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SUPERSYMMETRY, GRAND UNIFICATION

AND PROTON DECAY *

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ABSTRACT

In this talk, I review some phenomenological issues pertaining to supersymmetric grand unified theories (SUSY GUTs), with special emphasis on new features for proton decay.

I. Supersymmetry and the Hierarchy Problem in Grand Unified Theories

Grand Unified Theories - GUTs for short, see [1] for recent reviews - provide an appealing framework for a true unification of the strong and electroweak interactions successfully described by the standard $SU(3) \times SU(2) \times U(1)$ low energy theory. Theories of this type lead to unique new insights into the systematics of quark and lepton masses and interactions. A most impressive result in GUTs is the accurate prediction of the neutral current mixing angle $\sin^2 \theta_W$ (see [2] for a review of $SU(5)$ GUT phenomenology). GUTs also offer an explanation for electric charge quantization and lead to the striking prediction that all baryonic matter is unstable [1]. Still, GUTs leave some very basic questions largely unanswered: For example, why the replication of fermion generations? Another difficulty arises as a result of the existence of two widely disparate symmetry breaking scales: In addition to the usual low-energy electroweak scale $O(M_W)$, GUTs involve a superheavy scale M_X , characterizing baryon number violating processes. Typically, one finds that $M_W/M_X \lesssim 10^{-12}$. The possibility of any real quantitative predictive

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FIGURE 1 Contributions to the light scalar self-mass

power is predicated on there being a "Grand Desert" between these scales in which coupling constants run unhindered by the influence of new particles and interactions with a priori unknown parameters. The existence of these two widely different scales, and of the Desert in between, are at the roots of the hierarchy problem.

To illustrate some aspects of the hierarchy problem, consider a gauge theory with scalar fields ϕ and Φ with potential $V(\phi, \Phi)$. At tree level, one can look for vacuum expectation values v and V for these fields by solving a pair of minimization equations for the potential. If we require that $v \ll V$, this amounts to two simultaneous equations for what is, to $O(v^2/V^2)$, essentially one unknown V . Consistency will require a very fine tuning of the bare parameters in the potential, to accuracy $O(v^2/V^2)$: Suppose this is done. Now, however, the fact that the low-energy theory (characterized by the scale v) is imbedded in a larger one means that radiative corrections to its parameters are meaningful and not just to be absorbed in counter-terms. As a result, the parameter v is dragged up to a value comparable to V . To see how this disastrous situation obtains, consider the light scalar particle mass, which is closely related to v , and which receives radiative corrections from a variety of graphs, as illustrated in Figure 1. One obtains an equation for the scale-dependent scalar mass, of the form:

$$M^2(v^2) = M^2(V^2) + \sum_i A_i \alpha_i \int_{v^2}^{V^2} \frac{dq^2}{q^2} + \sum_i B_i \alpha_i + O(\alpha^2) \quad (1)$$

Here, $M(v^2)$ is the effective mass at low energies, while $M(V^2)$ is the "bare" mass, defined at the superheavy scale at which new physics appears. The sums run over loops of virtual scalars, fermions and gauge particles, with couplings α_i , and with coefficients $A_i \sim O(1)$ and $B_i \sim O(\log V^2/v^2)$. Because of this quadratic dependence of the scalar self-mass on the high energy cut-off V , any relation between bare parameters arranged to give $v \ll V$ will be spoiled by radiative corrections. There is also the related issue that the standard Higgs doublet is associated with a color triplet scalar in a GUT multiplet (e.g. a $\underline{5}$ of $SU(5)$) and that a fine

tuning of parameters in the potential is also required to give this color triplet a superheavy mass so as to prevent catastrophic proton decay. This too is subject to radiative corrections.

