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Beyond the Standard Model

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BEYOND THE STANDARD MODEL*

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Abstract

The unresolved issues of the standard model are reviewed, with emphasis on the gauge hierarchy problem. A possible mechanism for generating a hierarchy in the context of superstring theory is described.

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INTRODUCTION

As you just heard from the previous speaker, the Standard Model describes observed physics well—in fact so well that we are left with no clue as to how to proceed from here. Expected to lie "beyond the Standard Model" are answers to the many questions that the theory leaves unresolved. I will start by briefly enumerating these.

What is the origin of electroweak symmetry breaking? This is the most immediate question facing us, because we know [1] that some indication of the answer, that is, some manifestation of the (elementary or composite) "Higgs sector" must show up at hard collision energies of a few TeV or less, within reach of currently planned, if not existing, collider facilities. A closely related issue is the infamous gauge hierarchy problem, which will be a central theme of this talk.

What is the origin of CP violation, and what determines fermion mass hierarchies and weak flavor mixing? These questions are connected to the overall issue of electroweak symmetry breaking; in the Standard Model the associated parameters are all determined by the Higgs Yukawa couplings to fermions—that is, by a large number of arbitrary constants. The underlying physics relevant to these questions may be manifest only at energies considerably higher than a TeV, possibly out of reach of any foreseeable accelerator facility. B-physics will play an important role in addressing these issues, at the very least in pinning down accurately the parameters of the Kobayashi-Maskawa matrix. Continued searches for neutrino masses and/or neutrino (and charged lepton) flavor mixing, and for a nonvanishing neutron dipole moment may either turn up clues or severely constrain the viable possiblities.

What is the origin of the particle spectrum itself, and, for that matter, of the gauge group? LEP has now provided a convincing case for the most standard of standard models, namely the three-generation one. New physics that might shed light on these questions surely lies well beyond a TeV. Rare decay searches that provide limits on lepton flavor-changing couplings (relevant to a gauged family symmetry) and on flavor-changing axion emission (relevant to a global family symmetry) can probe such ideas up to scales of 10's to 100 TeV.

Is the observed gauge group unified by a larger, simple group, i.e., a GUT? If so, the measured couplings of the observed group tell us that the scale of the relevant physics is 10^{15} GeV or more, so we must rely only on indirect probes such as proton decay and neutrino masses and oscillations. A very important low energy indicator is the precise value of the weak mixing angle, $sin^2\theta_w$.

Are the observed gauge interactions unified with gravity? If so, the relevant physics lies at the Planck energy scale of about 2×10^{18} GeV, and we don't even know what we might look for as a low energy probe.

"Is there a Theory of Everything?" is a more fashionable way to phrase the last

question. If the answer is positive, the T.O.E. will of course answer all of the above. In spi of meager theoretical progress in making contact with observed physics, superstring theo. [2] is still the prime candidate for a T.O.E.. I will outline one possibility as to how the gau hierarchy may emerge in this context.

THE GAUGE HIERARCHY PROBLEM

The gauge hierarchy problem may be simply expressed in the context of the Standa. Model by writing the renormalized Higgs mass m_H as

$$m_H^2 = \frac{\lambda}{8}(TeV)^2 = m_H^2(\text{tree}) + \frac{g^2}{16\pi^2}\Lambda^2 + \cdots. \qquad ($$

Here g is the weak gauge coupling constant, and λ is the renormalized coupling constant f scalar self-couplings. The right hand side of (1) represents the classical value plus the sum quantum corrections, which are quadratically divergent, as indicated by the appearance of tl cut-off Λ. If perturbation theory makes sense, λ can be no larger than 1 (or at least 4π). Th the first equality suggestes $m_H < (.35\text{–}1.2)\ TeV$, and so we need $\Lambda < (8\text{–}30)\ TeV$. Of cours purely within the context of the renormalizable standard model, there is not really a gau hierarchy problem. The infinite quadratic divergences can be absorbed into a redefiniti of the Higgs mass, whose value is simply fixed by measurement. However if the underlyi theory includes Higgs couplings to heavier particles, such as GUT vector bosons, quantu. corrections will include terms with Λ in (1) replaced by the masses of these particles.

There are three standard "solutions" to the gauge hierarchy problem, which I brief recall. I will list them in what I view as increasing order of plausibility; many people woul disagree with my ordering.

