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by

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RECENT ASPECTS OF GUT PHENOMENOLOGY*

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Abstract

The simplest grand unified theories (GUTs) have been ruled out for some time by the nonobservation of proton decay, new experimental values for $\sin^2\theta_W$, and the fact that they are not ambitious enough in their goals. However, many variations and extensions of the simplest models are still viable. Moreover, the original motivations for GUTs (unifications of the microscopic interactions, an explanation of the electrical neutrality of atoms, and a dynamical origin for the baryon asymmetry of the Universe) are still sufficiently strong that many of the GUT ideas are likely to survive. In this talk I will briefly recall the basic ideas of ordinary and supersymmetric GUTs, and will then review the status of phenomenological implications, including coupling constant predictions, proton decay, $n\bar{n}$ oscillations, extra gauge bosons, extra fermions, and the baryon asymmetry of the Universe.

1 INTRODUCTION

The standard $SU_3\times SU_2\times U_1$ model is almost certainly correct at some level [1]. However, nobody considers the standard model to be a serious candidate for the ultimate theory of nature because it is so complicated and leaves so many questions unanswered. In particular, the simplest version of the standard model (combined with classical general relativity) has 21 free parameters.[1] In addition, the standard model suffers from

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[1] Three gauge couplings, 2 CP violating θ parameters (θ_{QCD} and an analogous θ_{weak}), 9 fermion masses, 3 KMC angles, 1 CP violating phase, M_W, M_ϕ, m_P, the cosmological constant, minus one overall mass scale.

1. *The gauge problem.* The standard model is a complicated direct product of three gauge groups with three gauge coupling constants. Also, there is no explanation for charge quantization (the observed equality of the magnitudes of the proton and electron electric charges.)

2. *The fermion problem.* There is no explanation of the observed repetition of fermions into families or prediction of their masses (which are observed to vary over five orders of magnitude) and mixings.

3. *The Higgs/hierarchy problem.* Since the Higgs mechanism is assumed to generate the weak scale one expects a Higgs mass[2] $M_\phi^2 = O(M_W^2)$ (i.e. the Higgs mass is most likely in the range from a few GeV to 1 TeV). However, quadratically divergent gauge, Higgs, and fermion loops typically produce radiative "corrections" $\delta M_\phi^2 \sim 10^{34} M_W^2$, assuming that the divergent integrals are somehow cut off by quantum gravity at the Planck scale $m_P = G_N^{-1/2} \sim 10^{19}\ GeV$. Hence, an unbelievable fine tuning between the bare (lowest order) value of M_ϕ^2 and δM_ϕ^2 to some 34 decimal places is required.

4. *The strong CP problem.* One can add a P, T and CP violating term $\frac{\theta}{32\pi^2} g_s^2 F\tilde{F}$ to the QCD Lagrangian. Limits on the neutron electric dipole moment [2] require $\theta < 10^{-9}$. However, radiative corrections associated with weak CP violation are expected to shift θ by $\simeq 10^{-3}$, again requiring a severe fine-tuning of the original (bare) value of θ.

5. *The graviton problem.* There is no fundamental unification of gravity with the other interactions in the standard model. Even if classical general relativity is incorporated by hand there is no satisfactory quantum theory of gravity: attempts to quantize gravity within the standard model framework lead to terrible divergences and a non-renormalizable theory. Finally, the vacuum energy density associated with the Higgs mechanism leads to an effective cosmological constant $\delta\Lambda_{SSB} = 8\pi G_N \langle 0|V|0\rangle$ fifty orders of magnitude larger than observational limits. This requires a fine-tuned cancellation to fifty decimal places between $\delta\Lambda_{SSB}$ and the primordial Λ.

6. *Experiment.* The only experimental shortcomings of the standard model are (a) the Solar neutrino problem, and (b) the unexplained origin of the dark matter [3] in galaxies, clusters, and presumably the Universe as a whole. It is not known whether these are particle physics or astrophysics problems.

For all of these reasons it is clear that there must be new physics beyond the standard model. Some possibilites for new physics are listed in Table 1. Extra gauge, fermion, or scalar particles do not by themselves solve any problems, but they often emerge as a remnant of something else. Family symmetries or compositeness

Table 1: Some possible extensions of the standard model.

Model	Typical Scale (GeV)	Motivation
New W's, Z's, fermions, Higgs	$10^2 - 10^{19}$	Remnant of something else
family symmetry	$10^2 - 10^{19}$	Fermion (No compelling models)
composite fermions	$10^2 - 10^{19}$	Fermion (No compelling models)
composite Higgs	$10^3 - 10^4$	Higgs (No compelling models)
composite W, Z (G, γ ?)	$10^3 - 10^4$	Higgs (No compelling models)
New global symmetry (e.g. Peccei-Quinn ⇒ axion)	$10^8 - 10^{12}$ (SN1987A: 10^{12}? [4])	Strong CP
Kaluza - Klein Higgs (0) ⇔ gauge (1) ⇔ graviton (2) ($d > 4$)	10^{19}	Graviton
Grand unification strong ⇔ electroweak	$10^{14} - 10^{19}$	Gauge
Supersymmetry/Supergravity fermion ⇔ boson	$10^2 - 10^4$	Higgs, graviton
Superstrings strong ⇔ electroweak ⇔ gravity fermion ⇔ boson ($d > 4$)	10^{19}	All problems!?

could in principle shed light on the fermion and Higgs problems, but at present no particularly compelling models have emerged. In this talk I will concentrate on the GUT/supersymmetry line of thinking, which is motivated by the gauge, Higgs, and gravity problems. Such ideas may or may not emerge from superstring theories. [5]

2 IDEAS OF GUTs AND SUPERSYMMETRY

2.1 Grand Unified Theories (GUTs)

In GUTs [6] one embeds the standard model gauge group $SU_3 \times SU_2 \times U_1$ into a simple group[2] G. There is only one underlying gauge coupling constant g_G, with the difference between the observed standard model gauge couplings g_s, g, and g' due to spontaneous symmetry breaking (SSB). Also, quarks, antiquarks, leptons, and antileptons are related by the enlarged gauge symmetry, so charge quantization

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[2] G can also be a direct product of identical factors related by discrete symmetries.

emerges naturally, at least up to possible ambiquities concerning the embedding of U_1^{EM} into G. Hence, GUTs naturally solve the gauge problem, but by themselves offer no help with the fermion, strong CP, or graviton problems.

The new gauge bosons in GUTs almost always lead to proton decay. A typical diagram is shown in Figure 1.

