STRING PHENOMENOLOGY *

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Abstract

Following Dyson’s analogy between the quantum field theory and the 19th-century chemistry—both explain how but not why—one could also establish an analogy between atomic physics and string theory. Atomic physics was needed to answer the question why in chemistry, string theory is trying to answer the question why in the standard model. This attempt is very briefly reviewed in this talk. After discussing the phenomenological aspects of string theory, the study of soft terms is emphasized as a possible connection between theory and experiment. Special attention is paid to the issues of flavor changing neutral currents, loop effects, charge and color breaking minima, and M–theory versus weakly coupled string theory.

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1 Introduction

Dyson, in an entertaining article written in 1953 [1], drew the following analogy between the quantum field theory and the 19th–century chemistry: "The latter described the properties of the chemical elements and their interactions. How the elements behave; it did not try to explain why a particular set of elements, each with its particular properties, exists. To answer the question why, completely new sciences were needed: atomic and nuclear physics. (...) The quantum field theory treats elementary particles just as 19th–century chemists treated the elements. The theory is in its nature descriptive and not explanatory. It starts from the existence of a specified list of elementary particles, with specified masses, spins, charges and specified interactions with one another. All these data are put into the theory at the beginning. The purpose of the theory is simply to deduce from this information what will happen if particle \( A \) is fired at particle \( B \) with a given velocity. We are not yet sure whether the theory will be able to fulfill even this modest purpose completely. Many technical difficulties have still to be overcome. One of the difficulties is that we do not yet have the complete list of elementary particles. Nevertheless the successes of the theory in describing experimental results have been striking. It seems likely that the theory in something like its present form will describe accurately a very wide range of possible experiments. This is the most that we would wish to claim for it".

Now, in 1998, we do have the complete list of elementary particles (at least at energies below the electroweak scale, and given some caveats related with the Higgs sector)–the proton, pion meson, etc. which appeared in the chart of fundamental particles in Dyson’s presentation should be regarded as an amusing historical anecdote–and we do know that the theory fulfilling the modest purpose mentioned by Dyson is the standard model. What the 19th–century chemistry did with the chemical elements, the 20th–century standard model does with the elementary particles. It describes how the elementary particles behave but does not try to explain why a particular set of elementary particles, each with its particular properties, exists. To answer the question why it seems that new sciences are not needed, as atomic and nuclear physics in the case of chemistry, but just new theories. This is the precisely the purpose of the string theory.