Compositeness. In this scenario, the standard model is an effective theory, some all of whose "elementary" particles are bound states of yet more elementary objects. Tl theory makes sense up to momentum scales of order of the inverse radius of compositene r_c, so

$$\Lambda \to \Lambda_c \sim r_c^{-1} \qquad ($$

in (1). If quarks and leptons are composite, those with common constituents should couple t one another via four-fermion interactions with an effective Fermi constant $G \sim 4\pi r_c^2$. Existin experiments suggest $r_c < (TeV)^{-1}$; recent results from Tristan [3] give more stringent limit with $\Lambda_c > 5\ TeV$ in one channel.

Technicolor. In this case only the Higgs sector is composite. The theory [4] mimi the observed properties of QCD. New asymptotically free gauge interactions are assume which break the electroweak symmetry via a technifermion condensate

$$< \bar{f}^T f^T > \simeq (f_{\pi T})^3 \equiv (\frac{1}{4}TeV)^3. \qquad (3$$

Here f_{π^T} is the strength of the coupling to the axial current of the technipion π^T, analogous to the pion decay constant, f_π. This number is fixed at 250 GeV, so as to correctly reproduce the observed W, Z masses. The scale at which the effective "low energy" theory ceases to be valid is determined by the scale Λ_{TQCD} at which the technigauge interactions become strong:

$$\Lambda \to \Lambda_{TQCD} \sim f_\pi^T \simeq 250\ GeV. \tag{4}$$

As yet, no one has succeeded in constructing an experimentally viable, nor a grand unifiable, model that incorporates this idea.

SUperSYmmetry. In this case [5] the quantum corrections on the right hand side of (1) are damped by cancellations between boson and fermion loops, which are complete if SUSY is unbroken. Since observation tells us that SUSY is certainly broken, the effective cut-off is provided by the fermion-boson mass splitting:

$$\Lambda \to \Lambda_{SUSY} = |m_{fermion} - m_{boson}|. \tag{5}$$

It is possible to construct viable SUSY extensions of the standard model, but the scale parameter (5) is simply put in by hand, so we have not really solved the gauge hierarchy problem in this way.

Before proceeding to a T.O.E., I wish to emphasize that one cannot evade the gauge hierarchy problem by a strongly interacting scalar sector, i.e., by letting $\lambda \gg 1$ in (1). In this case the scalar sector, described classically by the Standard Model Higgs potential

$$\mathcal{L}_{\text{Higgs}} = \frac{\lambda}{4}[(H+v)^2 + \varphi_0^2 + 2\varphi^+\varphi^- - v^2]^2, \quad v = 250\ GeV, \tag{6}$$

becomes a system of strongly interacting Goldstone bosons [6]. At energies $E \ll m_H$, the physical Higgs field H is not excited, and $\varphi^+, \varphi^-, \varphi^0$, which are in fact the longitudinally polarized components W_L^+, W_L^-, Z_L of the weak vector bosons, interact in exactly the same way as the pions π^+, π^-, π^0 of low energy QCD, with the replacement $f_\pi \simeq 125\ MeV \to v \simeq 250\ GeV$. These interactions should be observable [7], with sufficiently high energy and luminosity, such as planned for the SSC, as an excess of W and Z pairs with invariant masses of a TeV or more. Their interactions are described by an effective lagrangian $\mathcal{L}_{eff}$ whose low energy form is dictated by the gobal symmetry of the potential (6), analagous to the chiral symmetry of QCD. Including quantum corrections,

$$\mathcal{L}_{eff} = \frac{1}{2}\partial_\mu\varphi^i\partial^\mu\varphi^j\Big(\delta_{ij} + \frac{\varphi_i\varphi_j}{v^2 - |\varphi|^2}\Big)\Big(1 - \frac{\Lambda^2}{8\pi^2 v^2} + \cdots\Big)$$
$$+ \text{ higher derivative terms } + \text{ resonance effects.} \tag{7}$$