To alleviate these difficulties requires an appeal to some new physics: One tack is to let the Desert bloom. For example, we may let the interactions in the scalar sector only become strong, thus invalidating the above perturbative analysis: This would lead to a new strong interaction sector around or above 1 TeV [3], while not necessarily spoiling GUT predictions for gauge and Yukawa interactions. We may try to do away completely with elementary scalars, as in the technicolor scenario (see [4] for a recent review), where again there is new physics around 1 TeV: *There are however serious difficulties in implementing this program in the context of GUTs.*

A more attractive possibility is that a symmetry exists which ensures that $\sum A_i \alpha_i = 0$. This would entail cancellations between fermionic and bosonic loop contributions in Figure 1: What is needed is a symmetry relating fermions to bosons, and vice-versa, in other words, global supersymmetry [5].

It has in fact been known for some time that globally supersymmetric theories exhibit drastically softened quantum divergences as compared to non-supersymmetric ones. An example of the so-called non-renormalization theorems of supersymmetric theories [6] is the absence of independent coupling constant or mass renormalization for matter fields, with only logarithmically divergent wave-function and gauge coupling constant renormalization.

As a consequence of supersymmetry (SUSY), bosons and fermions are paired, arranged in supermultiplets, and their contributions to quadratic divergences in scalar self-masses cancel. This may provide a solution for both aspects of the radiative hierarchy problem: SUSY GUTs would only require one "unnatural" adjustment of parameters at the superheavy scale, and this would be unaffected by radiative corrections, as long as SUSY is unbroken.

Of course, the real world is conspicuously non-supersymmetric, with no sign of degenerate multiplets of fermions and bosons in nature. On the other hand, for SUSY to be useful in the solution of the hierarchy problem, it can only be broken at a relatively low energy scale. To see this, let SUSY be broken at a scale Λ_{SS} , leading to a lifting of the degeneracy between say fermions f and their scalar partners sf : We can

then expect that $m_{sf}^2 - m_f^2 \sim O(\Lambda_{SS}^2)$, roughly. Then the cancellation of quadratic divergences will be imperfect with the result that $M^2(v^2) \sim O(\alpha(m_{sf}^2 - m_f^2)) \sim O(\alpha\Lambda_{SS}^2)$. Requiring that $M^2(v^2) \lesssim v^2$, we are led to the constraint $\Lambda_{SS}^2 \lesssim v^2/\alpha$ and with $v^2 \sim O(M_W^2/\alpha)$, finally to the conclusion that

$$\Lambda_{SS} \lesssim M_W/\alpha \sim O(1-10) \text{ TeV}$$

The hierarchy problem has thus been rephrased: The question is now why should SUSY be broken at such low energies ?

For a variety of reasons, supersymmetry in fact turns out to be quite resilient against breaking. Still, it may be broken either spontaneously à la O'Raifeartaigh or with a Fayet-Iliopoulos D-term [7], or it can be broken explicitly, but softly [8] (recently it has been suggested that gravitational effects could mimic explicit SUSY breaking[9]). Either way seems as good as the other, as the non-renormalization theorems hold in both cases [8]. We will assume here that SUSY is explicitly broken [10] and pursue the consequences of this assumption.

The difficulties in formulating a low-energy $SU(3) \times SU(2) \times U(1)$ model with broken SUSY are formidable and while progress has recently been made towards this goal (some attempts are reviewed in [11]), a consistent model is still lacking. In spite of this, it seems worthwhile to analyze, in as general terms as possible, the properties expected of a SUSY GUT [10, 12, 13].

II. Phenomenology of a Minimal SUSY GUT: Particle Content, Grand Unification Scale, and All That.

We will consider the minimal $SU(5)$ GUT, extended to include an unbroken $N=1$ global supersymmetry at the superheavy scale M_{SX} . The symmetry breaking pattern will then be

$$\begin{aligned} SU(5) \times (N=1 \text{ SUSY}) &\xrightarrow{M_{SX}} SU(3) \times SU(2) \times U(1) \times (N=1 \text{ SUSY}) \\ &\xrightarrow{\Lambda_{SS}} SU(3) \times SU(2) \times U(1) \\ &\xrightarrow{M_W} SU(3) \times U(1)_{em} \end{aligned}$$

For definiteness, we will set $\Lambda_{SS} = M_W$, which will also then be the mass about which the unseen supersymmetric partners are clustered. The superfield content of this minimal Super- $SU(5)$ [10,12,13] is as follows:

