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PROTON DECAY THEORY

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1.1 MINIMAL SU(5) PREDICTIONS

The SU(5) Georgi-Glashow [1] model provided much of the motivation for ongoing proton decay experiments as well as a theoretical framework for estimating expected rates and branching ratios. In the so-called "minimal" model, one assumes the existence of a "great desert", i.e. no new particles up to m_X, the unification mass scale. This simplistic assumption has an appealing consequence; it leads to rather definite predictions. If those predictions turn out to be wrong, it doesn't necessarily imply that the concept of grand unification or even that the SU(5) model is invalid. Instead, it would most likely suggest that new physics populates the desert and modifies the predictions.

The renormalization group is the principle tool used to study grand unified theories (GUTS) [2]. That formalism has been refined to the next-to-leading log level, so theoretical uncertainties are negligible [3]. Employing $\alpha = 1/137.035965$, the known fermion masses, and a specific value for $\Lambda_{\overline{MS}}$, the QCD mass scale, one predicts (assuming a great desert) m_X and $\sin^2\theta_W(m_W)$, the weak mixing angle defined by modified minimal subtraction at the $W^\pm$ mass [4,5]. In addition, the $SU(2)_L \times U(1)$ model formulas [4,6]

$$m_W = 38.5\ \text{GeV}/\sin\theta_W(m_W) \quad (1a)$$

$$m_Z = 77.1\ \text{GeV}/\sin 2\theta_W(m_W) \quad (1b)$$

provide precise predictions for m_W and m_Z. Results of such an analysis [3] are illustrated in Table I.

Notice that m_X exhibits a sensitive dependence on $\Lambda_{\overline{MS}}$ ($m_X \simeq 1.3 \times 10^{15} \Lambda_{\overline{MS}}$). What is the currently accepted value of $\Lambda_{\overline{MS}}$? A 1981 survey by A. Buras [7], which I believe is still valid, found

$$\Lambda_{\overline{MS}} = 0.16^{+0.10}_{-0.08}\ \text{GeV}. \quad (2)$$

$\Lambda_{\overline{MS}}$ (GeV)	m_X (GeV)	$\sin^2\theta_W(m_W)$	m_W (GeV)	m_Z (GeV)
0.10	1.3×10^{14}	0.2164	82.8	93.6
0.16	2.1×10^{14}	0.2136	83.3	94.1
0.20	2.7×10^{14}	0.2124	83.5	94.3
0.40	5.5×10^{14}	0.2084	84.3	94.9
0.50	6.9×10^{14}	0.2070	84.6	95.1

TABLE I: Predictions of the minimal SU(5) model for a variety of $\Lambda_{\overline{MS}}$ values.

Accepting that range, one obtains the following predictions [3]:

$$m_X = (2.1\,^{+1.7}_{-1.2}) \times 10^{14}\ \text{GeV} \tag{3a}$$

$$\sin^2\theta_W(m_W) = 0.214\,^{+0.004}_{-0.003} \tag{3b}$$

$$m_W = 83.3 \pm 0.7\ \text{GeV} \tag{3c}$$

$$m_Z = 94.1 \pm 0.6\ \text{GeV} \tag{3d}$$

How do these predictions compare with experiment? Deep-inelastic ν-N scattering and e-D scattering asymmetry measurements, including $O(\alpha)$ radiative corrections yield [8,9]

$$\sin^2\theta_W(m_W) = 0.215 \pm 0.014 \quad (R_\nu \text{ data}) \tag{4a}$$

$$\sin^2\theta_W(m_W) = 0.216 \pm 0.020 \quad (\text{e-D asymmetry}) \tag{4b}$$

These results are in excellent agreement with the prediction in Eq. [illegible], and thus provide strong support for minimal SU(5). It would be n[illegible] to reduce the experimental errors in Eqs. (4) and then use $\sin^2\theta_W(m_W)$ to predict m_X, $\Lambda_{\overline{MS}}$ etc. Eventually, m_W and m_Z will be determined (at CBA and LEP) to within 0.1–0.2 GeV; then Eq. (1) can provide a precise $\sin^2\theta_W(m_W)$.