Just as the quadratic divergence in (1) can be absorbed into the definition of the physical Higgs mass, the one in (7) can be absorbed into the definition of the physical (i.e., renormalized) vacuum expectation value $v_R \equiv 250\ GeV$:

$$\mathcal{L}_{eff} = \frac{1}{2}\partial_\mu\varphi_R^i\partial^\mu\varphi_R^j\Big(\delta_{ij} + \frac{\varphi_i^R\varphi_j^R}{v_R^2 - |\varphi_R|^2}\Big) + \cdots,$$
$$\frac{\varphi_R}{\varphi} = \frac{v_R}{v} = \Big(1 - \frac{\Lambda^2}{8\pi^2 v^2} + \cdots\Big)^{\frac{1}{2}}. \tag{8}$$

However once the theory is embedded in a larger theory (as it should be, since a pure scalar field theory is apparently not self-consistent) including large mass scales, one still has to invoke a physical origin for the cut-off, $\Lambda < 3\ TeV$, to understand the "small" observed value of v_R. Technicolor in fact provides an explicit example of a theory with the effective lagrangian (7), and with the cut-off (4). The resonances in (7) are in this case predictable, roughly by scaling observed resonance masses in QCD by the factor v/f_π.

SUSY, GUTS AND SUSY GUTS

There is no direct evidence for supersymmetry in nature. You have heard at this meeting the limits on sparticle masses from the LEP collaborations, and will hear more from CDF. (The CDF collaboration has previously reported squark and gaugino mass limits as high as about 100 GeV, but these entail decay branching ratio assumptions that are apparently not valid in the relevant mass range [8].) Moreover, results from Higgs searches at LEP are closing the window of allowed parameters in the minimal SUSY extension of the Standard Model, with just two $SU(2)_L$ doublets of scalar fields and their fermionic partners. However there is no particular reason—especially within the context of a T.O.E.—to believe that a SUSY extension of the Standard Model should be minimal. If one adds just one chiral supermultiplet (i.e. a complex scalar and a Weyl fermion) that is a singlet under the Standard Model gauge group, the parameters are much less constrained, and one even loses the prediction that the lightest scalar is lighter than the Z.

There is also no direct evidence for a Grand Unified Theory. Limits on the lifetime for nucleon decay to mesons and leptons presumably rule out the minimal [9] $SU(5)$ GUT (with the caveat as to whether the value of the $SU(3)_c$ fine structure constant α_S—or, equivalently, Λ_{QCD}—is sufficiently well established). On the other hand, predictions in the context of SUSY GUTs, or a T.O.E., are highly model dependent.

Do we have indirect evidence for either of these ideas? If the Standard Model gauge interactions are unified at some scale, their values, as determined by the renormalization group equations, should all become equal at a single energy scale [10]. Modulo assumptions about massive gauge nonsinglet particles that can contribute to the R.G.E.'s, coupling constant unification can be checked by comparing the measured value of $sin^2\theta_w$ with the predicted one, with the fine structure constants α and α_S as input. Here I will quote verbatim from

Sirlin's talk at Les Arcs [11]. He gave the value of $sin^2\theta_w$ at the Z mass scale, in the modified minimal subtraction scheme, averaged over the results of UA1, UA2, CDF and LEP, as

$$sin^2\theta_{\overline{MS}}(m_Z) = 0.2327 \pm 0.0012. \tag{9}$$

The comparable value, after appropriate radiative corrections [11], from the CHARM II collaboration is 0.232, with a similar (experimental + theoretical) error. These results apparently [11] differ by a few standard deviations from the Standard Model prediction, but are consistent with the minimal SUSY prediction obtained by Marciano's estimate:

$$sin^2\theta_{\overline{MS}}(m_Z) = 0.237^{+0.003}_{-0.004} - \frac{4}{15}\frac{\alpha}{\pi}\ln\left(\frac{\Lambda_{SUSY}}{m_W}\right). \tag{10}$$

Thus an optimist might conclude that there is indirect evidence for a SUSY GUT. Aside from modern refinements that should be included [11] in the estimate (10), this result could be modified by contributions from nonstandard massive particles, and the conclusions may be subject to the above-mentioned caveat. However, the predictions for $sin^2\theta_w$ are much less sensitive to uncertainties (which are reflected in the quoted theoretical errors) in Λ_{QCD} than are those for the proton lifetime.

