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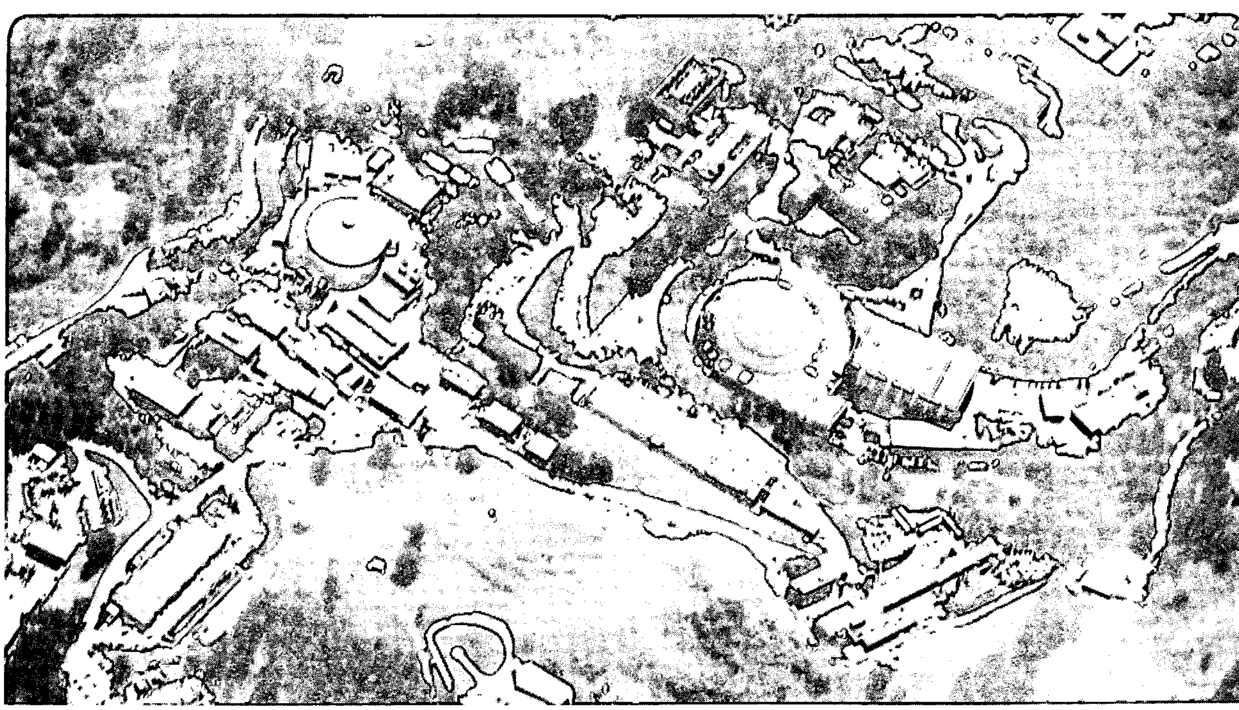

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Flavor Tests of Quark-Lepton Unification* †

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How will we ever be convinced that grand unification, or string theory, or some other physics at very high energies, is correct? Two ways in which this could happen are:

1. The structure of the theory is itself so compelling and tightly constrained, and the links to observed particle interactions are sufficiently strong, that the theory is convincing and is accepted as the standard viewpoint. String theory is a candidate for such a theory, but connections to known physics will require much further understanding of the breaking of its many symmetries.

2. The theory predicts new physics beyond the standard model, which is discovered. If the structure of the theory is not very tightly constrained, several such predictions will be necessary for it to become convincing. Grand unification is a candidate for such a theory, but as yet there have been no discoveries beyond the standard model. Supersymmetric grand unified theories do have a constrained gauge structure, and this has led to the successful prediction of the weak mixing angle at the 1% level of accuracy [1, 2, 3, 4]. While significant, this is hardly convincing. Nevertheless, supersymmetric grand unified theories offer the prospect of many further tests. In this talk I make the case that experiments of this decade, and the next, allow for the possibility that we might become convinced that grand unification is correct.

Any grand unified theory must have at least two sectors: the gauge sector, which contains the gauge interactions, and the flavor sector containing the interactions which generate the quark and lepton masses. In supersymmetric versions there are also the supersymmetry breaking interactions. I include the gaugino masses in the gauge sector, and the supersymmetry breaking squark, slepton and Higgs masses and interactions in the flavor sector. There are no known direct observable consequences of the interactions of the superheavy gauge bosons: they are predicted to be too heavy even to mediate proton decay at an observable rate.

