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GUTs, SUSY GUTs AND SUPER GUTs

Mary K. Gaillard

July 1982

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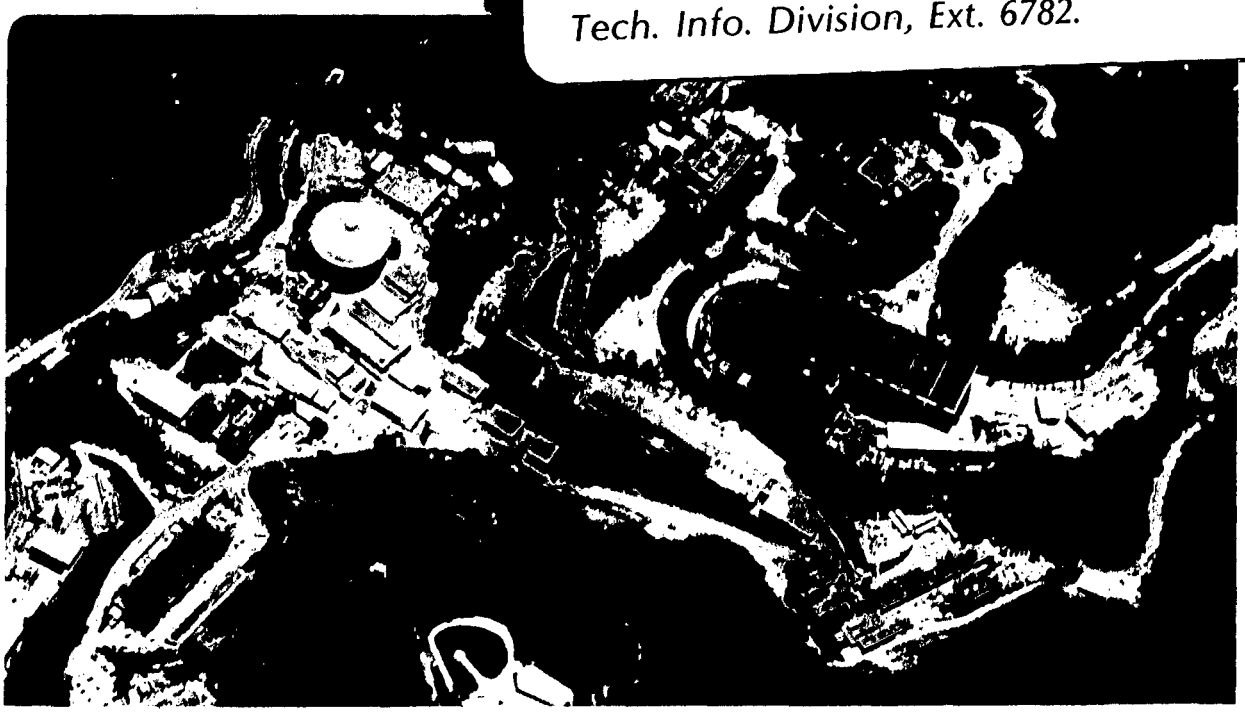

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GUTs, SUSY GUTs AND SUPER GUTs*

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Dedicated to Leon M. Lederman on the occasion of his 60th birthday.

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GUTs, SUSY GUTs AND SUPER GUTs

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ABSTRACT

We review the motivations for extending grand unified theories with particular emphasis on supersymmetry and its phenomenological and cosmological fallout, and comment on the relevance of quantum gravity.

INTRODUCTION

The notion that the elementary forces of nature should ultimately reveal themselves as part and parcel of a single unified force has been around for some time.[1] The prototype SU(5) model[2] for unification of the now "standard" $SU(3)_C \otimes SU(2)_L \otimes U(1)$ theory of strong, electromagnetic and weak interactions was proposed at a time when experimentalists were still uncertain as to even the existance of neutral currents. However the original[3] and simplest version of a renormalizable electroweak theory withstood the test of time and survived experimental scrutany to the point where deviationists from theoretical orthodoxy have been forced to artifically adjust their more complex scenerios to mimic the straight-forward predictions of the standard model. The present explosion of variations on grand unified models (GUTSs): technicolored[4] (TC), supersymmetric (SUSY)[5-9] supercolored,[10] superunified,[11,12] weak-confining,[13] compactified[14,15] ..., is reminiscent of the earlier proliferation of electroweak models, with the unfortunate difference that there is very little data to stem the flow of speculation.