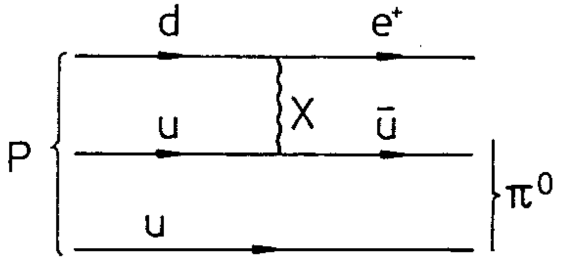

Figure 1: A typical diagram for proton decay into $e^+\pi^0$. X is a superheavy color antitriplet gauge boson of charge 4/3.

Because of the stringent limits on the proton lifetime [7] the GUT unification scale M_X must be $\geq 10^{15}$ GeV. This enormous scale actually aggravates the Higgs/hierarchy problem, by promoting it to a difficulty at the tree rather than loop level: one requires two drastically different scales of SSB, M_W and M_X, with $(M_W/M_X)^2 < 10^{-26}$. However, one typically expects $(M_W/M_X)^2 = O(1)$ unless fine-tunings are performed on the parameters of the Higgs potential.

The simplest and most popular GUT is the Georgi-Glashow SU_5 model. [8] The fermion representations are still rather complicated in SU_5, with each family assigned to a reducible $\underline{5}^* + \underline{10}$:

$$W^\pm \updownarrow \quad \underset{\leftarrow X,Y \rightarrow}{\overset{\underline{5}^*}{\begin{pmatrix} \nu_e & \bar{d} \\ e^- & \end{pmatrix}_L}} \quad \underset{\leftarrow X,Y \rightarrow}{\overset{\underline{10}}{\begin{pmatrix} e^+ & \begin{matrix} u \\ d \end{matrix} & \bar{u} \end{pmatrix}_L}} \tag{1}$$

In addition to the twelve generators and corresponding gauge bosons ($W^\pm, Z, \gamma$, 8 gluons) of the standard model, there are twelve new bosons associated with transformations between adjacent columns of (1). These are an SU_2 doublet, color antitriplet of superheavy gauge bosons X and Y (with charges 4/3 and 1/3, respectively), and their antiparticles.

In the larger gauge group SO_{10} the $\underline{5}^* + \underline{10}$ are combined with an SU_5-singlet Weyl neutrino $\bar{\nu}_L$ (which is usually assumed to acquire a large Majorana mass) to form a $\underline{16}$-plet: $(\underline{5}^* + \underline{10} + \underline{1})_{SU_5} \to (\underline{16})_{SO_{10}}$. The extra gauge generators in SO_{10} allow many possible SSB patterns, such as

$$\begin{array}{lcl} SO_{10} & \to & SU_{4c}\times SU_{2L}\times SU_{2R} \\ SO_{10} & \to & SU_{3c}\times SU_{2L}\times SU_{2R}\times U_{1\ B-L} \\ SO_{10} & \to & SU_5\times U_{1\chi} \\ SO_{10} & \to & SU_{3c}\times SU_{2L}\times U_1\times U_{1\chi} \end{array} \tag{2}$$

A still larger group is E_6. In the most popular version each fermion family is assigned to a $\underline{27}$-plet: $(\underline{16}+\underline{10}+\underline{1})_{SO_{10}} \to (\underline{27})_{E_6}$. In addition to the $\underline{16}$ each family involves another (SO_{10}-singlet) Weyl neutrino S_L and a new

$$(\underline{10})_{SO_{10}} \to (\underline{5}^*)_{SU_5} + (\underline{5})_{SU_5} = \begin{pmatrix} N & \bar{D} \\ E^- & \end{pmatrix}_L + \begin{pmatrix} E^+ & D \\ \bar{N} & \end{pmatrix}_L , \tag{3}$$

where the $\begin{pmatrix} N \\ E^- \end{pmatrix}_L$ and $\begin{pmatrix} N \\ E^- \end{pmatrix}_R$ are an SU_2-doublet neutrino and charged lepton, and D_L and $\bar{D}_R$ is an SU_2-singlet with the same charge and color as the d quark. There are many SSB patterns for E_6, such as

$$E_6 \to SO_{10}\times U_{1\psi},\ \ SU_{3c}\times SU_{2L}\times U_1\times U_{1\chi}\times U_{1\psi}. \tag{4}$$

It is also possible to have large GUTs (e.g. SO_{18}) in which the fermion families are combined in the same irreducible representation (i.e. which incorporate a family symmetry).

From these examples it is clear that GUTs larger than SU_5 generally contain: (a) new neutral or charged gauge bosons with B and L - conserving couplings. (b) new fermions with exotic $SU_2 \times U_1$ transformation properties. Depending on the SSB pattern these may be superheavy (e.g. in the 10^{15} GeV range), light (in the 100 GeV - 1 TeV range), or anywhere in between.

There has been a recent revival of interest [9] in "flipped SU_5 GUTs" [10] based on the group $SU_5'\times U_1$. (The recent attention has concentrated on the supersymmetric version). Flipped - SU_5 is not by itself a GUT, because there is no reason for the gauge couplings g'_5 and g of the two factors to be equal unless $SU_5'\times U_1$ is embedded in a higher symmetry such as SO_{10}. Each family of fermions is assigned to a $\underline{5}^* + \underline{10} + \underline{1}$ representation (which includes an extra Weyl neutrino $\bar{\nu}_L$):

$$\begin{array}{ccc} \underline{5}^* & \underline{10} & \underline{1} \\ \begin{pmatrix} \nu_e & \bar{u} \\ e^- & \end{pmatrix}_L & \begin{pmatrix} \bar{\nu} & u & \bar{d} \\ & d & \end{pmatrix}_L & (e_L^+) \end{array} \tag{5}$$

The charge assignments are different from the ordinary SU_5 model because the electric charge generator is partially contained in the U_1 factor. The principal advantage of flipped- SU_5 is that all SSB can be accomplished by the low dimensional Higgs representations $\underline{1}, \underline{5}$, and $\underline{10}$, i.e. there is no need for adjoint ($\underline{24}$) Higgs representations (which are not present in standard superstring theories).

2.2 Supersymmetry/Supergravity/Superstrings

The supersymmetric (SUSY) extension of the standard model involves a doubling of the particle spectrum (e.g. $q \to \tilde{q}$, $l \to \tilde{l}$, $W^\pm \to \tilde{w}^\pm$, $\phi \to \tilde{\phi}$, where $\tilde{q}$ and $\tilde{l}$ are scalar quarks and leptons, $\tilde{w}$ is the spin-$\frac{1}{2}$ wino, $\tilde{\phi}$ is a spin-$\frac{1}{2}$ Higgsino, etc.), and also requires the addition of a second Higgs doublet and its fermionic partners (to give mass to both u and d quarks). The dimension-4 couplings involving the SUSY partners are related by SUSY to those of the ordinary particles, as in Figure 2. However, since degenerate boson - fermion pairs are not observed SUSY must be softly broken[3] so that $M_F \neq M_B$. Similarly, supersymmetric GUTs require a doubling of the entire particle spectrum, including the superheavy particles.