- Vector supermultiplet (24 of $SU(5)$) containing the $SU(3)$, $SU(2)$ and $U(1)$ gauge bosons, as well as the superheavy leptoquark bosons X and Y , and their spin-1/2 superpartners, the gauginos, denoted by a tilde ($\tilde{W}$, $\tilde{B}$, $\tilde{g}$, $\tilde{X}$ and $\tilde{Y}$, winos, binos, gluinos,...)
- Three generations of left-handed $(\underline{5} + \underline{10})_L$ quark and lepton chiral superfields, containing the usual quarks and leptons and their spin-0 superpartners, the squarks (sq) and sleptons (sl).
- Two Higgs chiral superfields ($\underline{5}_L$ and $\overline{\underline{5}}'_L$), containing the scalars H_1 and H_2^* and their spin-1/2 partners (Higgsinos).
- A left-handed chiral supermultiplet of adjoint Higgs ϕ_L , whose scalar components break $SU(5)$ by acquiring a vacuum expectation value in the usual way down to $SU(3) \times SU(2) \times U(1)$ [10].

Note that this minimal SUSY GUT has more than twice the usual number of states in standard $SU(5)$. In particular, two distinct $\underline{5}$ -plets of Higgs supermultiplets are required [10,12,13], for at least two reasons. First, to get a reasonable fermion spectrum, a point first emphasized by Sherry [14]: The new constraint of SUSY on Yukawa couplings forces the existence of separate $\underline{5}_L$ and $\overline{\underline{5}}'_L$ left-handed chiral superfields to give masses to up-type and down-type fermions respectively. Second, the couplings of spin-1/2 Higgsinos within a single chiral superfield $\underline{5}$ -plet will lead to anomalies, unless there is an accompanying $\overline{\underline{5}}$ to cancel them.

Given this new particle spectrum, it is a simple matter to write down the appropriate renormalization group equations (taking higher order effects into account) to determine the evolution of the gauge coupling constants and the new grand unification scale M_{SX} . This is shown schematically in Figure 2 where we contrast coupling constant evolution in both the usual $SU(5)$ GUT and its minimal supersymmetric extension.

Grand Unification Scale

The significant new result is that both the SUSY GUT unification scale and the grand unified coupling α_{SUM} are increased as compared to the corresponding quantities in minimal $SU(5)$. This is easily understood to follow from the proliferation of new fermionic species whose presence modifies the evolution equations [15,16,17,18] so that the non-abelian couplings are less asymptotically free than before: As seen in Figure 2, the $SU(2)$ coupling α_2 in fact increases with E in SUSY GUT. This defers grand unification to a higher scale, while making α_{SUM} larger than the corresponding α_{GUT} . Quantitatively, M_{SX} is extremely sensitive to the

FIGURE 2 Schematic representation of coupling constant evolution in Minimal SU(5) [dashed lines] and its supersymmetric extension [solid lines]

number N_H of light Higgs doublets[15,16,17,18]:

$$M_{SX} \simeq 6 \times 10^{16} \Lambda_{\overline{MS}} [\text{GeV}] \text{ GeV} \quad (\text{for } N_H = 2) \quad (2)$$

$$\simeq 3 \times 10^{15} \Lambda_{\overline{MS}} [\text{GeV}] \text{ GeV} \quad (\text{for } N_H = 4) , \quad (2')$$

as compared to the usual SU(5) result [1,19]

$$M_X \simeq 1.5 \times 10^{15} \Lambda_{\overline{MS}} [\text{GeV}] \text{ GeV} .$$