In fact experimental support for the idea of grand unification rests essentially on a single piece of data: the value[16,17] of the parameter $\sin^2\theta_w$ which characterizes the strength and structure of weakly coupled neutral currents. There has been a steady convergence between the radiatively corrected[18,19] experimental value

$$\sin^2\theta_w = 0.215 \pm 0.002.$$

and the value predicted from the simplest version of SU(5), most recently evaluated at[18]

$$\sin^2\theta_w = 0.214 \pm 0.002.$$

This model also relates some quark and lepton masses. A recent comparison[21] between estimates of quark masses from analyses of low

energy data and from SU(5) calculations indicates agreement within 20% for the b-quark to τ mass ratio and about a factor two for the s-quark to μ mass ratio. Perhaps one can't expect better: application of perturbative QCD techniques to low energy becomes increasingly unreliable especially since thresholds are involved. It is well known that the d-quark to electron mass ratio is incorrectly predicted but it has been argued[22] that this discrepancy can be accounted for by effects of quantum gravity in that these masses are so tiny that effects of order m_{GUT}/m_P relative to the overall fermion mass scale are not negligible.

So why all the fuss? The objections to the minimal GUT are largely aesthetic. While GUTs unify the three independent coupling constants of the low energy theory, there remains a large number of parameters which must be put in by hand: the Yukawa coupling of scalars to fermions which determine the fermion mass spectrum and the Cabbibo-like angles which govern weak decays; the scalar self couplings which govern the pattern of symmetry breaking and hence the vector boson mass spectrum; the θ-parameter of QCD which characterizes the strength of P and CP violation in "strong" interactions. Two of these "fine tuning" problems are particularly acute: the ratio of mass scales characteristic of SU(5) breaking and of $SU(2)_L \otimes U(1)$ breaking which differ by 14 orders of magnitude, and the θ-parameter which must be adjusted to a very tiny value. The first problem is the notorious gauge hierarchy problem: it is this problem which forms the focal point for most of the attempts at generalizing the minimal GUT. The "strong CP" problem which has been discussed by Dine[23] may in fact also be brushed under the gravitational rug,[24] since introducing a cut-off $\Lambda \simeq m_P$ in the radiative corrections to θ yields an acceptably small value for the neutron dipole moment. On the other hand if we are using quantum gravity as a garbage pail for our lack of understanding we must ultimately address the second major failing of GUTs: it makes extrapolations from present day laboratory energies to energy scales only four orders of magnitude below the Plank scale, but cannot include gravitational interactions in the unified picture. This is because the renormalizable gauge theories based on local (i.e. space-time dependent) internal symmetries cannot accommodate fields of spin greater then one, whereas quantum gravity requires a spin-2 graviton.

The two major failings of GUTs - arbitrariness of parameters and the failure to include gravity - has led theorists to take seriously the possibility that supersymmetry[25] may have something to do with nature. Supersymmetry goes beyond ordinary internal symmetries in that it relates fields of different spin. This means that gauge couplings can be related by supersymmetry to Yukawa couplings and to scalar self-couplings, thus promising to remove the arbitrariness aluded to above. In addition, the higher degree of symmetry provides extra cancellations among divergent contributions to radiative corrections, and it is hoped that supergravity (SUGRA),[26]

the supersymmetric version quantum gravity, will provide a tractable theory of gravity as well as its unification with gauge theories. Unfortunately, these ambitious programs require what is called extended supersymmetry which embeds internal symmetries with supersymmetries. On the other hand, the data forces us to describe our particle world by chiral gauge theories, in which left and right handed fermions couple with different strengths to gauge bosons. A chiral gauge theory, it turns out, can be embedded only in a simply supersymmetric theory, which does not lead to a finite theory of gravity, nor does it remove any arbitrariness as applied to our present unified gauge theories. All it does is to double the number of particle species.