T.O.E.: THE HETEROTIC STRING

According to the presently most popular hope for a fully unified theory, the Standard Model is an effective theory that is a low energy limit of the heterotic string [12] theory. Starting from a string theory in 10 dimensions with an $E_8 \times E_8$ gauge group, one ends up, at energies sufficiently below the Planck scale, with a supersymmetric field theory in 4 dimensions [13], with a generally smaller gauge group $\mathcal{H} \times \mathcal{G}$. $\mathcal{H}$ describes a "hidden sector", that has interactions with observed matter of only gravitational strength, and $\mathcal{G} \supset SU(3)_c \times SU(2)_L \times U(1)$ is the gauge group of observed matter. Part of the gauge symmetry may be broken (or additional gauge symmetries may be generated) by the $10 \to 4$ dimensional compactification process itself, and part of it may be broken by the Hosotani mechanism [14], in which gauge flux is trapped around space-tubes in the compact manifold. There are now many more examples of effective theories from superstrings than one once thought could emerge. For illustrative purposes, I will stick to the original "conventional" scenario, in which the "observed" E_8 is broken to E_6, long known to be the largest phenomenologically viable GUT, by the compactification process. Then the observed sector is a supersymmetric Yang-Mills theory, with gauge bosons and gauginos in the adjoint representation of $\mathcal{G} \subset E_6$, coupled to matter, i.e., to quarks, squarks, leptons, sleptons, Higgs, Higgsinos, ...

The hidden sector is assumed to be described by a pure SUSY Yang-Mills theory, $\mathcal{H} \subset E_8$, which is asymptotically free, and therefore infrared enslaved. At some energy scale Λ_c, below the compactification scale Λ_{GUT} at which all the gauge couplings are equal, the hidden gauge multiplets become confined and chiral symmetry is broken, as in QCD, by a

fermion condensate. In this case the fermions are the gauginos of the hidden sector:

$$< \bar{\lambda}\lambda >_{hid} \sim \Lambda_c^3 \neq 0. \tag{11}$$

The condensate (11) breaks SUSY [15], and by itself would generate a positive cosmologic constant. If this were the only source of SUSY breaking, and of a cosmological constan the condensate would be forced dynamically to vanish, due to the condition that the vacuu energy be minimized.

Another source of SUSY breaking is the (quantized) vacuum expectation value of a antisymmetric tensor field H_{LMN}, that is present in 10-dimensional supergravity:

$$H_{LMN} = \nabla_L B_{MN}, \quad L, M, N = 0, \ldots, 9,$$
$$\int dV^{lmn} < H_{lmn} >= 2\pi n \neq 0, \quad l, m, n = 4, \ldots, 9 \tag{12}$$

The *vev* (12) can arise if H-flux is trapped around a 3-dimensional space-hole in the compac 6-dimensional manifold, in a manner analagous to the Hosotani mechanism for breaking th gauge symmetry. When (11) and (12) are both present, λ and H_{LMN} couple in such a wa [16] that the overall contribution to the classical cosmological constant vanishes. There ar other potential sources of SUSY breaking, such as a gravitino condensate [17], that migh play a similar role.

The particle spectrum of the effective four dimensional field theory include the gauge supermultiplets $W^\alpha = (\lambda^\alpha, F^\alpha_{\mu\nu} - i\tilde{F}^\alpha_{\mu\nu})$ (gauginos and gauge bosons) and chir supermultiplets $\Phi^i = (\varphi^i, \chi^i)$ that contain the matter fields (φ^i = squarks, sleptons, Higg particles, ..., χ^i = quarks, ...). In the "conventional" scenario these are all remnants of th gauge supermultiplets in ten dimensions:

$$A_M \to A_\mu + \varphi_m, \quad \mu = 0, \ldots, 3, \quad m = 4, \ldots, 9. \tag{13}$$

Thus for each gauge boson A_M in ten dimensions, there are potentially one gauge boso A_μ and six scalars φ_m (and their superpartners) in four dimensions. However not all these are massless. In the "conventional" picture ($E_8 \to E_6$ in the obseved sector) th massless 4-vectors are in the adjoint of E_6, while the massless scalars are in $(27 + \overline{27})$ that make up the difference: $(\text{adjoint})_{E_8} - (\text{adjoint})_{E_6}$. In addition there are gauge single chiral supermultiplets associated with the structure of the compact manifold. Two of thes $S = (s, \chi^S)$ and $T = (t, \chi^T)$ are of special interest. Their scalar components are [18]

$$s = e^{3\sigma}\phi^{-\frac{3}{4}} + 3i\sqrt{2}D,$$
$$t = e^{\sigma}\phi^{\frac{3}{4}} - i\sqrt{2}a + \frac{1}{2}\sum_i |\varphi^i|^2. \tag{14}$$