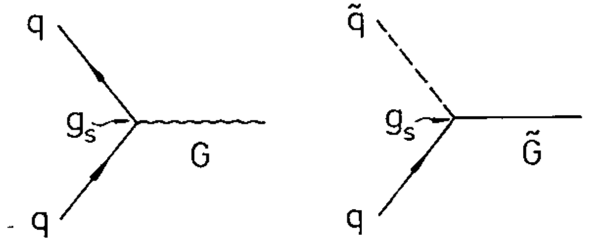

Figure 2: Typical dimension-4 (renormalizable) vertex.

The major motivation for supersymmetry is the Higgs/hierarchy problem. Actually, there are three aspects to the problem, all of which are addressed in some versions of SUSY.

(a) *The origin of the hierarchy* $M_W = 0(M_\phi) << m_P$ *(or* $M_W << M_X$ *in a SUSY-GUT.*[4]) The hierarchy can be explained in many hidden sector models, in which SUSY is broken at a scale $F << m_P$ (or $F << M_X$) in a sector of the theory that is coupled only very weakly (usually only by gravity) to the ordinary sector. The hidden sector breaking may occur because of a gaugino condensate, for example. In that case F is the scale at which a hidden sector gauge coupling becomes strong. The SUSY breaking is then manifested in the ordinary sector by a gaugino ($m_{1/2}$) or gravitino ($m_{3/2}$) mass of order $F(F/m_P)^K << F << m_P$, where K is some positive power. $m_{1/2}$ or $m_{3/2}$ ultimately set the weak scale.

(b) *Large radiative corrections.* In the standard model quadratically divergent

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[3] SUSY breaking can occur in mass terms and in dimension-3 cubic scalar couplings. It cannot appear in dimension-4 terms without destroying the cancellation of quadratic divergencies in M_ϕ^2.

[4] One can also forbid certain dangerous quartic interactions in SUSY-GUTs, without them being generated in higher orders.

corrections to M_ϕ^2 from Higgs, gauge boson, and fermion loops lead to huge renormalizations

$$\delta M_\phi^2 = O(\lambda, g^2, h^2)m_P^2, \tag{6}$$

where λ, g and h are quartic-Higgs, gauge, and Yukawa couplings, respectively. In a SUSY model, however, the supersymmetry forces a concellation between the divergent parts of the boson and fermion loops. Because of the soft SUSY-breaking, finite parts of the diagrams remain, leading to

$$\delta M_\phi^2 = O(\lambda, g^2, h^2)|M_B^2 - M_F^2|. \tag{7}$$

This will be sufficiently small (i.e. $\delta M_\phi^2 \leq 0(M_W^2)$ if the effective SUSY breaking scale (the splitting between the ordinary particles and their SUSY partners) is $|M_B - M_F| \leq O(1\ TeV)$.
(c) ***Multiplet splitting (SUSY-GUTs).*** In ordinary SU_5 one must introduce a $\underline{5}^*$ of Higgs in order to break $SU_2 \times U_1$. This $\underline{5}^*$ contains the ordinary Higgs doublet $(\phi^0\phi^-)^T$ as well as a color anti-triplet $\bar{H}_\alpha$ of charge-$\frac{1}{3}$ scalars. The $\bar{H}_\alpha$ can mediate proton decay, so their mass must exceed $10^{12}\ GeV$. Hence, one requires a splitting of the 5^* into light (ϕ^0, ϕ^-) and superheavy $(\bar{H}_\alpha)$ sectors.

In ordinary SU_5 this splitting can only be achieved via a highly contrived fine-tuning of parameters in the Higgs potential. However, in SUSY-GUTs the splitting can occur naturally by the missing partner mechanism. [12] The idea is that in a SUSY-GUT one has $M_H \simeq M_{\tilde{H}}$, $M_\phi \simeq M_{\tilde{\phi}}$, up to splittings of order SUSY breaking. However, fermion mass terms are always of the form $M\bar{\psi}_L\psi_R + h.c.$, i.e. transitions between right and left-handed fermions. It is possible to choose representations for the Higgs particles and their partners so that $\tilde{H}_L$ has a right-handed partner and therefore achieves a superheavy mass in the original SU_5 breaking, but for which $\tilde{\phi}_L$ has no such partner. The $\tilde{\phi}$ and (ϕ) are therefore protected from acquiring masses until later stages of symmetry breaking at much lower scales.

This missing partner mechanism is very elegant in principle. However, it can only be implemented in SUSY-GUTs if very complicated ("baroque") Higgs representations (such as $\underline{50}$'s and $\underline{75}$'s are used. [12] A primary motivation for the SUSY-flipped SU_5 model is that the missing partner mechanism can occur for low $(\underline{1}, \underline{5}, \underline{10})$ dimensional Higgs multiplets. [9]

Various supersymmetric-GUTs (or the SUSY standard model) therefore solve some or all aspects of the Higgs/hierarchy problem. If the supersymmetry is made into a local symmetry (supergravity or SUGRA) one also has a unification of gravity with the microscopic interactions. However, the gravity problem is only partially solved: supergravity does not solve the divergence problem of quantum gravity (it is still nonrenormalizable) or (most likely) the cosmological constant problem.

An exciting possibility, which may incorporate many aspects of the SUGRA-GUTs, are the currently popular superstring theories, [5] such as $E_8 \times E_8$ string models in ten space-time dimensions. These presumably compactify to a SUSY gauge theory based on a subgroup $G \epsilon E_8 \times E_8$ in four dimensions. Superstring theories naturally incorporate gravity. Moreover, gravity and the other interactions are almost certainly finite (not just renormalizable) to all orders in perturbation theory. One may think of this as due to the fact that the vibrations of the string represent an infinite number of particle states, with couplings arranged to give finite higher order corrections. Hence, except for the cosmological constant (the status of which is uncertain) the graviton problem is solved.

Superstring theories have no free parameters, and the number of fermion families and their masses and mixings are controlled by the compactification, so the fermion problem is solved in principle. However, in practice there are enormous number of possible compactifications (and therefore low energy theories), and we have no way at present of selecting between them. Hence, at present the superstring has little or no predictive power. Superstring theories do, however, provide an existence proof that there are possible solutions beyond the Planck scale for many of the diseases of the standard model. For definiteness I will mention one class of string-inspired models that have received much attention, viz. compactification on a Calabi-Yau manifold, leading to an effective SUSY $G \times E_8$ field theory in four dimensions. The ordinary particles are singlets under E_8, which can therefore play the role of a hidden sector for SUSY breaking. G is a subgroup of E_6, containing at least an extra U_1 factor (which probably survives to low energies) in addition to the standard model. Matter fields occur in $\underline{27}$-plets. (There may be additional incomplete $\underline{27}$ or $\underline{27}^*$-plets).