SIMPLE SUPERSYMMETRY

Nevertheless, simply supersymmetric grand unified theories, or SUSY GUTs have become very popular as a line of attack[27] on the gauge hierarchy problem, which can be formulated as follows. If the scalar sector of the unified gauge theory can be described using convergent perturbation theory, then phenomenology requires[28]

$$m_H \leqslant 1 \text{ TeV} \tag{1}$$

in the standard electroweak model.[3] However the natural scale[2,16] of the strong and electroweak unified model is 10^{15} GeV. Fermion masses can be much smaller than this scale because they are protected by chiral symmetry, and vector boson masses are similarly protected by gauge symmetries. The problem for scalars is that their masses are unprotected in an ordinary gauge theory; that is, one expects them to be governed by the largest mass scale around since all the interacting scalars communicate with one another through radiative corrections.

Supersymmetry offers a simple solution: protect the mass of the standard model Higgs doublet by tying it to the mass of a chiral fermion superpartner. But in a realistic GUT, things are not so simple. For example, in the minimal SU(5) model[2] the Higgs doublet is part of an SU(5) 5-plet which also contains scalars which transform like a triplet under color SU(3). These scalars can mediate proton decay and are therefore constrained to be very heavy:

$$M_{triplet} \geqslant 10^{11-12} \text{ GeV} \tag{2}$$

as opposed to (1). These phenomenological requirements can be simultaneously satisfied,[17] but this requires an artificial adjustment of parameters which in an ordiniary gauge theory is highly unstable against radiative corrections. One of the (somewhat mysterious) properties of supersymmetric theories is that they allow[29] such a parameter adjustment to be stable against radiative corrections. In minimal SU(5) it remains arbitrary,[5] but this can be cured by appealing to a higher symmetry.[6]

If we wish to protect the electroweak Higgs mass using

supersymmetry, then the above argument suggests that the scale m_S of supersymmetry breaking should be no more than a TeV. This would imply[30] that quarks (q) and leptons (ℓ) have scalar supersymmetric partners called squarks ($\tilde{q}$) and sleptons ($\tilde{\ell}$) with masses

$$m_{\tilde{q}}, m_{\tilde{\ell}} \leqslant m_S \leqslant 1 \text{ TeV}. \tag{3}$$

In addition the gauge bosons have supersymmetric fermionic partners (inos); those associated with the massless photon and gluons aquire masses only through radiative corrections, so we expect for the photino ($\tilde{\gamma}$) and gluinos ($\tilde{g}$):

$$m_{\tilde{\gamma}} \leqslant \frac{\alpha}{\pi} m_S \leqslant \text{a few GeV}$$

$$m_{\tilde{g}} \leqslant \frac{\alpha_S}{\pi} m_S \leqslant 30 \text{ GeV}. \tag{4}$$

Experimental evidence against the existance of these objects is meager; for example, analyses[32] give only $m_{\tilde{g}} \geqslant 2$ GeV, with almost no limit on $m_{\tilde{\gamma}}$. Groups[33] at PETRA have looked for the process

$$e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-, \quad \tilde{\ell}^\pm \to \tilde{\gamma} + \tilde{\ell}^\pm.$$

giving limits

$$m_{\tilde{\ell}} \geqslant 16 \text{ GeV} \tag{5}$$

if the photino does not decay to produce a photon shower in the detector. A similar limit[34] for the smuon ($\tilde{\mu}$) mass follows from the experimental and theoretical errors on the muon anomalous magnetic moment.[35] It should be possible[36] to push the limit on the selection mass beyond the beam energy in e^+e^- reactions by looking for single selectron production via the quasi-real photon process

$$\gamma + e \to \tilde{\gamma} + \tilde{e}, \quad \tilde{e} \to \tilde{\gamma} + e \tag{6}$$