In (14) ϕ is the dilaton of ten-dimensional supergravity, D and a are two axions that are remnants of the antisymmetric tensor (12):

$$a \propto \epsilon^{lm} B_{lm}, \quad \partial_\mu D \propto \epsilon_{\mu\nu\rho\tau} \phi^{-\frac{3}{2}} e^{6\sigma} H^{\nu\rho\tau}, \tag{15}$$

and σ is the "breathing mode" or "compacton" whose *vev* determines the size of the compact manifold with metric $g_{lm} = g_{lm}^{(0)} e^{\sigma}$. Thus the GUT—or compactification—scale, which is the inverse of the radius R of compactification, is determined by the *vev* (in Planck mass units)

$$\Lambda_{GUT}^2 = R^{-2} =< e^{-4\sigma} >=< (\mathrm{Re}s\mathrm{Re}t)^{-1} > . \tag{16}$$

The total number of gauge singlet chiral multiplets, as well as the number of matter generations ($\#27$'s $- \#\overline{27}$'s) is determined by the detailed topology of the compact manifold.

The lagrangian of the effective four dimensional field theory, with nonperturbative SUSY breaking included [16] has, in a broad class of models, the following properties at the classical level. The gravitino mass $m_{\tilde{G}}$ can be nonvanishing, so that local supersymmetry is broken. The cosmological constant vanishes, as do the observable gaugino masses $m_{\tilde{g}}$, the gauge nonsinglet scalar masses m_φ, and "A-terms", which are trilinear gauge nonsinglet scalar self-couplings that, if present, would also break SUSY. Thus there is no manifestation of SUSY breaking in the observable sector.

One loop corrections have been evaluated [19] in this effective (nonrenormalizable) theory, which is cut off at the scale of gaugino condensation

$$\Lambda_c = e^{-b_0/2g^2} \Lambda_{GUT} = \left\langle \frac{e^{-b_0 \mathrm{Re}s/2}}{\sqrt{\mathrm{Re}s\mathrm{Re}t}} \right\rangle. \tag{17}$$

The first equality in (17) is just the standard R.G.E. result, where b_0 is a group theory number that determines the β-function of the hidden sector Yang-Mills theory. The second equality follows from (16) and the relation (there are no free parameters in the T.O.E.!) between the *vev* of s and the gauge coupling constant g at the GUT scale:

$$g^2(\Lambda_{GUT}) =< (\mathrm{Re}s)^{-1} > . \tag{18}$$

The result found [19] is that the classical features described above are unchanged at the one loop level.

In fact, the class of 4-d theories considered possesses [20] a classical nonlinear, noncompact global symmetry. They are in fact nonlinear σ-models, much like the effective pion theory of low energy QCD, where chiral $SU(2)$ symmetry is realized via nonlinear transformations among the pion fields. The difference here is that the global symmetry group is

the noncompact group $SU(1,1) \times U(1)$. The group of transformations includes [21] a subset under which

$$t \to a/t, \tag{19}$$

where a is a finite, continuous, real parameter. The string scale M_S is related to the Planck scale M_P by

$$M_P =< (\mathrm{Re}s)^{\frac{1}{2}} > M_S, \tag{20}$$

so when the theory is expressed in string mass units, (19) corresponds to an inversion of the radius of compactification (16):

$$R^2 = \Lambda_{GUT}^{-2} =< \mathrm{Re}s\mathrm{Re}t > /M_P^2 =< \mathrm{Re}t > /M_S^2 \to a/R^2. \tag{21}$$

For the special case of integer a, this is the well known "duality" transformation, which leaves the string spectrum invariant. It has recently been conjectured [21] that this classical $SU(1,1) \times U(1)$ symmetry is responsible for the cancellation of observable SUSY breaking effects, as found [19] by explicit calculation.