2 String Phenomenology

In string theory the elementary particles are not point–like objects but extended, string–like objects. It is surprising that this apparently small change may allow us to answer fundamental questions that in the context of the quantum field theory of point–like particles cannot even be posed: why do we live in four dimensions?, why is the gauge group \( SU(3) \times SU(2) \times U(1) \)?, why are there three families of particles?, why is the pattern of quark and lepton masses so strange?, why is the fine structure constant given by \( \alpha = 1/137 \)?, etc. For example, with respect to the last two questions, let us remark that in string theory there are no free parameters, all coupling constants are in fact no constants but fields. In particular the measured experimental
values of the gauge coupling constants and Yukawa couplings correspond to the vacuum expectation values (VEVs) of those fields. The gauge singlet field $S$, called dilaton, determines the gauge couplings whereas the gauge singlet fields $T_i$, called moduli, determine the Yukawa couplings. These fields are generically present in four–dimensional models: the dilaton arises from the gravitational sector of the theory and the moduli parametrize the size and shape of the compactified variety (let us recall that string theory can only be quantized in ten dimensions). Although the most phenomenologically promising string theory, the heterotic string, has a gauge group $E_8 \times E_8$ in ten dimensions, there exist different methods to build standard–like models (i.e. gauge group $SU(3) \times SU(2) \times U(1)$ with three families) in four dimensions: orbifolds, Calabi–Yau spaces, fermionic strings, covariant lattices, Gepner models, etc. In spite of these achievements it is fair to say that the standard model has not been obtained yet. In this sense the problem of string theory is that it is too ambitious: the correct model must reproduce not only the gauge group and families of the standard model but also the correct values of the gauge coupling constants, the correct mass hierarchy for quark and leptons, a realistic Kobayashi–Maskawa matrix, etc., i.e. the nineteen parameters fixed by the experiment in the standard model. In order to reach such a goal thousands of models (vacua) can be built due to the fact that there are many consistent ways to compactify the extra dimensions. Many models have a number of families different from three, no appropriate gauge groups, no appropriate matter, etc., but others have the gauge group of the standard model or grand unified gauge groups, and three families of particles. Then, using the experimental results available (e.g. fermion masses or mixing angles), to discard most of the models in order to obtain the standard model is possible in principle. Unfortunately, the model space is so huge that this type of analysis is very cumbersome in practice. Another possibility is to select the correct model (vacuum) using some (unknown for the moment) dynamical mechanism. In this sense duality symmetries may help to solve the problem. The five consistent string theories, type I with gauge symmetry $SO(32)$, heterotics with gauge symmetries $E_8 \times E_8$ or $SO(32)$, type IIA and type IIB, are in fact connected by dualities and may be the thousands of vacua of these theories are also connected. Thus due to these connections some mechanism could select one point in the huge model space. Besides, it has recently been proposed that the five string theories can be derived from a single theory, called M–theory. This might be the underlying fundamental theory of elementary particles. For example, the strong coupling limit of the ten–dimensional $E_8 \times E_8$ heterotic string may be obtained compactifying the eleven–dimensional M–theory on an orbifold. The resulting theory, unlike the weakly coupled heterotic string, provides an attractive framework for the unification of couplings. Although the quantum version of M–theory is yet to be built, some properties are already known. It is related with membranes and its low–energy limit is eleven–dimensional supergravity (SUGRA).
3 "Soft" Phenomenology

We saw in the previous section that to obtain a connection between theory and experiment (i.e. the standard model) in strings is possible in principle but difficult in practice. Here we will discuss a possible way--out to this problem. If Nature is supersymmetric (SUSY) at the weak scale, as many particle physicists believe, eventually the spectrum of SUSY particles will be measured providing us with a possible connection with the superhigh--energy world of string theory. The point is that the SUSY spectrum is determined by the soft SUSY--breaking parameters which can be computed in principle in the context of (super)string models. To compare then the superstring theory predictions about soft terms with the experimentally observed SUSY spectrum would allow us to test the goodness of this theory. This is the path, followed in the last years by several groups, that I will try to review very briefly in this sect. I will concentrate in subsect. 3.1 on weakly coupled heterotic string models leaving the discussion of strongly coupled strings (from M--theory) for subsect. 3.2.

3.1 From Superstrings

As is well known the soft parameters, scalar masses $m_\alpha$, gaugino masses $M_a$, trilinear $A_{\alpha\beta\gamma}$ and bilinear $B_{\alpha\beta}$ coefficients, can be computed in generic hidden sector SUGRA models [6]. They depend on the three functions, which determine the full N=1 SUGRA Lagrangian: the Kähler potential $K$, the superpotential $W$, and the gauge kinetic function $f$. However one can think of many possible SUGRA models (with different $K$, $W$ and $f$) leading to different results for the soft terms. This arbitrariness can be ameliorated in SUGRA models deriving from superstring theory, where $K$, $f$, and the hidden sector are more constrained. They have a natural hidden sector built--in: the dilaton field $S$ and the moduli fields $T_i$. The associated effective SUGRA Kähler potentials, at the superstring tree level, are of the type:

$$K = -\ln(S + \overline{S}) + \hat{K}(T_i, \overline{T_i}) + \hat{K}_{\alpha\beta}C^\alpha \overline{C^\beta} + \frac{1}{4}\hat{K}_{\alpha\beta\gamma\delta}C^\alpha \overline{C^\beta}C^\gamma \overline{C^\delta} + \frac{1}{2}Z_{\alpha\beta}C^\alpha C^\beta + \frac{1}{2}Z_{\alpha\beta\gamma}C^\alpha C^\beta \overline{C^\gamma} + \frac{1}{6}Z_{\alpha\beta\gamma\delta}C^\alpha C^\beta C^\gamma \overline{C^\delta} + h.c. + ... \quad (1)$$