We note in both cases the familiar linear dependence on the QCD scale parameter, here expressed in GeV. We can immediately deduce from previous experience the expected proton lifetime in SUSY GUT arising from the exchange of superheavy gauge bosons (GEX): Using the scaling law $\tau_p^{\text{GEX}} \sim (\text{const.}) \times M_X^4$ leads to the estimates

$$\tau_p^{\text{GEX}} \simeq 4 \times 10^{38 \pm 1} \times (\Lambda_{\overline{MS}} [\text{GeV}])^4 \text{ years} \quad (\text{for } N_H=2) \quad (3)$$

$$\simeq 2 \times 10^{33 \pm 1} \times (\Lambda_{\overline{MS}} [\text{GeV}])^4 \text{ years} \quad (\text{for } N_H=4) , \quad (3')$$

with the usual guess of the uncertainties involved [1, 19]. We see that if GEX is the only contribution to proton decay, SUSY GUT with $N_H = 2$ in all likelihood leads to an unobservably long lifetime, which for the case $N_H = 4$ may be experimentally accessible, given a plausible value of $\Lambda_{\overline{MS}}$, say between 100 and 200 MeV. However, taking $N_H = 4$ also leads to an unacceptably large value of $\sin^2 \theta_W$, as we will see. In any case, we will argue in the next section that there are in fact new contributions to proton decay arising from dimension-5 operators which unless forbidden by a symmetry will lead to an observable decay rate for the proton with $N_H = 2$.

The new value of the grand unified coupling should also be mentioned: One obtains that $\alpha_{\text{SUM}} = 1/24$, to be compared with the usual $\alpha_{\text{GUT}} = 1/42$.

Neutral Current Mixing Angle

It is also found that the predicted value of the neutral current mixing angle is increased in SUSY GUT [15,16,17,18] :

$$\sin^2 \theta_W(M_W) \simeq 0.236 \pm 0.002 \quad (\text{for } N_H = 2) \quad (4)$$

$$\simeq 0.259 \pm 0.002 \quad (\text{for } N_H = 4) \quad (4')$$

to be compared with the usual SU(5) prediction [2]

$$\begin{aligned} \sin^2 \theta_W(M_W) &= 0.208 + 0.006 \log (0.4 \text{ GeV}/\Lambda_{\overline{MS}}) \\ &= 0.214 \pm 0.002 \end{aligned}$$

On the other hand, the radiatively corrected experimental average value for this quantity is [2] :

$$\sin^2 \theta_W^{\text{exp}} = 0.215 \pm 0.012$$

Thus while the case $N_H = 2$ merely looks uncomfortable, $N_H = 4$ seems to disagree with experiment.

Quark-Lepton Mass Ratios

The usual SU(5) predictions in the symmetry limit remain of course unchanged in SU(5) SUSY GUT. What is surprising is that when effective masses are renormalized down to physical values, the prediction $m_b/m_\tau = 3.0$ also remains unchanged in SUSY GUT. Needless to say, the same problems remain for light quark and lepton masses.

Raising the SUSY Breaking Scale

Finally, we may ask what happens if we slightly increase the SUSY breaking scale, to a value $\Lambda_{SS} > M_W$, thus displacing the SUSY partner thresholds into the Desert. It is found in this case that both M_{SX} and $\sin^2\theta_W(M_W)$ are slightly lowered [18]: for $N_H = 2$,

$$M_{SX} = (9 \pm 3) \times 10^{15} \text{ GeV} \quad (\text{when } \Lambda_{SS} = M_W) \quad (5)$$

becomes

$$M_{SX} = (4 \pm 2) \times 10^{15} \text{ GeV} \quad \text{when } \Lambda_{SS} = 10 \text{ TeV}, \quad (6)$$

while

$$\sin^2\theta_W = 0.236 \pm 0.002 \quad (\text{when } \Lambda_{SS} = M_W)$$

becomes

$$\sin^2\theta_W = 0.233 \pm 0.002 \quad \text{when } \Lambda_{SS} = 10 \text{ TeV}. \quad (7)$$

We now turn to a description of a new mechanism for proton decay peculiar to SUSY GUT, through closed loops of supersymmetric partners of the usual matter and gauge fields. We will see that this may lead to proton decay with a peculiar signature and with an observable lifetime, the increase in the grand unification scale notwithstanding.