ANOMALIES AS THE SEED OF OBSERVABLE SYMMETRY BREAKING

Under the classical $SU(1,1) \times U(1)$ symmetry of the effective low energy theory, the fermions undergo chiral phase transformations:

$$f_L \to e^{i\alpha} f_L, \quad f_R \to e^{-i\alpha} f_R, \tag{22}$$

so at the quantum level the symmetry is broken by the chiral anomaly. In addition, $SU(1,1) \times U(1)$ includes the scale transformation $t \to \eta t$, under which the cut-off for the theory (at energies above the scale of hidden gaugino condensation) scales as

$$\Lambda_{GUT}^2 \propto < (\mathrm{Re}t)^{-1} > \to \eta^{-1} \Lambda_{GUT}^2, \tag{23}$$

so the symmetry is further broken at the quantum level by the conformal anomaly.

The dominant effect of these anomalies arises from the highest mass scale at which nonperturbative effects come into play. In the context of the effective 4-d field theory, these are associated with instantons and gaugino condensation in the hidden Yang-Mills sector. Just as one can construct low energy effective Lagrangians for pseudoscalar mesons that are $q\bar{q}$ bound states using the symmetries of QCD and the chiral and conformal anomaly, one can use [21] $SU(1,1) \times U(1)$ and its anomalies, together with supersymmetry [22], to construct an effective lagrangian for the lightest hidden sector chiral multiplet, denoted $H = (h, \chi^H)$, which is a bound state, with mass m_H, of the hidden gauge supermultiplet. Retaining loop corrections from these additional degrees of freedom, whose couplings explicitly include the

anomalous symmetry beaking, one finds [21,23] that gaugino masses are generated in the observable sector that are of order

$$m_{\tilde{g}} \sim \frac{1}{(16\pi^2 m_P^2)^2} m_{\hat{G}} m_H^2 \Lambda_c^2. \tag{24}$$

The factor $(4\pi)^{-4}$ appears in (24) because the effect arises first at two-loop order in the effective theory, the factor $m_{\hat{G}}$ is the necessary signal of SUSY breaking, the factor m_H^2 is the signal of $SU(1,1) \times U(1)$ breaking, and Λ_c^2 is the effective cut-off. This last factor arises essentially for dimensional reasons: the couplings responsible for transmitting the knowledge of symmetry breaking to the observable sector are nonrenormalizable interactions with dimensionful coupling constants proportional to m_P^{-2}.

Solving [19] the minimization conditions for the effective theory at the one-loop level yields, for vacua with broken supersymmetry, the values

$$m_{\hat{G}} \simeq \frac{1}{3} m_H \simeq \frac{1}{3}\Lambda_c \simeq (10^{-2}\text{–}10^{-1})\frac{m_P}{\sqrt{b_0 c}}, \tag{25}$$

where the parameter c is proportional to the *vev* (12) of H_{LMN}. The quantization condition (12) and dimensional analysis suggest [19] $c > 10^3 n$ if $c \neq 0$, or

$$m_{\tilde{g}} < 10^{-15} m_P \simeq 2\, TeV. \tag{26}$$

Once gauginos acquire masses, gauge nonsinglet scalars (in particular the Higgs particles) will acquire masses $m_\varphi \sim \frac{\alpha}{4\pi} m_{\tilde{g}}$ at the next loop order in the renormalizable gauge interactions.

The superstring context used here is not the most general one, but there is a broad class of models with similar features, so these results suggest that there is hope, after all, of extracting meaningful physics from the superstring T.O.E..

IMPLICATIONS FOR EXPERIMENT?

Unfortunately, there is not at present a single unambiguous prediction for experimentally accessible phenomena from superstrings. Basically, experimenters should continue searching for all the things they are already looking for.

Needless to say the search must continue for Higgs particles and SUSY—if SUSY does play a role in the solution to the gauge hierarchy problem, at least some sparticles must have masses below the TeV scale. There might be additional gauge bosons in the observable group $\mathcal{G}$—although at what masses is an open question.