where the coefficient functions depend upon $T_i$, $\overline{T_i}$ and the ellipsis denote the terms which are irrelevant for the present calculation. The first piece is the usual term corresponding to the complex dilaton $S$ that is present for any compactification. The second piece is the Kähler potential of the moduli fields, which in general depends on the compactification scheme and can be a complicated function. For the moment we leave it generic, but in the following we will analyze some specific classes of superstring models where it has been computed. The same comment applies to the coefficient functions $\hat{K}_{\alpha\beta\gamma}(T_i, \overline{T_i})$, $Z_{\alpha\beta}(T_i, \overline{T_i})$, etc. Finally, for any four–dimensional superstring the tree–level gauge kinetic function is independent of the moduli sector and is simply given by

$$f_a = k_a S \ , \quad (2)$$

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where $k_a$ is the Kac–Moody level of the gauge factor. On the other hand, the superpotential $W$ is more involved since it is related with the mechanism of SUSY breaking. For example, non–perturbative gaugino condensation is an interesting mechanism giving rise to an effective superpotential $W(S, T_i)$ which breaks SUSY at the same time that $S$ and $T_i$ acquire reasonable VEVs. The structure of soft parameters can be analyzed and in particular, at low–energies, squarks are almost degenerate with sleptons and much heavier than gluinos [7]. However, one should be cautious about this result due to the fact that the cosmological constant generated by this mechanism is non–vanishing.

On the other hand, without specifying the SUSY–breaking mechanism, just assuming that the auxiliary fields of $S$ and $T_i$, $F^S$ and $F^i$ respectively, are the seed of supersymmetry breaking, still interesting predictions for this simple class of models can be obtained [6]. This is the approach that we will discuss here.

Let us focus first on the very interesting limit where the dilaton $S$ is the source of all the SUSY breaking. At superstring tree level the dilaton couples in a universal manner to all particles and therefore, this limit is compactification independent. In particular, since $\tilde{K}_{\alpha \beta}(T_i, \bar{T_i})$ in (1) is independent on $S$, the soft scalar masses turn out to be universal $m_\alpha = m_{3/2}$. Because of the simplicity of this scenario [1], the predictions about the low–energy spectrum are quite precise [6]. For example, for the first two generations, squarks are almost degenerate with gluinos and much heavier than sleptons.

In general the moduli fields, $T_i$, may also contribute to SUSY breaking, and in that case their effects on soft parameters must also be included. Since different compactification schemes give rise to different expressions for the moduli–dependent part of $K$ [1], the computation of the soft parameters will be model dependent. To illustrate the main features of mixed dilaton/moduli–dominated SUSY breaking, let us concentrate first on the simple situation of diagonal moduli and matter metrics. This is the case of most $(0, 2)$ symmetric Abelian orbifolds which have $\tilde{K}_{\alpha \beta} = \delta_{\alpha \beta} \Pi_i (T_i + \bar{T_i})^{n_i^\alpha}$, where $n_i^\alpha$ are the modular weights of the matter fields $C^\alpha$. Then e.g. the scalar masses are given by:

$$m_\alpha^2 = m_{3/2}^2 + \sum_i \frac{n_i^\alpha}{(T_i + \bar{T_i})^2} |F^i|^2$$

With this information one can analyze the structure of soft parameters and in particular the low–energy spectrum [3]. Although continuous Wilson–line moduli may also contribute to SUSY breaking, the results turn out to be similar [6].

Universality is a desirable property for phenomenological reasons, particularly to avoid flavor changing neutral currents (FCNC). Notice however that the scalar masses [3] show in general a lack of universality due to the modular weight dependence [10]. So, even with diagonal matter metrics, FCNC effects may appear. Of course, the same situation will appear for the few orbifolds, $Z_3$, $Z_4$ and $Z_6'$, where off–diagonal metrics are present in the untwisted sector giving rise to a generic matrix structure for the scalar masses $m_\alpha \bar{\beta}$ [11]. This potential problem seems to be endemic in superstring

\footnotetext[1]{Modifications to this scenario due to the effect of possible superstring non–perturbative corrections to the Kähler potential have also been analyzed [3].}
models [12]. E.g. in Calabi–Yau compactifications off–diagonal metrics is the generic situation and therefore the mass eigenvalues are typically non–degenerate [13].