I know of only one prediction in the gauge sector, other than $\sin^2\theta$: ratios of the gaugino mass parameters, $M_i, i = 1,2,3$ for $U(1), SU(2)$ and $SU(3)$. If the supersymmetry breaking is hard up to scales above the unification mass, M_G, then above M_G the unified symmetry requires M_i to be independent of i. Beneath M_G, renormalizations induce splittings between the M_i, in fact they scale exactly like the gauge couplings: $M_i = \alpha_i M$. The prediction of two gaugino mass ratios is a very important consequence of super unification. These predictions occur in the gauge sector, and are robust to modifications of the theory. However, unlike the weak mixing angle, these predictions are occurring in the supersymmetry breaking sector, and even if the supersymmetry breaking is hard at M_G, there are situations when they are broken [5]. Furthermore, these relations can occur without grand unification. *

Fortunately, the flavor sector has many signatures, listed in Table 1 in 5 categories.

Table 1

	Requires BSM discovery	"Present" in all[†] models	Requires Susy breaking hard at M_G
(I) p decay	√	X	X
(II) ν masses	√	X	X
(III) u, d, e masses and mixings	X	X	X
(IV) $\tilde{u}, \tilde{d}, \tilde{e}$ masses	√	√	√
(V) $L_{e,\mu,\tau}$ and CP violation	√	√	√

Characteristic features of the 5 flavor tests of supersymmetric grand unification.

*Suppose supersymmetry is broken in the multi-TeV region in a sector which communicates to the observable sector only via standard model gauge interactions. Then one expects $M_i \propto \alpha_i$ as before. However, it is by no means guaranteed that the constant of proportionality is independent of i.

Proton decay [6, 7] and neutrino masses [8, 9] are the earliest and most well-known signature of grand unification. However, the theoretical expectation for these classic signals is plagued by a power dependence on an unknown superheavy mass scale. For neutrino masses this is the right-handed Majorana mass M_R. If we naively set $m_{\nu_i} = m_{u_i}^2/M_R$ with $M_R = M_G = 2 \times 10^{16}$ GeV, then all three neutrino masses are too small to be detected in any laboratory experiment, although they could lead to MSW oscillations in the sun. While the many hints for detection of neutrino oscillations are extremely interesting, and theorists are full of ideas for suppressing M_R, if we fail to detect neutrino masses then we learn very little about grand unification. On the other hand, several observations hint at the presence of neutrino masses, and measurements of neutrino masses, and measurements of neutrino mass ratios and mixing angles would provide a very important probe of the flavor structure of unified models.

The leading supersymmetric contribution to the proton decay rate is proportional to M_H^{-2}, [10, 11] where M_H is a model dependent parameter, which arises from the unified symmetry breaking sector of the theory. The simple expectation that $M_H \simeq M_G$ is excluded as it produces too short a proton lifetime [10, 11]. There are many mechanisms that effectively allow M_H to be enhanced, thereby stabilizing the proton, but there is no argument, which I would defend, demonstrating that proton decay will be within reach of future experiments. If we are lucky, proton decay may be discovered; the modes and branching ratios will probe flavor physics in an important way. However, as for neutrino masses, the meaning of the X in the middle column of Table 1 for these signals is that if a signal is not seen, little of use is learnt about the question of grand unification.

The third signature of the flavor sector of grand unified theories is provided by relations amongst the masses and mixings of the quarks and charged leptons, which was also first studied in the 1970s [12]. This signature has the very great advantage over all others that data exists: there is no need for discoveries beyond the standard model. Since the late 70s this field has developed considerably, in step with our continually increasing knowledge of the quark and lepton masses and the Kobayashi-Maskawa matrix elements. These signatures are based on the hope that the flavor interactions which generate the fermion masses are relatively simple, involving few enough parameters that relations among the 13 observables can be derived. While there is no guarantee that this is true, it is an assumption which is reasonable and which could have an enormous payoff. A considerable fraction of high energy physics experiments aim at extracting more precise valves for the quark masses and mixings; each time an error bar is reduced, this probe of grand unification becomes more incisive. Among the interesting results obtained so far are:

- Evolution of the b and τ Yukawa couplings to high energies in the standard model does not lead to their unification, as expected from the simple $SU(5)$ boundary condition. Such a unification does work well if evolution is done with weak scale supersymmetry and a heavy top quark [13, 14, 15, 16].