As always, rare decays (including proton decay!) can provide important probes. For example, in the "conventional" scenario, matter particles are in 27's of E_6, which have the $SU(5)$ decomposition

$$\{27\}_{E_6} = \{(\bar{5}+10) + 1 + 1 + (5+\bar{5})\}_{SU(5)}. \tag{27}$$

The $(\bar{5}+10)$'s contain the matter spectrum of the standard model—quarks and leptons—and their superpartners. The $(5+\bar{5})$'s contain the Higgs particles (and Higgsinos) of the (SUSY) Standard Model, as well as exotic $SU(3)_c$ triplet "leptoquarks" that could induce [24] rare quark- and lepton-flavor changing transitions.

Dark matter searches may turn up clues. The standard candidates, such as SUSY sparticles or axions, can all find a home in models obtained from superstrings. In addition, these models provide new "hidden" matter, which however, if it interacts with our world with only gravitational strength, does not offer much prospect for detection.

Other exotic phenomena like neutrino masses and oscillations could also shed light on the superstring T.O.E., just as they probe very generally physics beyond the standard model.

In spite of the absence of clear-cut predictions from superstring theory, or for that matter from any well motivated extension of the Standard Model, we should not despair. We know—on the basis of simple unitarity arguments [1]—that some manifestion of the Higgs sector, and therefore of the physics governing electroweak symmetry breaking and the generation of a hierarchy of scales, must show up at energies at or below the TeV scale.

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References

1. M. Veltman, *Acta Phys. Pol.* **B8:** 475 (1977); B.W. Lee, C. Quigg and H. Thacker, *Phys. Rev.* **D16:** 1519 (1977); M.S. Chanowitz and M.K. Gaillard, *Phys. Lett.* **142B:** 85 (1984).
2. M. Green and J. Schwarz, *Phys. Lett.* **B149:** 117 (1984).
3. A. Miyamoto, XXVth Rencontres de Moriond, Les Arcs, France, March 4–11 (1990).
4. S. Weinberg, *Phys. Rev.* **D13:** 974 (1976); L. Susskind, *Phys. Rev.* **D16:** 1519 (1977).
5. J. Wess and B. Zumino, *Nucl. Phys.* **B70:** 39 (1974).
6. T.Appelquist and C. Bernard, *Phys. Rev.* **D22:** 200 (1980).
7. M.S. Chanowitz and M.K. Gaillard, *Nucl. Phys.* **B261:** 379 (1985).
8. H. Baer, X. Tata and J. Woodside *Phys. Rev. Lett.* **63:** 352 (1989).

9. H. Georgi and S.L. Glashow, *Phys. Rev. Lett.* **32:** 438 (1974).

10. H. Georgi, H.R. Quinn, S. Weinberg, *Phys. Rev. Lett.* **33:** 451 (1974).

11. A. Sirlin, XXVth Rencontres de Moriond, Les Arcs, France, March 4–11 (1990).

12. D. Gross, J. Harvey, E. Martinec and R. Rohm, *Phys. Rev. Lett.* **54:** 502 (1985).

13. P. Candelas, G. Horowitz, A. Strominger and E. Witten, *Nucl. Phys.* **B258:** 46 (1985).

14. Y. Hosotani, *Phys. Lett.* **129B:** 75 (1985).

15. H.P. Nilles, *Phys. Lett.* **115B:** 193 (1982).

16. M. Dine, R. Rohm, N. Seiberg and E. Witten, *Phys. Lett.* **156B:** 55 (1985).

17. K. Konishi, N. Magnoli and H. Panagopoulos, *Nucl. Phys.* **B309:** 201 (1988).

18. E. Witten, *Phys. Lett.* **155B:** 151 (1985).

19. P. Binétruy, S.Dawson, M.K. Gaillard and I. Hinchliffe, *Phys. Lett.* **192B:** 377 (1987), and Phys. Rev. **D37:** 2633 (1988).

20. S.P. Li, R. Peschanski and C.A. Savoy, *Phys. Lett.* **178B:** 193 (1986) and *Phys. Lett.* **194B:** 193 (1987).

21. P. Binétruy and M.K. Gaillard, *Phys. Lett.* **232B:** 83 (1989).

22. G. Veneziano and S. Yankielowicz, *Phys. Lett.* **113B:** 231 (1982); T.R. Taylor, *Phys. Lett.* **164B:** 43 (1985).

23. P. Binétruy and M.K. Gaillard, in preparation.

24. B.A. Campbell, *et al.*, *Int. J. Mod. Phys.* **A2:** 831 (1987).

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