III. Super-Nucleon Decay: New Features

It is well-known that the phenomenological consequences at low-energy of a theory with new interactions at a superheavy mass scale M^* are conveniently parametrized by an effective Lagrangian involving local operators transforming as singlets of the low-energy residual symmetry group [20]. In analyzing GUT predictions, for example, one writes an expansion

$$\mathcal{L}_{\text{eff}} = \sum_d A_d (M^*)^{4-d} O^{(d)} \quad (8)$$

in terms of $SU(3) \times SU(2) \times U(1)$ symmetric operators $O^{(d)}$, of dimension d , and of the superheavy mass M^* . For baryon number violation in standard GUTs, the minimal dimension operator must involve at least three quark fields to form a color singlet, and have an even number of fermions for Lorentz invariance: Thus it is of the form $qqql$ and has dimension six, and so the effective interaction is of the form

$$\mathcal{L}_{\text{eff}}^{\text{GUT}} = O(g^2) M_X^{-2} q q \bar{q} \ell + \dots \quad (9)$$

Now it was pointed out by Weinberg [21] and by Sakai and Yanagida [22] that if the low energy theory is extended to be $SU(3) \times SU(2) \times U(1) \times \text{SUSY}$ symmetric, new baryon number violating operators will be generated. Given the superfield content of the minimal SUSY GUT, we can immediately write down the dimension-four operator

$$\int d^2\theta U_{R\alpha} D_{R\beta} D_{R\gamma} \epsilon^{\alpha\beta\gamma} \quad , \quad (10)$$

with U_R, D_R right-handed $SU(2)$ singlet quark superfields, and α, β, γ color indices. The operator in (10) gives rise to an effective interaction between two quarks and a squark, with no suppression by inverse powers of M_{GX} , leading to an extremely short proton lifetime and so it must be forbidden [21,22,23]. This can be achieved in a number of ways, the simplest being to impose a discrete family reflection symmetry, under which the quark and lepton superfields are replaced by their negatives. Such a symmetry could even be considered "natural" in the context of the simply supersymmetric grand unified theory considered here [10,13]

Under these conditions, there will still survive some dimension - five operators contributing to baryon decay, of the form:

$$\begin{aligned} & \int d^2\theta Q_{Li\alpha} Q_{Lj\beta} Q_{Lk\gamma} L_{Ln} \epsilon^{\alpha\beta\gamma} \epsilon^{ij} \epsilon^{kn} \\ & \int d^2\theta Q_{Li\alpha} Q_{Lj\beta} Q_{Lk\gamma} L_{Ln} \epsilon^{\alpha\beta\gamma} (\vec{\tau}\epsilon)^{ij} (\vec{\tau}\epsilon)^{kn} \\ & \int d^2\theta U_{R\alpha} U_{R\beta} D_{R\gamma} \ell_R \epsilon^{\alpha\beta\gamma} \quad \dots \end{aligned} \quad (11)$$

where Q_L and L_L are left-handed doublet quark and lepton superfields, with $i, j, k, \dots$ $SU(2)$ indices, and ℓ_R is a right-handed singlet lepton superfield. Note the following important property: These operators must involve three distinct quark flavors, or vanish identically (generation indices are suppressed in (11)). To see this, note that when expressed in component form, these operators yield interactions involving for example two squarks and a quark and lepton. The requirement of color antisymmetrization will thus clash with that of Bose symmetry unless more than one generation of quarks are involved. As a consequence of this, we expect that in SUSY GUTs, strange particle final states will be dominant in proton decay [17,23].

A diagram giving rise to just such a dimension five operator is shown in Figure 3, leading to an effective baryon number violating inter-

FIGURE 3 A diagram contributing to a dimension-five operator with baryon number violation.

action of the form:

$$\mathcal{L}_{\text{eff}} \sim \frac{g_H^2}{M_{H_X}} [(sq \ sq \ q \ \ell) \text{ or } (sq \ s\ell \ q \ q)] \quad (12)$$

as a result of mass mixing between the spin-1/2 superpartners of the (superheavy) color triplet components of the $\underline{5}$ and $\underline{\bar{5}}$ of Higgs scalars. We will in fact assume that $M_{H_X} \sim M_{S_X}$. Also, g_H^2 will be a typical Higgs coupling, of the form (cf. Figure 3):

$$g_H^2 = \sqrt{2} \ G_F \ m_S m_U \times 2K \quad (13)$$

with $2K = v_0^2/v_1 v_2 = (v_1^2 + v_2^2)/v_1 v_2 > 1$, a numerical factor related to the Higgs v.e.v. in the standard model v_0 and to the v.e.v.'s v_1 and v_2 of the two Higgs doublets in the minimal SUSY GUT.