3 PHENOMENOLOGICAL IMPLICATIONS

3.1 Coupling Constants

There is only one underlying gauge coupling in grand unified theories, so the properly normalized running couplings

$$\alpha_1 \equiv \frac{5}{3}\frac{g'^2}{4\pi}, \quad \alpha_2 \equiv \frac{g^2}{4\pi}, \quad \alpha_3 \equiv \frac{g_s^2}{4\pi}, \tag{8}$$

are expected to meet at the unification scale M_X. One can predict M_X and $\sin^2\theta_W \simeq g'^2/(g^2 + g'^2)$ from the observed ratio of α/α_s and the renormalization group equations (RGE) provided
(a) there are only two mass scales (M_W and M_X), with a grand desert in between, so that the three couplings all meet at one point.
(b) The quantum numbers of a full G-multiplet are known (so that the normalizations of the α_i can be computed).
(c) The light particle quantum numbers are known (so that the RGE coefficients can be computed.

Using the average

$$\Lambda^{(4)}_{\overline{MS}} = 150^{+150}_{-75}\ MeV \tag{9}$$

for the QCD scale parameter, defined by

$$\alpha_s(Q^2) = \frac{6\pi}{32 - n_q}\left[\ln \frac{Q}{\Lambda^{(n_q)}_{\overline{MS}}}\right]^{-1} + \text{h.o.t.}, \tag{10}$$

one obtains [13]

$$\begin{aligned} M_X &= 2.0^{+2.1}_{-1.0}\times 10^{14}\ GeV \\ \sin^2\hat{\theta}_W(M_W) &= 0.214^{+0.003}_{-0.004} \end{aligned} \tag{11}$$

for SU_5 and similar two scale models. The $\sin^2\hat{\theta}_W(M_W)$ prediction in (11) is $\simeq 2\frac{1}{2}\sigma$ below the experimental average [13,14]

$$\sin^2\hat{\theta}_W(M_W)_{exp} = 0.228 \pm 0.0044, \tag{12}$$

(which is dominated by the W and Z masses and recent high precision deep inelastic neutrino scattering experiments. [13,14]) The value in (12) is for $m_t = 45\ GeV$ and $M_\phi = 100\ GeV$. The discrepancy increases for larger m_t, as can be seen in Figure 3, or for additional fermion families.

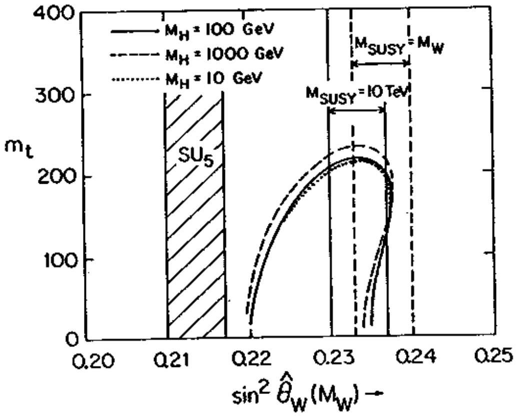

Figure 3: Allowed region (90% *c.l.*) in $\sin^2\hat{\theta}_W(M_W)_{exp}$ vs m_t for various values of the Higgs mass, compared with the predictions of ordinary and supersymmetric SU_5. M_{SUSY} is the SUSY breaking scale.

The discrepancy can also be seen in Figure 4, in which are shown the couplings $\alpha_i(Q^2)^{-1}$ determined by the experimental values of α, $\Lambda^{(4)}_{\overline{MS}}$, and $\sin^2\hat{\theta}_W(M_W)$. It is seen that the α_i^{-1} do not all meet at a point, although the statistical significance is not compelling.

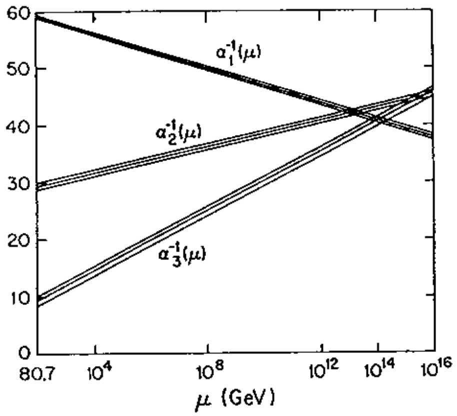

Figure 4: The running couplings $\alpha_i^{-1}(Q^2)$ (68% *c.l.* bands), from ref [13].

The failure of the $\sin^2\hat{\theta}_W(M_W)$ prediction in (11) provides strong evidence (independent of the non-observation of proton decay) against the simplest GUTs. However, the discrepancy is small, suggesting that the GUT ideas may be approximately correct but that there is new physics in the desert.

For example, one could have a SO_{10} model breaking in two stages to the standard model [15]

$$\begin{aligned} SO_{10} \ &\underset{M_X}{\rightarrow}\ SU_{3c}\times SU_{2L}\times SU_{2R}\times U_1' \\ &\underset{M_R}{\rightarrow}\ SU_{3c}\times SU_{2L}\times U_1 \end{aligned} \tag{13}$$

where $M_X \sim M_5(M_5/M_R)^{1/2} > M_5$, and M_5 is the SU_5 prediction in (11). For $M_R \sim 10^{12}\ GeV$, for example, one has an acceptable $\sin^2\hat{\theta}_W(M_W) \sim 0.224$ and $M_X \sim 10 M_5 \sim 2\times 10^{15}\ GeV$ (leading to a suppression of proton decay). It should be emphasized that $\sin^2\hat{\theta}_W(M_W)$ is no longer predicted: it is a function of M_R.

In the minimal supersymmetric extension of SU_5 one has $M_X/M_5 \sim 25$ because of the effect of the new particles on the RGE. One finds [13,16]

$$M_X \sim 5\times 10^{15}\ GeV \tag{14}$$

$$\sin^2\hat{\theta}_W(M_W) \sim 0.237^{+0.003}_{-0.004} - \frac{4\alpha(M_W)}{15\pi}\ln\left(\frac{M_{SUSY}}{M_W}\right) \tag{15}$$

The $\sin^2\hat{\theta}_W(M_W)$ prediction is in reasonable agreement with (12) as can also be seen in Figure 3. However, the prediction is slightly high ($1\frac{1}{2}\sigma$), suggesting (a) a large $\Lambda_{\overline{MS}}$, (b) a large m_t, or (c) a large SUSY breaking scale.

Another relevant observable is the parameter[5]

$$\rho \equiv \frac{M_W^2}{M_Z^2\cos^2\theta_W} \tag{16}$$

ρ is predicted to be unity (in an appropriate renormalization scheme) in theories in which there are no Higgs SU_2-triplets (or high higher dimensional representations) in the low energy theory. This is the case for minimal SU_5 and is a reasonably firm prediction of superstring theories. Experimentally [13,14]

$$\rho_{exp} = 0.998 \pm 0.0086, \tag{17}$$

in impressive agreement with unity.