signed by an energetic, large angle electron from the selectron decay with the spectator electron emerging at a very small angle with respect to the beam direction; if the photino has a short enough lifetime the high $p_\perp$ of the decay electron would be partically balanced by photons from the photino decays. The total cross section corresponds to 5% of a unit of R for $m_{\tilde{e}} = E_{beam}$ and drops to 0.15% for $m_{\tilde{e}} = 1.5\ E_{beam}$. At present "low energy" supersymmetry seems to be phenomenologically acceptable. But is it not without difficulties. Aside from the fact that it has proven quite difficult[37-40] to write down a realistic SUSY model of just the electroweak and strong gauge theories, the upper limit (1) is itself somewhat artificial and in

fact rather generous. It corresponds to allowing the self coupling constant λ of the Higgs scalar to reach its unitarity limit

$$\lambda = 4\pi \gg 1. \tag{7}$$

The more plausible value $\lambda = O(g^2)$, where g is the weak gauge coupling constant, would reduce the limit on m_H by an order of magnitude and correspondingly reduce the limits (3) and (4) on squark, slepton and ino masses. As usual, an eventual conflict with experiment can be avoided by enlarging the theory. If one puts[40,7,8] the supersymmetry breaking into a sector of the theory which doesn't couple directly to the Higgs scalars, one can get

$$m_H \sim (\frac{\alpha}{\pi})^n \, m_S \times (\text{GIM type suppression factors}) \tag{8}$$

where the power n can be made arbitrarity high, or the mass suppression factors arbitrarily small, allowing m_S to become arbitrarily large-perhaps even as large as the Planck mass m_P[7] - depending on the extent to which one is willing to complexify the theory.

Having dispensed with the immediate phenomenological problems, we should address aesthetic problems. We started out in the hope of limiting the number of independent mass scales. Let's see what has been acheived. In the standard GUT-less strong and electroweak theory we had two scales: m_W and the parameter Λ of QCD which measures the energy scale at which the strong coupling constant becomes strong. Incorporating this theory into a GUT, we introduced a third scale, m_X (the mass of superheavy gauge bosons), but also eliminated one: the value of Λ can be related[16] to the value of m_X through the effects of radiative corrections. Going now to a SUSY GUT, we end up a priori with three mass scales: m_W, m_X and m_S. In all cases we still have the Planck mass m_P unrelated to anything (except that if $m_S \sim 1$ TeV, one finds that m_X actually approachs m_P in magnitude), as well as all the fermion masses which one tends to ignore in discussions of scales on the grounds that they are really Yukawa couplings - but this makes them no less arbitrary. In short, supersymmetry has forced us to introduce more parameters and removed none. Can we remedy this?

In fact, in models[7,8,40] of the type leading to Eq. (8), the breaking of $SU(2)_L \otimes U(1)$ and consequently the ratio m_W/m_S is determined by radiative corrections (which, however, depend on the arbitrary Yukawa couplings). Can we also get the ratio m_X/m_S from radiative corrections? As emphasized by Witten,[41] spontaneously broken supersymmetric theories have a large vacuum degeneracy which is lifted by radiative corrections where one encounters a dependence

on scales of the form $\alpha/\pi\ \ell n(m_1/m_2)$ which could lead, under certain conditions, to a ratio of scalar field vacuum expectation values $m_1/m_2 \sim \exp(\pi/\alpha)$. This is similar to the effect of radiative corrections in determining[16] the ratio Λ/m_X and also to previous attempts to determine the ratio m_W/m_X by introducing technicolor[4] (for which a viable GUT model was never found and which has serious phenomenological difficulties with strangeness changing neutral currents) or by radiative corrections[42] in the standard model with m_H = 10 GeV (which involves an ad hoc assumption). It seems fair to say that while the SUSY context appears a more promising framework for realizing this scenario, a quantitative and realistic example of its implementation has not yet been formulated although interesting work[8] in that direction is going on. Unfortunately, specific calculations[43] without fine tuning yield scale hierarchies which are only of order $m_1/m_2 \sim \exp(1/2\pi\alpha)$, which is not very large in a GUT model.