To get an operator actually resulting in proton decay, the scalars involved in the dimension five operators must still be transformed into fermions, quarks and leptons. This can be achieved via the loop diagram shown in Figure 4. The cross on the gaugino line ($\tilde{W}$, $\tilde{B}$ and $\tilde{g}$) represents a Majorana mass insertion which explicitly breaks supersymmetry: In fact, in the absence of such breaking, supersymmetry leads to a vanishing of such loop contributions [24]! Naturally, the values of the various SUSY partners' masses are just so many free parameters, but we may consider some limiting cases. For example, if (as assumed in Figure 4) we let $M_{\tilde{W}} \gg m_{sf}$ we get an effective interaction for baryon decay,

$$\mathcal{L}_{\text{eff}} \sim C \frac{g_H^2 g_2^2}{M_{H_X} M_{\tilde{W}}} q_L \ q_L \ q_L \ \ell_L \quad (14)$$

Figure 4 Loop diagram contributing to baryon decay. Here, as in Figure 3, arrows denote helicities.

where C is an important numerical factor, to be compared with the usual GUT result of Equation (9). One would at once suspect that since $M_{\tilde{W}} \sim \sim O(\Lambda_{SS}) \ll M_{\tilde{\chi}}$, such an interaction would lead to much too rapid proton decay. A careful analysis shows, however, that this is not necessarily the case [17,23]. For example, one finds for the coefficient C in Equation (14) the result

$$C = \frac{1}{32\pi^2} \log \frac{M_{\tilde{W}}^2}{m_{sf}^2} \quad . \quad (15)$$

If, on the other hand, we take say $m_{\tilde{g}} \ll m_{sf}$, the entire coefficient of $qqql$ becomes

$$\frac{1}{16\pi^2} \cdot \frac{8g_3^2}{3} \cdot \frac{m_{\tilde{g}}^2 g_H^2}{m_{sq}^2 M_{H_{\tilde{\chi}}}} \quad . \quad (16)$$

Using these interactions, and taking into account the renormalization effects as usual (with suitable modifications!) we can compute the proton lifetime and obtain bounds on the various SUSY partners' masses consistent with existing limits from experiment. Taking as a benchmark the value $M_{\tilde{\chi}} = 4 \times 10^{14}$ GeV for the usual GUT scale, we find a lifetime exceeding a lower bound of 10^{30} years or so, provided [17]

$$M_{\tilde{W}} \cdot M_{H_{\tilde{\chi}}} \geq (0.4 \text{ to } 4) \times 10^{18} \text{ GeV}^2 \quad .$$

Assuming $N_H = 2$ and therefore $M_{H_{\tilde{\chi}}} \sim M_{S\tilde{\chi}} = (0.5 \text{ to } 2) \times 10^{16}$ GeV, this yields the bound (applicable to the case $M_{\tilde{W}} \gg m_{sf}$)

$$M_{\tilde{W}} \geq (10 \text{ to } 10^3) \text{ GeV}, \quad (17)$$

or a factor of 20 larger if $N_H = 4$. This is clearly compatible with

one's naive expectations for SUSY GUTs as outlined above. The other case, $m_{\tilde{g}} \ll m_{sq}$ (lighter gaugino exchange) leads to the bound

$$m_{sq}^2/m_{\tilde{g}} \geq 0(0.1 \text{ to } 6) \text{ TeV} \quad (18)$$

which is also not impossible to arrange.

These numbers suggest that SUSY GUTs would be most comfortable with a nucleon lifetime that is close to the experimental limit.