In many simple GUT models[6] (*not* including Calabi-Yau string models) the Yukawa couplings to the b quark and τ lepton are equal at the unification scale. Including RGE effects on m_b this implies [6] the successful prediction

$$m_b(5\ GeV) \simeq 5\ GeV \tag{18}$$

(m_b is too large for four or more families). Unfortunately, the same models also predict $m_s \sim 500\ MeV$, which is much larger than phenomenological determinations ($100 - 200\ MeV$), and $m_s/m_d = m_\mu/m_e \sim 200$, which is an order of magnitude larger than the current algebra ratio $\simeq 20$. To save such models one must hope that new physics (e.g. associated with the Planck scale) perturbs the smaller masses m_d and m_s without greatly modifying m_b.

3.2 Proton Decay

The most dramatic prediction of grand unification is proton and bound neutron decay. Unfortunately, even within minimal SU_5 the expected proton lifetime has large uncertainties both from $\Lambda_{\overline{MS}}$ (which determines M_X) and also from the poorly known hadronic matrix elements of the effective four-fermion operators. There have been many theoretical calculations [17], based on relativistic and non-relativistic quark models, the MIT bag, PCAC, vector meson dominance, chiral Lagrangians, QCD sum rules, etc. Even for the same value of M_X these calculations vary in their predictions for the proton lifetime by as much as two orders of magnitude. A reasonable range for the partial lifetime (τ/B) into $e^+\pi^0$ is

$$\begin{aligned} \tau(p\to e^+\pi^0)(yr) &\simeq 3.7\times10^{29\pm0.7}\left[\frac{M_X}{2\times10^{14}GeV}\right]^4 \\ &< 3.3\times10^{31}yr, \end{aligned} \tag{19}$$

where (11) has been used for M_X, and where the theoretical uncertainty $10^{\pm0.7} \sim (5)^{\pm1}$ is a guess based loosely on the spread of theoretical estimates. The present experimental limit $\tau(p \to e^+\pi^0) > 4 \times 10^{32}$ yr. therefore essentially rules out minimal SU_5. However, it is hard to make an absolute statement to that effect because the uncertainties in $\Lambda_{\overline{MS}}$ and the matrix elements are large and difficult to quantify.

Other gauge groups G, such as SO_{10}, E_6, etc., typically predict slightly faster decays into $e^+\pi^0$ and enhanced branching ratios into neutrino modes because of the additional superheavy gauge bosons. Although the simplest SU_5 model is apparently ruled out, the basic ideas of grand unification are still alive and well. Many relatively simple modifications or extensions of minimal SU_5, some of which are natural and some ad hoc, lead to a longer lifetime and/or different decay modes. Unfortunately, they also tend to have less predictive power for $\sin^2\hat{\theta}_W(M_W)$.

The models with longer lifetimes fall into three principal classes. The first possibility is to add structure in the desert between M_W and M_X (e.g. in the form of new gauge, Higgs, or fermion mass scales), so that the renormalization group equations which determine M_X and $\sin^2\hat{\theta}_W(M_W)$ are modified. Some examples of this mechanism are: (a) it is possible to have more than two symmetry breaking (i.e. gauge boson mass) scales. For example, in the SO_{10} model in (13) τ_P is increased by some four orders of magnitude compared to (19). (b) Similarly, in supersymmetric SU_5 the unification scale is increased by $\simeq 25$, leading to a proton lifetime from X and Y exchange of $\sim 10^{35}$ yr. (Other sources of proton decay in SUSY models are discussed below). As we have seen, these two cases lead to reasonable $\sin^2\hat{\theta}_W(M_W)$ values.

(c) Another reasonable possibility is that there are heavy Higgs particles that are not quite degenerate with M_X. There are various cases [18] in which acceptable τ_P and $\sin^2\hat{\theta}_W(M_W)$ can be achieved with $(M_H/M_X) \sim 10^{\pm3}$, for example. (d) Approximately degenerate new G multiplets of fermions or scalars do not affect M_X to lowest order. On the other hand, split fermion or Higgs multiplets which have some light (e.g. $O(M_W)$) and some heavy ($O(M_X)$) particles can affect τ_P and $\sin^2\hat{\theta}_W(M_W)$ in either direction. Such multiplet splitting models are usually quite at hoc, and most splittings lead to unacceptable values of M_X and $\sin^2\hat{\theta}_W(M_W)$. Also, it is hard to understand how the mass splittings come about, although one splitting (of a $\underline{5}$ dimensional Higgs representation in minimal SU_5) is needed in any case to generate the $SU_2 \times U_1$ scale without having very fast proton decays mediated by the partners of the ordinary Higgs doublet.

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[5] In eqn. 16 $\sin^2\theta_W$ is defined using the mass definition $1 - M_W^2/M_Z^2$. See [13] for the relation between the various renormalization schemes.

[6] The mass predictions are generally lost in flipped SU_5 models. However, some string inspired versions have an extra symmetry which recovers the m_b (but not m_s or m_d) prediction. J. Ellis, private communication.

A very different possibility is that the proton decay rate is suppressed by mixing angle effects.[6] It is possible, though not very natural, that in models with complicated Higgs structures the light quarks and heavy leptons, for example, are associated together in multiplets. In this case the dominant amplitudes could be into energetically forbidden channels such as $p \to \tau^+\pi^0$. In most cases the lifetime is expected to increase by no more than $\sin^{-2}\theta_c \sim 20$, however. One exception to this limitation is models in which the proton is made absolutely stable by imposing an ad hoc new quantum number on the theory. Such models generally involve a doubling of the fermions and can lead to the dramatic signal of baryon number violation at accelerators. Many models in which proton decay is suppressed by mixing effects only (i.e. without changing the RGE or M_X) are expected to have difficulties with $\sin^2\hat{\theta}_W(M_W)$.

Finally, effective non-renormalizable operators [6] such as $Tr(F_{\mu\nu}F^{\mu\nu}\phi)/M$, where ϕ is the adjoint Higgs representation, could be generated if a GUT is embedded in a larger theory, such as supergravity or a Kaluza-Klein theory, with mass scale M. Such operators modify the gauge kinetic energy terms and can have the ultimate effect of increasing M_X.

3.3 Proton Decay in SUSY-GUTs

In SUSY-GUTs the proton decay rate from X and Y exchange is probably unobservably slow because of the increase of the unification scale. However, there are new mechanisms for proton decay, as shown in Fig. 5.