Another interesting prediction of minimal SU(5) concerns the ratio m_b/m_τ. Employing only a Higgs 5-plet to provide fermion masses leads to the natural lowest order relation [1] $m_b^0/m_\tau^0 = 1$. However, that ratio is strongly renormalised to [10,11,12]

$$m_b/m_\tau = 2.9 \pm 0.2 \tag{5}$$

for the $\Lambda_{\overline{MS}}$ range in Eq. (2). (A fourth generation increases this result by ≈ 0.25.) For comparison,

$$(m_b/m_\tau)^{exp} = 2.6 - 2.9 \tag{6}$$

The agreement is impressive; however, the same scenario leads to $m_s/m_d \approx 200$ whereas current algebra implies $m_s/m_d \approx 20$. Coupling a 45-plet of Higgs scalars to the fermions overcomes this problem. Unfortunately, all fermion masses, including m_b and m_τ are rendered arbitrary.

1.2 GAUGE BOSON MEDIATED PROTON DECAY

The SU(5) model contains a color triplet, $SU(2)_L$ isodoublet of gauge bosons ($X^{\pm 4/3}$, $Y^{\pm 1/3}$) with $m_X \approx m_Y$ which mediate proton decay. In higher rank groups such as SO(10), a second color triplet, isodoublet ($X'^{\pm 2/3}$, $Y'^{\mp 1/3}$) with $m_{X'} \approx m_{Y'}$ can also mediate such decays.

The exchange of X, Y and/or X', Y' gauge bosons between quarks and leptons gives rise to the B and L violating (dim. 6) four fermi Hamiltonian [13,14]

$$H = \frac{g^2(m_X)}{2m_X^2}\left(\frac{m_X^2+m_{X'}^2}{m_{X'}^2}\right) A\, \epsilon_{ijk}\left[\bar{u}^c_{k_L}\gamma_\mu u_{j_L}\left(\bar{e}^+_R\gamma^\mu d_{i_R} + r_e(\bar{e}^+_L\gamma^\mu d_{i_L})\right)\right.$$
$$\left. - \bar{u}^c_{k_L}\gamma_\mu d_{j_L}\ \bar{\nu}^c_{e_R}\gamma^\mu d_{i_R}\right] + \text{h.c.} + \text{other generations} \tag{7}$$

(in the SU(5) model set $m_{X'} = \infty$.) In this amplitude $g(m_X)$ is the value of the gauge coupling at unification, A is an enhancement factor [11] and $r_e = 2m_{X'}^2/(m_X^2 + m_{X'}^2)$.

In minimal SU(5) with 3 generations of fermions, one finds [3,9] $g^2(m_X)/4\pi = 0.0242$ and $A = 2.9$. Combining these values with m_X from Eq. (3a) determines H. To go from H to partial decay rates and lifetime predictions requires the evaluation of hadronic matrix elements which interpolate from an initial proton to the final state decay products. Unfortunately, the evaluation of such matrix elements is model dependent.

Consider the decay $p \to e^+\pi^0$ induced by H. That mode is the primary quest of the IMB experiment [15]. The matrix element for that process receives contributions from two sources, two quark annihilation and three quark fusion. These amplitudes are proportional to $1/R_p^{3/2}$ and $1/R_p^{3}$ respectively, where R_p is the effective proton radius. The relative importance of each contribution as well as the overall amplitude is sensitive to R_p. Most calculations find that the two parts are roughly equal and add constructively. Results form a variety of very different calculations are illustrated in Table II.
It is difficult to assess the uncertainty in such calculations. I will employ the results of Isgur and Wise [20], allowing for a factor of 5 uncertainty due to the model dependence of matrix elements. Then, including a factor of 10 uncertainty for the $\Lambda_{\overline{MS}}$ spread in Eq. (2), one finds ($10^{1.7} = 50$)

$$\tau_p = 2 \times 10^{29\pm1.7}\ \text{yr.} \qquad (8a)$$

$$1/\Gamma(p \to e^+\pi^0) = 4.5 \times 10^{29\pm1.7}\ \text{yr.} \qquad (8b)$$

Group	Method	τ_p(yr)	$1/\Gamma(p\to e^+\pi^0)$(yr)
Tomozawa [16]	PCAC	$(1-6)\times10^{29}$	$(1.5-10)\times10^{29}$
Berezinsky et al. [17]	QCD Sum Rule	4×10^{28}	8×10^{28}
Donoghue & Golowich [18]	MIT Bag	2.2×10^{29}	5.5×10^{29}
Lucha [19]	B-S Eq.	3.2×10^{29}	7×10^{29}
Isgur & Wise [20]	N.R.O.M.	2×10^{29}	4.5×10^{29}
Thomas & McKellar [21]	Cloudy Bag	3×10^{28}	6×10^{28}

TABLE II: Results of different calculations, normalized to $\Lambda_{\overline{MS}} = 0.16$ GeV, in the minimal SU(5) model.

