are of course a large number of requirements that a realistic string vacuum should satisfy. Here I list a few of these requirements:

- $\longrightarrow \quad SU(3) \times SU(2) \times U(1)^n \times hidden$
- Three generations
- Proton stable $\qquad (\tau_{\rm P} > 10^{30}$ years)
- Higgs doublets $\oplus$ potentially realistic Yukawa couplings

- N=1 SUSY (N=0)
- Agreement with $\underline{\sin^2\theta_W}$ and $\underline{\alpha_s}$ at M_Z (+ other observables).
- Light left–handed neutrinos
- $SU(2)\times U(1)$ breaking
  SUSY breaking
  No flavor changing neutral currents
  No strong CP violation
  Exist family mixing and weak CP violation
- + ...
- + **GRAVITY**

The fermionic formulation was developed in the mid–eighties [14]. Just like the point particle time parameter spans a world–line, the string time and internal parameters span the two dimensional string world–sheet conformal field theory. The equivalence of bosons and fermions of a two dimensional conformal field theory entails that a model constructed using the fermionic approach correspond to a model constructed using the bosonic approach in which the target–space is compactified on a six dimensional internal manifold. In this vein the free fermionic formalism correspond to using a free bosonic formalism in which the radii of the internal dimensions are fixed at a special point in the compact space. Deformation from the special point in the moduli space are parametrized in terms of world–sheet Thirring interactions among the world–sheet fermions. This equivalence is merely the simplest illustration of the relation between world–sheet rational conformal field theories and manifolds with $SU(n)$ holonomy [15]. The simplicity of the free fermionic formalism entails that the string consistency constraints are solved in terms of the world–sheet free fermion transformation properties on the string world–sheet, which are encoded in sets of basis vectors and one–loop GSO projection coefficients among the basis vectors. The formalism to extract the physical spectrum and superpotential interaction terms are also straightforward. The simplest free fermionic constructions correspond to a $Z_2\times Z_2$ orbifold of a six dimensional toroidal manifold, augmented with discrete Wilson lines that are needed to break the $SO(10)$ GUT symmetry. The quasi–realistic free fermionic heterotic–string standard–like models were constructed in the late eighties and early nineties. They provide a concrete framework to study many of the issue that pertain to the phenomenology of the Standard Model and string unification. A few highlights of these studies are listed below:

- Top quark mass ∼ 175–180GeV [6, 16]
- Generation mass hierarchy [17]
- CKM mixing [18]

- Stringy seesaw mechanism [19, 20]
- Gauge coupling unification [21, 22]
- Proton stability [23]
- Squark degeneracy [24]
- Minimal Standard Heterotic String Model (MSHSM) [10]
- Moduli fixing [25]
- Classification & spinor–vector duality [26]

Perhaps, the most tantalising achievement is the successful calculation of the top quark mass, which was obtained several years prior to the experimental discovery, and in the correct mass range. This calculation demonstrated how string theory enables the calculation of the fermion–scalar Yukawa couplings in terms of the unified gauge coupling. Furthermore, the string models offered an explanation for the hierarchical mass splitting between the top and bottom quarks. The top quark Yukawa coupling is obtained at the cubic level of the superpotential and is of order one, whereas the Yukawa couplings of the lighter quarks and leptons are obtained from nonrenormalizable operators that are suppressed relative to the leading cubic level term. Thus, only the top quark mass is characterised by the electroweak scale and the masses of the lighter quarks and leptons are naturally suppressed compared to it. As the heavy generation Yukawa couplings are obtained at low orders in the superpotential, the calculation of these Yukawa couplings is robust and is common to a large class of models. The analysis of fermion masses was then further pursued, and quasi–realistic fermion mass textures were shown to arise for reasonable choices of supersymmetric flat directions. Issues like left–handed neutrino masses, gauge coupling unification, proton stability and squark degeneracy were studied in concrete quasi–realistic free fermionic string models and for detailed solutions of the supersymmetric flat direction constraints. While an attempt to find a single solution that satisfies all the variety of phenomenological requirements listed above was not pursued, it was demonstrated that all of the above requirements can find satisfactory solutions in the context of the free fermionic string models. It was also demonstrated in ref. [10] that the free fermionic heterotic string vacua give rise to models that produce in the observable charged sector below the string unification scale solely the matter spectrum of the minimal supersymmetric standard model. Such models are dubbed Minimal Standard Heterotic String Models (MSHSM). The free fermionic models also provide important clues to the problem of moduli fixing in string theory. They highlight the fact that string theory may utilize geometrical structures that do not have a classical correspondence. Primarily, they allow boundary conditions that distinguish between the left– and right–moving coordinates of the six dimensional compactified space. Such boundary conditions necessarily lead to the projection of the moduli fields associated with the extra internal coordinates. The free fermionic models have also been instrumental in recent years to unravel a new duality symmetry under the exchange of spinor and vector representations of the GUT group.

String theory predicts that the number of degrees of freedom giving rise to the gauge symmetries of the standard model should be augmented by a specific number of additional degrees of freedom. An naive interpretation of some of those is as extra space–time dimensions. These additional degrees of freedom may be out of reach of contemporary experiments, and the development of phenomenological string models aims at bridging the gap. String models give rise to additional symmetries and matter sectors that do not arise in grand unified theories. These include: gauge symmetries that are external to the GUT symmetries and may play a pivotal role in explaining proton stability [27]; matter states that arise due to the breaking of non–Abelian gauge symmetries by Wilson lines, which gives rise to matter states that do not obey the GUT charge quantisation, and may lead to stable string relics [28]; specific soft SUSY breaking patterns and consequently specific predictions for the superpartners mass spectrum [24, 29]. While all of these will be parametrised in terms of point quantum field theory parameters, their experimental observations will provide further evidence for the validity of string theory and specific string compactifications with which they are compatible. The final step in this program is to seek the all elusive dynamical mechanism, based on first principles, that singles out the string vacuum. The free fermionic models, and the association of the free fermionic point in the moduli space with the self–dual point under T–duality, suggests that self–duality play a vital role in this selection principle [30].

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