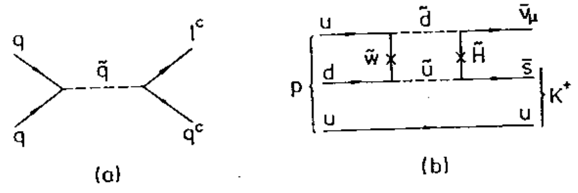

Figure 5: New proton decay diagrams that can occur in supersymmetric GUTs. (a) a dimension-4 diagram that must be forbidden to avoid a disastrously short lifetime. (b) a dimension-5 diagram.

The diagram of Figure 5a involves the exchange of a light scalar quark. It is not suppressed by any power of M_X^{SUSY} and, if present, would lead to a disastrously short proton lifetime. Fortunately, it can be forbidden by imposing discrete symmetries on the Lagrangian.

The colored Higgsino $(\tilde{H})$ exchange in the box diagram in Figure 5b leads to the dimension-5 operator

$$L \sim h^2 q l \tilde{q}\tilde{q}/M \qquad (20)$$

where h is a Yukawa coupling and $M \sim M_X^{SUSY}$ is the Higgsino mass. After dressing with a light wino or gluino, etc., these operators lead to proton decay, usually into $\bar{\nu}K^+$.

The predicted lifetime is of order M^2 (rather than the usual M_X^4). This appears disastrous, but in fact there are a number of suppressions to the decay rate ($M_X^{SUSY} > M_X, 1/16\pi^2$ from the loop, two small Yukawas, smaller higher order enhancement factors). The expected lifetime is typically in the range $10^{26} - 10^{31}$ yr (with large uncertainties from the superpartner masses) for models with hidden sector breaking. This is short compared to the current experimental limit $\tau(p \to \bar{\nu}K^+) > 7 \times 10^{31}$ yr, which excludes a large class of SUSY-GUTs. Nath and Arnowitt [19] have recently argued, for example, that the proton lifetime constraint places significant lower limits on the masses of the SUSY-partners in a class of "standard SUSY-GUTs", as is illustrated in Table 2. Of course, the proton lifetime and branching ratio can be modified in variations on the simplest SUSY-GUTs (e.g. by adding extra split supermultiplets), just as in ordinary GUTs. Also, the decay rate from dimension-5 operators is suppressed in flipped SU_5.[9]

Table 2: Lower bounds on the mass of the lightest squark, as a function of the lower limit of the photino mass, for a class of "standard SUSY-GUTs", from ref. [19] The columns A, B, and C refer to three assumptions concerning the relevant matrix elements, etc.

$(m_{\tilde{\gamma}})_{min}(GeV)$	$(m_{\tilde{q}})_{min}(GeV)$		
	A	B	C
10	3000	895	250
15	3750	1130	455
20	4300	1300	560
30	5300	1650	710

It is not possible to make a general prediction concerning proton decay in superstring models - there are too many possibilities. For example, superstring models involving an intermediate scale are likely to be similar to SUSY-GUTs, while models in which the gauge symmetry just below the compactification scale is $SU_3 \times SU_2 \times U_1 \times U_1'$ are likely to lead to unobservably long lifetimes. $\sin^2\hat{\theta}_W(M_W)$ is a useful constraint on superstring model building.

There are many other possibilities for proton decay (some outside of the GUT framework), such as the exchange of superheavy colored Higgs scalars, Pati-Salam type models, and compositeness. The predictions of many models are summarized in Table 3. Proton decay is a unique window on short distance physics that is

Table 3: Predictions for the proton lifetime and decay modes in various models.

Model	Typical τ_p (yr)	Important Modes
Simple two scale GUTs	10^{27} - 10^{31}	$e^+\pi^0$, $\bar{\nu}\pi^+$, $e^+\omega$, μ^+K^0, $\cdots$
Large M_X GUTs (3 scale)	10^{31} - 10^{35}	same
Mixing angle suppression ($\sin^2\theta_W$ problem)	10^{28} - 10^{32}	e^+M, μ^+M, $\bar{\nu}M$ ($M = \pi, \omega, K$, etc.)
Higgs exchange (require $M_H \geq 10^{12}\ GeV$)	arbitrary	μ^+K^0, $\mu^+\omega$, $\bar{\nu}K^+$
Supersymmetry	10^{26} - 10^{31}	$\bar{\nu}K^+$
Superstrings		
(1) $SU_3 \times SU_2 \times U_1 \times U_1{}'$ at m_P	∞	—
(2) intermediate scale	similar to SUSY	
Pati-Salam	arbitrary	$3\nu\pi$'s, $\nu\nu e^-\pi^+\pi^+$
compositeness	arbitrary	—

expected to occur at some level in many extensions of the standard model. It is very important to try to push the search for proton decay as far as possible. An ambitious but not impossible goal is to search for lifetimes as long as 10^{34} yr for as many modes as possible.

3.4 Neutron-Antineutron Oscillations

Another possiblity for baryon number nonconservation is $\Delta B = 2$ operators that can cause neutrons to oscillate into antineutrons. The current reactor limit [20] on the free neutron oscillation time $\tau_{osc} > 10^6$ sec. may ultimately be improved to 10^8 sec. [21] A more stringent but less direct limit may be obtained from the nonobservation of $\Delta B = 2$ processes in nuclei. Dover, Gal, and Richard [22] have done a thorough optical model study utilizing analyses of $\bar{p}$-atom level shifts and widths as well as low energy $\bar{p} - {}^{12}C$ scattering data from LEAR. They find that the limit [23] $\tau_{nuc} > 2.4 \times 10^{31}$ yr from IMB implies $\tau_{osc} > (1 \pm 0.3) \times 10^8$ sec., where the ± 0.3 is their estimate of the theoretical uncertainties.

Most models leading to $\Delta B = 2$ interactions involve heavy Higgs particle exchange. In many cases the Higgs particles are introduced in a rather ad hoc manner. Furthermore, τ_{osc} is proportional to M^5, where M is the typical mass of the particles mediating the interaction. Only for M in the rather narrow range $10^5 - 10^6\ GeV$ are neutron oscillations experimentally relevant. This range has not emerged in a natural way in any theory, and in particular a number of authors [24] have shown that it does not occur for any viable SO_{10} symmetry breaking pattern if one makes the reasonable requirement that M be associated with a gauge bosons mass scale. The theoretical estimates are therefore not very optimistic.

3.5 The Cosmological Baryon Asymmetry

One of the most attractive features of grand unification is that it can account for the observed baryon asymmetry [25]

$$\frac{n_B}{n_\gamma} \simeq 10^{-10}, \qquad n_{\bar{B}} << n_B, \tag{21}$$

where n_B, $n_{\bar{B}}$, and $n_\gamma \simeq 400/cm^3$ are the present average number densities of baryons, antibaryons, and microwave photons, respectively. If baryon number were exactly conserved, as in the perturbative standard model, then most likely the asymmetry $\Delta B/n_\gamma \equiv (n_B - n_{\bar{B}})/n_\gamma \simeq 10^{-10}$ would have to be imposed as an initial condition on the big bang. This is certainly possible, but not very attractive. Alternatively, one can imagine that there is no net asymmetry but that there is a large scale separation of baryons and antibaryons in the Universe. This view runs into severe difficulties, however.