- The unification of the three Yukawa couplings of the heavy generation in the MSSM [17], expected from a simple $SO(10)$ boundary condition, can occur perturbatively only if 165 GeV $< m_t <$ 190 GeV. [18].

- It is possible to construct $SO(10)$ models where all observed fermion masses and mixings are generated from just 4 interactions. Seven of the 13 flavor parameters are predicted [19].

- The observed quark masses and mixings are consistent with several patterns of the Yukawa matrices at the unification scale in which many of the entries are zero, suggesting they have a simple origin [20].

I have discussed the first three signatures of Table 1, stressing that only for fermion mass relations do we have any useful data, and stressing that none of these signatures is a necessary consequence of grand unification. These features are shown in the first two columns of the Table. We must now discuss supersymmetry breaking, which is relevant for the third column of the Table. The fundamental origin of the first three signatures (baryon number violation, lepton number violation, and Yukawa coupling relations) does not depend on supersymmetry breaking. However, for the last two signatures, the supersymmetry breaking interactions of the low energy effective theory contain all the information relevant to the signals.

A crucial question for these two signatures is: at what scale do the interactions which break supersymmetry become soft? This has nothing to do with the size of the parameters which violate supersymmetry — they are of order the weak scale. At any energy scale, μ, we can consider our theory to be a local effective field theory. What is the scale μ_c above which the supersymmetry breaking parameters, such as squark and gluino masses, do not arise from a single local interaction? Consider models where supersymmetry is broken spontaneously in a sector with a single mass scale, M, and is communicated to the observable sector by the known gauge interactions [21]. It is only when the particles of mass M are integrated out of the theory that local interactions are generated for squark and gluino masses. Hence $\mu_c = M$, which is of order M_W/α, or 10 TeV.

The breaking of supersymmetry in a hidden sector of $N = 1$ supergravity theories [22, 23, 24] has become a popular view, although it is not satisfactory in several respects. The interactions which generate squark and slepton masses are produced when supergravity auxiliary fields are eliminated from the theory, and hence are local at all energies up to the Planck scale, giving $\mu_c = M_{PL}$. For signatures IV and V the critical question is whether μ_c is larger or smaller than M_G, the unification mass. If $\mu_c \ll M_G$ then the local interactions which break supersymmetry are produced at energies beneath M_G, and hence these interactions are not renormalized by the interactions of the unified theory. On the other hand, if $\mu_c \gtrsim M_G$, then the supersymmetry breaking interactions appear as local interactions in the grand unified theory itself. At energies above M_G they take a form which is constrained by the unified symmetry. Furthermore, they are modified by radiative corrections induced by the unified theory, giving low energy signals which are not power suppressed by M_G [25].

For example, in any grand unified theory in which $\tilde{u}, \tilde{u}^c$ and $\tilde{e}^c$ are unified in the same irreducible representation, the unified theory will possess $m^2_{\tilde{u}} = m^2_{\tilde{u}^c} = m^2_{\tilde{e}^c}$. When the unified gauge symmetry is broken, such relations can be modified both radiatively and at tree level. However, it has been shown that in all models where the weak mixing angle is a significant prediction of the theory, there will be two scalar superpartner mass relations for each of the lightest generations [26].

Riccardo Barbieri and I have recently shown that a new class of signatures arises in supersymmetric theories which unify the top quark and τ lepton and have $\mu_c > M_G$ [27]. These effects are induced by radiative corrections involving the large top Yukawa coupling of the unified theory, λ_{tG}. The most promising discovery signatures are lepton flavor violation, such as $\mu \rightarrow e\gamma$[27, 28] and electric dipole moments for the electron and neutron, d_e and d_n [29, 28].

These signatures are complementary to the classic tests of proton decay and neutrino masses, as shown in the last two columns of Table 1. We believe that these new signatures are much less model dependent than the classic tests: they are present in all† models with $\mu_c > M_G$, the dagger meaning that by working hard counter examples can be constructed. The size of these signals does not depend on the power of an unknown superheavy mass; a crucial point when comparing with the classic tests.