GRAVITINO AND GRAVITY

Another feature of supersymmetric theories is that in addition to doubling the number of known particle species at least one new species must be added to the zoo. A spontaneously broken internal symmetry gives rise to a massless scalar particle called a Goldstone boson; in spontaneously broken gauge theories the Goldstone bosons are eaten by the massive vector mesons. A spontaneously broken supersymmetry gives rise to a massless fermion called a goldstino. This particle is eliminated in a similar way[44] if we include gravity in its supersymmetric form. Then we must introduce a spin-3/2 superpartner for the graviton (gravitino, $\tilde{G}$) which acquires a mass and eats the Goldstino when supersymmetry is broken.

This of course brings in gravity again and we wonder to what extent it can be ignored in the construction of models and in their phenomenological implications. For simple supergravity coupled to a simply supersymmetric matter theory, the observation that the cosmological constant as measured today is essentially zero leads to the prediction:[44]

$$m_{\tilde{G}} = \frac{m_S^2}{m_P} \equiv \kappa\ m_S^2 \tag{9}$$

in the tree approximation, where $\kappa = m_P^{-1}$ is the gravitational coupling constant. The longitudinal (helicity $\pm$ 1/2) components of the gravitino have enhanced couplings at high energy

$$g_{eff} = \kappa \frac{E^2}{m_{\tilde{G}}^2} = \frac{E^2}{m_S^2} \tag{10}$$

which will not necessarily be negligible at low energy if m_S is not too large. What about quantum[45] corrections? Since simple supergravity is not a renormalizable theory, we must introduce a cut-off, and unless a unified theory including gravity becomes effective below the Planck mass, the only available cut-off is the Planck mass itself. Then we expect that those particles (scalars, inos) whose masses are not protected by low energy gauge or chiral symmetries will get mass contributions of order

$$m_{ino} \sim m_{\tilde{G}} \frac{\kappa^2\Lambda^2}{\pi} \sim \frac{m_{\tilde{G}}}{\pi}$$

$$m^2_{scalar} \sim \pm\, m^2_{\tilde{G}} \frac{\kappa^2\Lambda^2}{\pi} \sim \frac{1}{\pi} m^2_{\tilde{G}} \qquad (11)$$

The bound (1) on m_H would then require $m_{\tilde{G}} \leqslant 1$ TeV or $m_S \leqslant 10^{11}$GeV. For the scalar fields ψ one should really consider the full effective potential

$$V_{eff}(\psi) = m^2_{\tilde{G}}\, \kappa^{-4} \frac{\Lambda^2}{\pi} f(\kappa^2\psi^2) + \text{less divergent terms} \qquad (12)$$

where f is a polynomial function of the dimensionless fields $\kappa\psi$. An amusing possibility is the case where V_{eff} has its minimum away from the origin. This would lead to a vacuum expectation value $\langle\psi\rangle \sim m_P$, independent of the value of m_S for the leading term. Since gravity sees no internal symmetries, the potential (12) depends only on $|\psi|^2 = \sum_{i=1}^{n} |\psi_i|^2$ where the sum is over all (complex) scalar particles in the theory. The vacuum is degenerate under SU(n) and leaves 2n - 1 massless Goldstone scalars. This degeneracy will be removed, and the remaining scalars acquire masses, when the gauge and other interactions are included. From the interplay of various radiative corrections one could imagine a scenario where the desired hierarchy of mass scales does arise, but in which the inclusion of gravity is an essential element.

SUPERUNIFICATION

Up to now we have concentrated on simple supersymmetry and abandoned our initial goals of removing arbitrary parameters and achieving the unification of gauge forces with gravity. For this program we turn to extended supersymmetry. The maximum number of supersymmetries we allow is 8; otherwise we are led[46] to an elementary particle spectrum including spins greater than 2, for which we cannot even write down a field theory. N = 8 extended supergravity is an ideal candidate for a truly unified theory: it has a unique particle spectrum[46] whose couplings are completely specified and there is hope that it may have finite S-matrix elements. The trouble is that it fails[47] to reproduce the "observed" particle spectrum, in spite of its richness. Among the 28 vector fields in the elementary N = 8 super-