In GUTs, the baryon asymmetry can be generated dynamically in the first 10^{-35} sec after the big bang when the temperature was comparable to M_X. In addition to B violation, the necessary ingredients are C and CP violation, to distinguish baryons from antibaryons, and nonequilibrium[7]. The latter is necessary because otherwise $n_B = n_{\bar{B}}$, since B and $\bar{B}$ are degenerate by CPT.

In most models the actual mechanism is the decay of super-heavy Higgs particles H and their antiparticles $\bar{H}$. CP violation allows the relative rates for $\bar{H} \to qq$ and $\bar{q}\bar{l}$ to differ from those for $H \to \bar{q}\bar{q}$ and ql. In the minimal SU_5 model with three fermion families the asymmetry requires a three loop diagram and is too small ($\sim 10^{-20}$). However, an adequate asymmetry can be generated for ≥ 4 families or if additional superheavy Higgs multiplets are added to the theory. [25]

Recently, a number of authors [27]-[31] have constructed models in which ΔB can be generated at temperatures much smaller than the GUT scale. This is possible in principle but is very difficult in practice: the expansion rate $H \propto T^2/m_P$ is sufficiently slow at low T that it is hard to achieve nonequilibrium.

One motivation is the gravitino problem in SUGRA GUTs: relic gravitinos may contribute too much to the energy density of the present Universe if their mass is in the range 1 KeV – 10^4 GeV, which includes the values favored by most models of radiative $SU_2 \times U_1$ breaking. These gravitinos can be diluted to a negligible density by a later period of inflation, but new gravitinos will be produced subsequently if the reheating temperature T_R is too high. It has been argued [32] that too much D and ${}^3He$ will be produced by the radiative breakup of ${}^4He$ by

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[7] An alternative would be to allow CPT breaking [26]

the photons produced in gravitino decay ($g_{3/2} \rightarrow \gamma + \tilde{\gamma}$) unless

$$T_R(GeV) < 2.5 \times 10^8 \left(\frac{100\ GeV}{m_{3/2}} \right). \tag{22}$$

In such a model one must generate a new baryon asymmetry at a temperature $T < T_R \ll M_X$. Possible mechanisms to achieve nonequilibrium include (a) The decay of a very weakly coupled heavy particle [27] (very complicated models are needed). (b) Heavy particle production via the anharmonic oscillations of a scalar field after inflation [28]. (c) Particle production in a first order phase transition [29] (the heavy particle mass is turned on suddenly at the time of the transition, allowing a much greater than equilibrium concentration). In the above mechanisms the asymmetry is produced by the subsequent B and CP violating decays. (d) A very interesting possibility [30] is that the Universe may have gone through an intermediate phase in which the squark and slepton fields possessed non-zero vacuum expectation values (i.e. B, L, and electric charge were spontaneously broken) after a period of inflation. Enormous asymmetries could have been generated in the subsequent evolution and decay of such scalar fields. (e) The Kuzmin-Rubakov-Shaposhnikov (KRS) mechanism[31] discussed below.

It has long been known [33] that there is B violation in the standard model due to anomalies, which allow the possibility of tunnelling between vacua with different baryon numbers. At $T = 0$ the tunnelling amplitude is negligibly small ($\propto \exp(-4\pi \sin^2\theta_W/\alpha) \sim 10^{-172}$). However, KRS [31] and others [34] have argued that such effects would be unsuppressed at the time of the electroweak (EW) phase transition $T \sim M_W/\alpha_W \sim 10\ TeV$, because thermal fluctuations would eliminate the need for tunnelling. The KRS effect is potentially disastrous, because it could very well wipe out any baryon asymmetry produced earlier. Possible ways out include: (a) The previous asymmetry was enormous, as might be possible in the Affleck-Dine model [30] ($\langle\tilde{q}\rangle, \langle\tilde{l}\rangle \neq 0$.) (b) The KRS mechanism conserves $B - L$. Hence, any preexisting asymmetry with $B - L \neq 0$ will survive. For example, an initial lepton asymmetry (e.g. generated by the decays of superheavy Majorana neutrinos [35]) would be partially converted into a baryon asymmetry. (c) The baryon asymmetry may have been created after the EW transition [27]. (d) The KRS mechanism is ineffective if the EW phase transition is first order ($M_\phi \leq 45\ GeV$) because M_W is turned on suddenly. In fact, it is even possible that the baryon asymmetry could be generated during the EW transition (i.e. without the need for new physics!) if $M_\phi \leq 45\ GeV$. Shaposhnikov [31] has gone a step further and argued that the baryon asymmetry suggests $M_\phi \sim 10\ GeV$ or $M_\phi \sim 45\ GeV$, because the asymmetry would be too large for intermediate values.

3.6 Other Implications of GUTS

3.6.1 Extra gauge bosons

Many GUTs larger than SU_5 predict the existence of additional neutral or charged gauge bosons (as in (2) and (4)), which could conceivably be light enough to be experimentally accessible. For most GUT-motivated extra Z's the best current limits are indirect constraints from the weak neutral current. These limits are quite weak: $M_{Z'} \geq 120 - 300\ GeV$, depending on the model. [13,14] Direct and indirect future searches at the Tevatron and at LEP/SLC, respectively, should be sensitive to at least 500 GeV.

The most likely candidate for a new W is the W_R occurring in $SU_{2L} \times SU_{2R} \times U_1$ models[8]. There is an indirect limit $M_{W_R} > 2.5\ TeV$ from the $K_L - K_S$ mass difference if U^R,the analogue of the Kobayashi-Maskawa-Cabibbo (KMC) mixing matrix for the right-handed current, is similar to the left-handed KMC matrix [36]. However, M_{W_R} could be as low as 300 GeV if U^R is arbitrary [37,38]. Also, muon decay constraints [39] imply $M_{W_R} > 400\ GeV$ if the neutrinos N_R in the right-handed leptonic current are lighter than m_μ (they are usually assumed to be much heavier). It is hard to accomodate a light (O(TeV)) W_R in GUTs if there is a left-right symmetry between the SU_{2L} and SU_{2R} factors (i.e. if parity is restored at M_{W_R}), because of (a) too large a value for $\sin^2\theta_W (\sim 0.28)$, (b) unacceptable cosmological domain walls in many cases, and (c) no baryon asymmetry (unless it is generated later) because CP is restored at high T. These problems can be avoided if M_{W_R} is very large ($\geq 10^{12}\ GeV$) or if the left-right symmetry is broken at a much larger scale ($\geq 10^{12}\ GeV$) than M_{W_R}. [15,6]