In fact, this situation may even be aggravated once one includes loop effects. On the one hand, superstring loop effects may spoil the universality in the dilaton–dominated SUSY–breaking limit due to an $S$–dependent contribution in $\tilde{K}_{\alpha\beta}$ [14]. On the other hand, the soft parameters are usually computed at the tree level of SUGRA interactions. However, as has been shown explicitly [15], there can be a significant modification in this procedure due to quadratically divergent SUGRA one–loop effects. In particular, due to the contributions of the pieces depending upon $Z_{\alpha\beta\gamma}$ and $\tilde{K}_{\alpha\beta\gamma\delta}$ in $K$ [1], the scalar masses will have a generic matrix structure with non–degenerate eigenvalues [2]. Let us remark that results from loop effects by SUGRA interactions are valid in general, and therefore can be applied to any superstring theory, and in particular to M–theory.

Nevertheless, we recall that the low–energy running of the scalar masses has to be taken into account. In particular, in the squark case, for gluino masses heavier than (or of the same order as) the scalar masses at the boundary scale, there are large flavour–independent gluino loop contributions which are the dominant source of scalar masses. This situation is very common e.g. in orbifold models. The above effect can therefore help in fulfilling the FCNC constraints [13].

Let us finally recall that another type of constraints arise from demanding the no existence of low–energy charge and color breaking minima deeper than the standard vacuum [17]. These restrictions are in general very strong and in the particular case of the dilaton–dominated scenario the whole parameter space $(m_{3/2}, B, \mu)$ turns out to be excluded on these grounds [18].

### 3.2 From M–Theory

Given the theoretical and phenomenological virtues of M–theory mentioned in sect. 2, it is crucial to examine how the pattern of soft terms changes when one moves from the weakly coupled heterotic string limit to the M–theory limit. For example, higher order corrections to the Kähler potential in the M–theory limit imply a large $S$–dependent contribution in $\tilde{K}_{\alpha\beta}$ [1] [19]. Under the same assumption than in the previous subsect., i.e. that SUSY is spontaneously broken by the auxiliary components of the bulk $S$ and $T_i$ superfields, it has been shown explicitly [20] that there can be a sizable difference between the heterotic string limit and the M–theory limit even in the overall pattern of soft terms. With respect to the issue of FCNC, due to the above mentioned $S$–dependent contribution, there can be a large violation of the scalar mass universality even in the dilaton–dominated scenario. Notice that a similar effect commented in the previous subsect. is expected to be much smaller since it is due to string loops.

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2 It is worth noticing here that in the case of the $\mu$ term these quantum corrections do not only modify the already known contributions from $\tilde{\mu}_{\alpha\beta}$ and $Z_{\alpha\beta}$ in the tree–level matching condition [1] but also provide new sources of the $\mu$ term, naturally of order the weak scale [15]. These sources depend upon the coefficients $Z_{\alpha\beta\gamma}$ and $Z_{\alpha\beta\gamma\delta}$ in $K$ and also possible coefficients $f_{\alpha\beta}$ in $f_a$. 


4 Final comments

Let us hope that the comment about chemists that Dyson wrote in the article mentioned in the introduction—"Looking backward, it is now clear that 19th–century chemists were right to concentrate on the how and to ignore the why. They did not have the tools to begin to discuss intelligently the reasons for the individualities of the elements. They had to spend a hundred years building up a good quantitative descriptive theory before they could go further. And the result of their labors, the classical science of chemistry, was not destroyed or superseded by the later insight that atomic physics gave.”—will also be written by somebody in the next century about 20th–century physicists substituting elements by elementary particles, science of chemistry by standard model and atomic physics by string theory.

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