multiplet, there are none that can be identified with the $W^{\pm}$, let alone the X and Y of the minimal SU(5) GUT. Among its 56 fermion fields there are none that can be identified with the muon or with the (τ, ν_τ, b, t) generation of fermions. Interest in N = 8 supergravity was renewed when Cremmer and Julia[48] discovered that this theory has a local SU(8) invariance associated with 63 gauge fields which are not elementary but are composites of the elementary "preon" fields of the N = 8 supergravity multiplet. This led to the conjecture[11] that, aside from the graviton, the preons are all confined and the "observed" spectrum, i.e. those particles which make up our unified gauge theories (neutrinos, leptons, quarks, photon, gluons, $W^{\pm}$, Z, X, Y and Higgs scalars) are all bound states. The N = 8 supersymmetry is dynamically broken in such a way that those states which survive in the "low energy" theory ($E \ll m_p$) are such as to allow a renormalizable effective field theory (SUPERGUT). This set includes vectors in the adjoint of the surviving gauge group, an anomaly free set of spin-1/2 fermions, and scalar particles. To date this speculation has not yielded much predictive power. It does restrict the simple group unifying the strong, weak and electromagnetic interactions to be no larger than SU(5), although it could allow for some extra U(1)'s such as have been found necessary[37] to introduce in constructing realistic supersymmetric gauge theories. It further restricts the type of representations to which scalars and fermions may be assigned. These constraints become tighter if one assumes[11] that the particle content of the effective renormalizable gauge theory arises from a single N = 8 supermultiplet. Then the maximal fermion content compatible with a viable SU(5) GUT is

$$3(\bar{5} + 10) + 9(1) + 3(5 + \bar{5}) + 9(10 + \overline{10}) + 4(24) + 45 + \overline{45}$$

for left handed fermions, along with their CPT conjugate right handed fermions. Under the hypothesis[11] that one of the original 8 supersymmetries remains unbroken at "low" energy leaving us with a simple SUSY GUT, the number of allowed singlets (1) is reduced to 6 and the $(10 + \overline{10})$ states to 3. In either case we can have the usual three generations of $\bar{5} + 10$, plus a number of additional fermions which are presumably super heavy because they can aquire SU(5) invariant masses, which are consequently "unprotected". Thus in addition to accommodating the spectrum of fermions, gauge bosons and scalars of the minimal SU(5) model a single supermultiplet of N = 8 supergravity bound states also accounts easily for the additional fermions and scalars (in a simple SUSY effective gauge theory one 24-plet of fermions is associated with the gauge vectors; each of the remaining fermions has a complex scalar superpartner) which appear to be necessary for the construction[5-9] of a realistic SUSY GUT.

An alternative approach to superunification is based on a generalization[14] to supergravity of the old Kaluza-Klein approach[49] to the unification of gravity with electromagnetism. One starts

with simple supergravity in a space of dimension greater than four. Upon "compactification" or the curling up of the extra dimensions into circles of infinitesimally small radius, their associated degrees of freedom appear as internal symmetry degrees of freedom of fields of lower spin. The difficulty with this approach is that it appears to generate non-chiral gauge theories.[14] Recently it has been shown[15] that chiral theories can be generated by compactification of initially non-chiral gauge theories in higher dimension, but these examples have no obvious relevance to gravity.

COSMOLOGICAL PROBES

Whatever the underlying theory, supersymmetric models tend to generate new stable or long-lived objects such as the gravitino, photino, selectron, or random Goldstone-like objects associated with either the spontaneous breaking of global chiral symmetries which are characteristic of SUSY models, or with the large vacuum degeneracy. Observational cosmology permits such an object if it is light enough to contribute negligibly to the cosmological mass density:[50,51]

$$m \leqslant 0(\mathrm{KeV}) \tag{13}$$

which from (1) implies[51]

$$m_S \leqslant 10^6 \mathrm{GeV} \tag{14}$$

for a stable gravitino. In models which rely on the Witten[41] mechanism one gets a pseudo-goldstone scalar of mass

$$m \simeq m_S^2/m_X \tag{15}$$

which would correspondingly require[52]