A complete calculation in the minimal $SU(5)$ and $SO(10)$ models [28] concludes that searches for the L_i and CP violating signatures provide the most powerful known probes of supersymmetric quark-lepton unification with supersymmetry breaking generated at the Planck scale. For example, an experiment with a sensitivity of 10^{-13} to B.R.($\mu \rightarrow e\gamma$) would probe (apart from a small region of parameter space where cancellations in the amplitude occur) the $SU(5)$ model to $\lambda_{tG} = 1.4$ and $m_{\tilde{e}_R} = 100$ GeV, and would explore a significant portion of parameters space for $m_{\tilde{e}_R} = 300$ GeV. In the $SO(10)$ case, where the present bound on $\mu \rightarrow e\gamma$ is already more stringent than the limits from high energy accelerator experiments, a sensitivity of 10^{-13} would probe the theory to $\lambda_{tG} = 1.25$ and $m_{\tilde{e}_R}$ close to 1 TeV.

Which search probes the theory more powerfully: rare muon processes or the electric dipole moments? In the minimal SU(5) theory, the electric dipole moments are very small so that the rare muon proccesses win. In the minimal SO(10) theory, the electric dipole moments are proportional to $\sin\phi$ where $\phi = \phi_d - 2\beta$ where $-\beta$ is the phase of the Kobayashi-Maskawa matrix element V_{td}, and ϕ_d is a new phase. There is a simple relation between B.R. $\mu \rightarrow e\gamma$ and d_e, shown in Figure 1, for various values of $\sin\phi$, which is expected to have a magnitude in the range of 0.1 to 1. For $\sin\phi = 0.5$, the present limits imply that the processes have equal power to probe the theory. The analysis of the data from the ongoing MEGA experiment should put the rare muon decay ahead, but eventually d_e may win because it falls only as the square of the superpartner mass, whereas the rare muon decay rate falls as the fourth power. At some point these processes could force the selectron masses to be higher than is reasonable.

Similar new flavor-changing tests of supersymmetric quark-lepton unification occur in the hadronic sector, where the best probes are non-standard model contributions to $\epsilon, b \to s\gamma$ and to CP violation in neutral B meson decays [30]. These signals could provide a powerful probe of the flavor sector of unified theories. However, unlike the lepton flavor violating and electric dipole signatures, they must be distinguished from the standard model contribution, and they are small when the gluino is heavy due to a gluino focussing effect on the squark masses.

Unified flavor sectors which are more complicated than the minimal ones lead to a larger range of predictions for these signals. There may be additional sources of flavor and CP violation other than those generated by the top Yakawa coupling. While cancelling contributions cannot be ruled out, they are unlikely to lead to large suppressions. Many other sources could provide effects which are larger than those generated by λ_{tG}, and hence it is reasonable to take the top contribution as an indication of the minimum signal to be expected.

Supersymmetric grand unified theories should be considered as a leading candidate for physics beyond the standard model because

- They provide an elegant picture of the generation structure of quarks and leptons, including an understanding of all the observed gauge quantum numbers.

- $\sin^2\theta$ is the only successful prediction of any parameter of the standard model at the 1% level of accuracy.

I have not yet mentioned the most crucial experimental hurdle which these theories must pass: superpartners must be discovered at the weak scale. Without this, I will never be convinced that these theories are correct. As I write, I imagine the sceptics who may read this (I dare to hope!) saying "suppose by 2010 we have measured neutrino masses and mixing angles, seen proton decay and other rare processes such as $\mu \to e\gamma$, d_e and d_n, found non-standard CP violation in B meson decays, and that we have even discovered superpartners and measured their masses. This still will not convince me that the theory behind this physics is quark-lepton unification." My reply is

- These discoveries will not necessarily make quark-lepton unification convincing, but they will make it the standard picture.

- These discoveries might make a particular model of quark-lepton unification completely convincing.

There is certainly no guarantee of the latter point, but let me illustrate it with an optimistic viewpoint. There are millions of possible flavor sectors of unified models. Some are so complicated that, if this is the way nature is, we are unlikely to ever uncover this structure from low energy experiments alone. Others are very simple with few interactions and parameters. The most constrained which I know has 10 parameters (8 flavor and 2 supersymmetry breaking) to describe all the flavor physics signals. As an example, consider something imbetween with, say, 15 parameters (eg. 12 flavor and 3 supersymmetry breaking). This has two parameters more than the flavor sector of the standard model. Suppose that we discover such a unified model with these two parameters correctly describing: the entire superpartner spectrum, the neutrino masses and mixing angles and the magnitudes of the non-standard model signals for $\mu \to e\gamma, d_e, d_n$ and B meson CP violation, and the masses of the two Higgs bosons, the pseudoscalar boson and the charged Higgs boson. It is certainly an optimistic scenario, but it is one which I would find convincing.