IV. Nucleon Decay Modes: A Test of Supersymmetry ?

The question of what precise decay modes will follow for protons in SUSY GUTs can only be partially answered, if relative model-independence is to be retained. We have already found out that strange final states will probably dominate: We also know that, for $SU(5) \times SUSY$, $B - L$ is conserved. This uniquely singles out the mode $n \rightarrow K^0 \bar{\nu}$ for neutrons bound in nuclei, while leaving as likely dominant modes $p \rightarrow K^0 \mu^+$ and $p \rightarrow K^+ \bar{\nu}$ for protons.

We may still want to take an admittedly model-dependent look at proton decay modes in minimal SUSY GUT, and make for example the following assumptions [17] :

- (a) include all possible superheavy Higgs scalar and Higgsino exchanges, as well as all "light" gaugino exchanges;
- (b) allow for three generations and all possible Higgs couplings (proportional to up-type and down-type quark mass matrices);
- (c) assume that all mixing angles in the new scalar and fermionic sectors of the theory are equal to the usual Cabibbo-Kobayashi-Maskawa angles, and take the resulting GIM cancellations seriously.

This last assumption is clearly the strongest and may be somewhat questionable. However, it does lead to some amazing cancellations, resulting in the following hierarchy of decays (where K and π generically denote strange and non-strange final states respectively):

$$\begin{aligned} N \rightarrow \bar{\nu} K &\gg N \rightarrow \bar{\nu} \pi & (\sim 10\% \text{ level}) \\ &\gg N \rightarrow \mu^+ K & (\sim 10^{-3}) \\ &\gg N \rightarrow \mu^+ \pi & (\sim 10^{-4}) \\ &\gg N \rightarrow e^+ K & (\sim 10^{-5}) \\ &\gg N \rightarrow e^+ \pi & (\sim 10^{-6}) \end{aligned}$$

a pattern in sharp contrast with standard $SU(5)$ expectations. In par-

ticular, note that many experiments are designed for maximum sensitivity to the $e^+\pi^0$ mode, which in the case of SUSY GUTs will be maximally suppressed (Yukawa couplings!) . For example, we may consider the IMB experiment with a projected benchmark sensitivity of 10^{33} years to the $p \rightarrow e^+\pi^0$ mode: Then, as a result of branching ratio effects and of less constrained kinematics, the sensitivities to the modes $p \rightarrow \bar{\nu} K^+$ and $n \rightarrow \bar{\nu} K^0$ are decreased to only $O(10^{31})$ years, whereas the mode $p \rightarrow \mu^+ K^0$, if appreciable, could be seen up to the $O(10^{32})$ years level [25]. *Caveat emptor !*

We may therefore summarise the possibilities for nucleon decay in SUSY GUTs:

1) via superheavy gauge boson exchange: As outlined above, this is likely to lead to an unobservably long partial lifetime (τ_p^{GEX} , Equations (3) and (3')) into the usual decay modes expected in SU(5);

2) via loops of scalar fermions and gauginos, with a very probably observable lifetime ($\tau_p \sim 10^{30\pm?}$ yrs), but with peculiar final states, dominated by kaons.

3) There remains the possibility, not mentioned above, of proton decay occurring via the exchange of color-triplet Higgs scalars of mass around $O(10^{11})$ GeV. This is what happens in the geometrical hierarchy model of Dimopoulos and Raby [26], and in a model of Nanopoulos and Tamvakis [27]. The main decay modes would again be dominated by strange final states, but with the modes involving muons and antineutrinos at roughly the same level. A lifetime of $O(10^{31})$ years is possible, but this decay mechanism could also conceivably happen in a standard GUT although such low masses (compared to M_X) for the color-triplet Higgs are unlikely in that case, especially when radiative corrections are present.

V. Conclusion

We have seen that, while there are many uncertainties tied to the large number of a priori unknown parameters, SUSY GUTs may yield an observable proton lifetime, arising from processes at the loop level, in spite of a larger unification scale, and with the promise of a solution of the hierarchy problem. It would indeed be ironic if the first indication of the importance of supersymmetry in Nature were to be the discovery of proton decay into predominantly strange final states !

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