$$m_S \leqslant 10^3 \mathrm{GeV}. \tag{16}$$

Alternatively such a stable object would be acceptable if it is heavy enough[53] to decay or annihilate very early in the expansion of the universe. This does not give a very strong constraint for the photino,[50] but it is relevant to more exotic objects which decouple at very high temperatures. Depending on whether one is considering a gravitino,[53] or a Wittino[52] one gets mass bounds in the range

$$m \geqslant 10^4 - 10^{11}\ \mathrm{GeV} \tag{17}$$

and SUSY breaking scales in the range

$$m_S \geqslant 10^{11} - 10^{16} \mathrm{GeV}. \tag{18}$$

Thus models with $10^6 \leqslant m_S \leqslant 10^{11}$ appear to be ruled out and a wider range of scales is excluded for Witten-type models.[41] However it should be remembered that the gravitino analyses are based on the

N = 1 SUGRA tree graph relation (9) which could be violated if the underlying theory is an extended SUGRA - in fact the only explicit example[54] of a broken N = 8 SUGRA (which is not a realistic model) provides a counter example to (9). In addition quantum corrections, which we have argued can give significant contributions to photino, gluino and scalar masses, may also invalidate the relation (9). We remark in passing that some of the above mentioned random goldstone particles are candidates for the invisible axion discussed by Dine,[23] so that SUSY theories may at least provide a neat, albeit nearly untestable, solution to the strong CP problem.[10,55]

LOW ENERGY PROBES

As a concluding remark, I would like to emphasize the importance of precision low energy experiments for probing the very high energy sector of our theory which may be out of reach of even the next generation of accelerators. The most exciting example is proton decay - a clear signal for any decay mode is of prime importance in itself. If supersymmetry is valid down to mass scales of 1 TeV or less, then the mass of the superheavy X of the GUT gets pushed up[56] to a value much higher than 10^{15} GeV, and proton decay is no longer dominated by X-exchange. In some models the most important contributions[38,57] arise from diagrams involving superheavy fermions. These are higher order in the coupling constant but lower order in the inverse superheavy mass. If they dominate one expects[58] the dominant modes for nucleon decay to be $N \to K + \nu$. On the other hand if the dominant mechanism is the exchange[8] of the usual color triplet Higgs of SU(5), the dominant mode will be $K\mu$. But beware of drawing conclusions. By adding scalars in 10-plets of SU(5) one can recover[59] the minimal SU(5) prediction that the πe mode is dominant. A second example is the neutron electric dipole moment. If the resolution of the strong CP problem lies in the existance of an axion, visible or not, most theories predict a neutron dipole moment much smaller than the present experimental limit,[60] whereas in the absence of an axion,[61] the observed baryon to photon cosmological density ratio suggests that the neutron dipole moment should be within the reach of future experiments.[62]

Rare K-decays can continue to play an important role in constraining theorists' fantasies. As an example an experiment[63] which could reach the level of 10^{-10} in branching ratio for the process $K^+ \to \pi^+ +$ nothing would contain a considerable amount of physics. Firstly, a null result is not expected, except in the advent of a perverse cancellation. The standard model alone predicts[64]

$$\text{B.R.}(K^+ \to \pi^+ + \nu\nu) \sim 10^{-10} + \text{top quark correction} \quad (19)$$

and this is undoubtedly, among the various K-decay processes, the theoretically cleanest test of weak radiative corrections. The same experiment would probe the mass of a mediator of generation-changing neutral processes like $K^+ \to \pi^+ \nu_e \bar{\nu}_\mu$ to a scale of 25 TeV. Under the hypothesis that photinos are quasi massless and quasi stable it would probe the squark mass to some fraction[65] of m_W. General flavor changing neutral current processes which provide a severe headache for technicolor theories[4] are more limited in their ability to restrict[66] SUSY model building - tending to yield limits on, e.g., slepton and squark mass differences rather than slepton or squark masses. Mass differences among squarks of a given flavor appear to be more strongly constrained by measurements of parity violating nuclear transitions.[67]

To conclude: theorists are off on a binge of unrestrained speculation; we badly need guidance from experiment.

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