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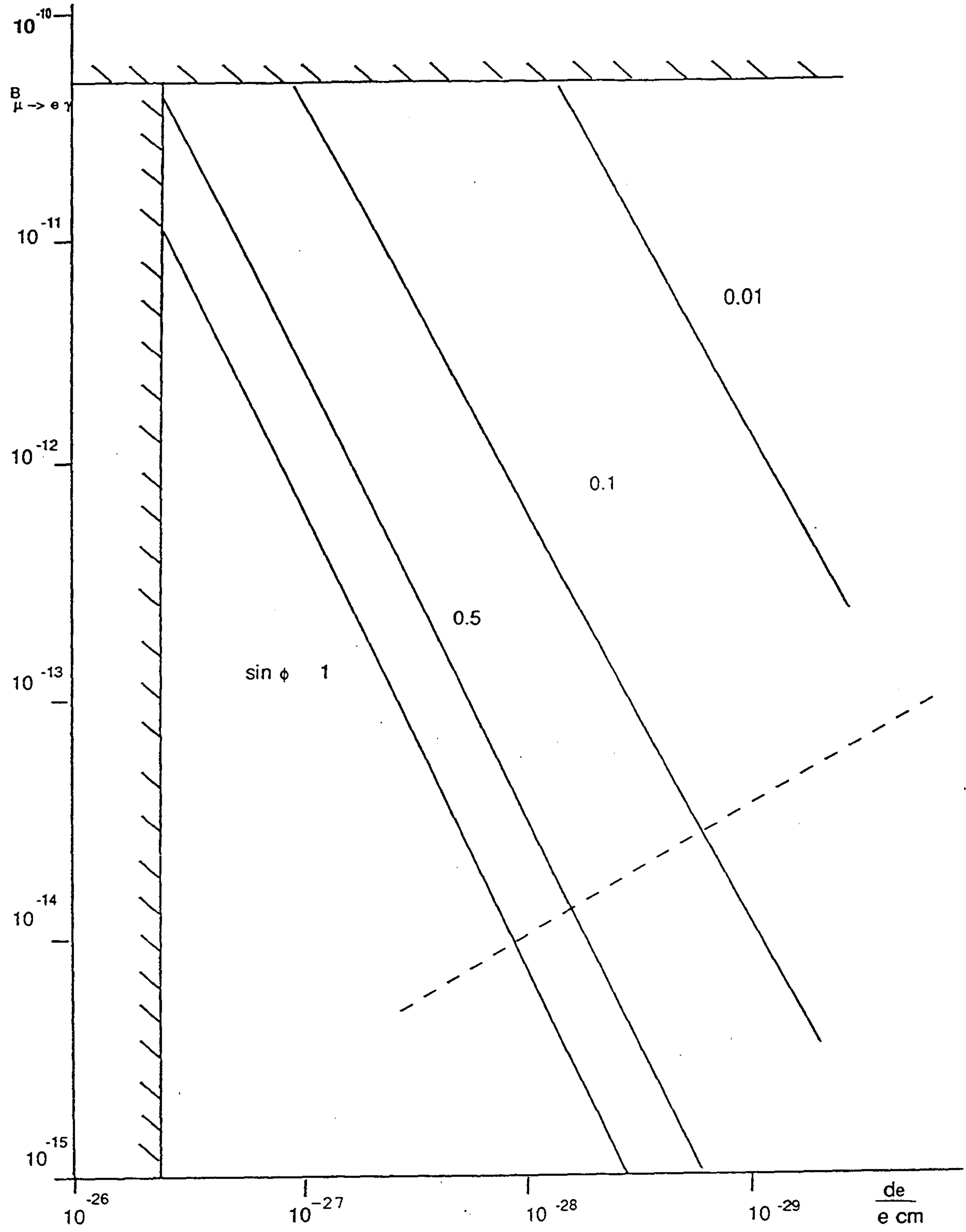

Figure 1: A comparison of the predictions for the branching ratio for $\mu \rightarrow e\gamma$ and the electron electric dipole moment in superymmetric unified $SO(10)$ theories.

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