3.6.2 Exotic fermions

Many models predict the existence of exotic new fermions [40,41], as in the SO_{10} and E_6 examples in section 2.1. The direct production limits are quite weak:

$$\begin{aligned} M_N &\geq 18\ GeV \\ M_{E^-}, M_U, M_D &\geq 23\ GeV \end{aligned} \tag{23}$$

from PEP and PETRA[9]. Also, mixing between SU_2 doublets and singlets will generally induce flavor-changing neutral currents (FCNC) $\lambda^a_{ij} \bar{\psi}_{ia} \gamma^\mu \psi_{ja} Z_\mu$, $a = L$ or R, between the ordinary fermions. Typically,

$$\lambda_{ij} \sim a_{ij} \left(\frac{m_i m_j}{M^2} \right)^\kappa , \tag{24}$$

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[8] A new boson coupling to the same (left-handed) current as the ordinary W is hard to generate in a gauge theory, but could exist if the W is composite.

[9] For some classes of exotic fermions stronger limits of $O(40\ GeV)$ may be obtainable from the $Sp\bar{p}S$, but these have not been systematically explored.

where m_i and M are the masses of the light and heavy fermions, and κ is of $O(1)$. For example, $\kappa = 1$ if the light masses are generated by the ordinary Higgs mechanism with mixing masses of the same order, while $\kappa = \frac{1}{2}$ if the light masses are generated by the mixing. α_{ij} is a model dependent constant $(0 \leq \alpha_{ij} < O(1))$. The limits on the λ_{ij} are extremely stringent (table 4); the implied lower limits on M are quite weak for $\kappa = 1$, but are rather stringent for $\kappa = \frac{1}{2}$ and $\alpha \sim 1$. However, these limits can be fine-tuned away ($\alpha_{ij} \simeq 0$) in models in which each light fermion mixes with a unique heavy fermion. Other limits on light-heavy mixing [40,41] from flavor-diagonal neutral currents, from charged-current universality and limits on induced right-handed currents, and from the relation between G_F and $M_{W,Z}$ are weaker but cannot be fine-tuned away. Finally, the new exotic fermions may have leptoquark or diquark couplings [5,42], but they cannot have both simultaneously (otherwise they could mediate fast proton decay).

Table 4: Limits on FCNC, from [40], and associated lower limits on exotic fermion masses for two typical models.

	Limit	Source	$M/\alpha^{1/2}$ (GeV) $\kappa = 1$	M/α (GeV) $\kappa = \frac{1}{2}$
λ_{ds}	6×10^{-5}	$K_L K_S, K_L \to \mu^+\mu^-$	4	500
λ_{cu}	5×10^{-4}	$D^0 \bar{D}^0$	5	200
λ_{bd}	4×10^{-4}	$B_d^0 \bar{B}_d^0$	11	600
λ_{bs}	10^{-2}	$B \not\to l^+ l^- X$	7	70
$\lambda_{\mu e}$	3×10^{-6}	$\mu \not\to e\gamma$	6	3300

3.6.3 Neutrino mass

Most GUTs other than minimal SU_5 predict non-zero neutrino masses [43]. For example, simple GUT seesaw models [44] predict Majorana masses around 10^{-11} eV, $10^{-6} eV$, $10^{-3} eV$ for the ν_e, ν_μ, and ν_τ, respectively. Similarly, models with intermediate ($\sim 10^9$ GeV) scales typically yield predict Majorana masses around 10^{-7} $eV, 10^{-2} eV$, and 10 eV. These masses are hopelessly small for laboratory experiments (except possibly for $\nu_\mu \to \nu_\tau$ oscillations in the intermediate scale case). However, they are in the right range to solve the Solar neutrino problem using the Mikheyev-Smirnov-Wolfenstein (MSW) mechanism [45] of matter-enhanced conversions. One would have $\nu_e \to \nu_\tau$ and $\nu_e \to \nu_\mu$ conversions for the GUT and intermediate scale seesaws, respectively. Also the ν_τ would be an excellent dark matter candidate in the latter case.

It is difficult to implement the seesaw model in most superstring inspired models (this is not the case for flipped-SU_5) because there is no appropriate Higgs field to generate a large seesaw mass scale. [5] It has been suggested [46] that the large scale could be generated by a higher order effective operator, but such models may run into serious cosmological problems [47]. Another possibility is that the neutrinos are Dirac, and that they are so light because their masses are forbidden at tree level by some new symmetry. [48]

3.6.4 Superheavy magnetic monopoles

All grand unified theories predict the existence of superheavy (mass $\simeq M_X/\alpha_G \simeq 10^{16}$ GeV) magnetic monopoles. In addition to their electromagnetic interactions, GUT monopoles may catalyze baryon number violating processes such as $Mp \to Me^+\pi^0$ with strong interaction strength (much larger than the naive geometric estimate $\sigma \sim M_X^{-2} \sim 10^{-56}$ cm^2). Monopoles could have been prolifically produced in phase transitions in the early Universe. The present energy density from these relic monopoles would be far too large in the simplest models, but can be reduced to arbitrarily small amounts by a subsequent period of inflation (this was the primary original motivation for inflation). Hence, there is no prediction for the present monopole flux. A number of sensitive monopole searches are now underway [49]. However, astrophysical limits are already very stringent [50], especially for monopoles which can catalyze proton decay.

4 Summary

- There must be new physics beyond the standard model.
- Grand unified theories solve the gauge problem, but not the fermion, Higgs, strong CP , or graviton problems. The simplest models are ruled out by new experimental results on $\sin^2\theta_W$and by the non-observation of proton decay, but more complicated (e.g. three scale) models are still viable. The generation of the cosmological baryon asymmetry is still a very appealing aspect of GUTs, though the situation is confused by the KRS mechanism. On the whole, it appears that the simple GUT idea is probably too naive, but that some aspects may well survive.
- SUSY and supergravity GUTs stabilize the weak scale, and some versions may even be able to generate it. Supergravity unifies gravity with the other interactions, but it is still non-renormalizable. SUSY GUTs predict an acceptable value for $\sin^2\theta_W$, but do not explain the fermion or strong CP problems, and $p \to \bar{\nu} K^-$ is a serious problem for many models.
- Superstring theories probably yield a finite quantum theory of gravity, and are in principle unique (i.e. the fermion problem is solved). However, we are currently far from understanding whether the compactification is unique, and therefore from making contact with low energy physics. String models *may* incorporate some of the ideas of (SUGRA) GUTs.

- We clearly need experimental guidance. Promising areas for GUTs include searches for new fermions and gauge bosons, neutrino mass, magnetic monopoles, and proton decay.

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