Note that the partial lifetime in Eq. (8b) is well below the IMB bound [15]

$$1/\Gamma(p \to e^+\pi^0) > 6 \times 10^{31}\ \text{yr.} \qquad \text{(IMB Exp.)} \qquad (9)$$

reported at this meeting. That bound appears to rule out minimal SU(5) with a great desert unless $\Lambda_{\overline{MS}} > 0.3$ GeV and the $p \to \pi^0e^+$ matrix elements are actually smaller than the estimates in Table II.

The simplest SO(10) models with symmetry breaking patterns that leave m_X unchanged predict a shorter τ_p, i.e. Eq. (8) is reduced by

$$\frac{5}{4}\left[\frac{r_e^{\,2}}{1 + r_e^{\,2}}\right] \qquad (10)$$

where $r_e = 1$ for $m_X = m_{X'}$ (see (Eq. (7)). Of course, there are symmetry breaking schemes in SO(10) which allow intermediate mass gauge bosons to populate the desert and render m_X arbitrary [22]. In those cases τ_p may be much longer.

Baryon number violating neutron decay can also be induced by H. Isospin implies $\Gamma(n \to e^+\pi^-) = 2\Gamma(p \to e^+\pi^0)$; so one expects

$$\tau_n = 1.5 \times 10^{29\pm1.7}\ \text{yr.} \qquad (11a)$$

$$1/\Gamma(n \to e^+\pi^-) = 2.2 \times 10^{29\pm1.7}\ \text{yr.} \qquad (11b)$$

Cerenkov radiation from $n \to e^+\pi^-$ should be readily discernable in the IMB experiment.

What other decay modes are induced by H? The branching ratios for $p \to e^+\omega^0$ or ρ^0 should be about 30 – 35%. In addition the relation

$$\Gamma(p \to \pi^+\bar{\nu}_e) = \frac{2}{1+r_e^{\,2}}\,\Gamma(p \to \pi^0e^+) \qquad (12)$$

implies about a 16% B.R. for $p \to \pi^+\bar{\nu}_e$. A few of the anticipated branching ratios are given in Eq. (13)

$$p \to e^+\pi^0, \quad e^+\omega^0 \text{ or } \rho^0, \quad \bar{\nu}_e\pi^+, \quad \mu^+K^0, \quad \bar{\nu}_\mu K^+$$
$$0.40 : \quad 0.30 : \quad 0.16 : \quad 0.03 : \quad 0.03 \qquad (13)$$

$$n \to e^+\pi^-, \quad e^+\rho^-, \quad \bar{\nu}_e\pi^0, \quad \bar{\nu}_\mu K^0$$
$$0.80 : \quad 0.05 : \quad 0.08 : \quad 0.02$$

1.3 UNCERTAINTIES IN τ_p

The proton lifetime prediction in Eq. (8) has about a factor of 10 uncertainty, primarily from the allowed range in $\Lambda_{\overline{MS}}$ [3,9]. In addition, the model dependence of matrix elements implies about another factor of 5 uncertainty. These uncertainties are not sufficient to reconcile minimal SU(5) and the IMB bound in Eq. (9). What other sources of uncertainty exist? The Higgs sector introduces the largest degree of uncertainty; it will be elaborated on separately in Section 2.

What about the uncertainty in the top quark mass, m_t? Fortunately, m_t enters only at the next-to-leading log level; so, ignorance of its value induces less than a 10% uncertainty in τ_p [3,9].

What about added fermion generations? For charged fermions with masses $\approx m_W$, a fourth generation increases τ_p by about 30%, while a fifth and sixth generation increase τ_p by factors of about 2 each [9,23]. Additional larger representations (technifermions?) cause similar modifications.

Nuclear physics effects can enhance or diminish the proton decay rate depending on the mode [24]. Such effects are about a factor of 2. They are taken into account in the IMB bound.

2.1 HIGGS SCALAR EFFECTS

The only Higgs scalar multiplets that can couple to the known fermions in the SU(5) model are 5, 10, 15, 45 and 50 plets. All of these are included in the 126 of SO(10), but only the 5 and 45 are reqired in SU(5). Some of these scalars induce exotic effects such as proton decay [13], Majorana neutrino mass, neutrinoless double beta decay, n-$\bar{n}$ oscillations [25], H-$\bar{H}$ oscillations [26] etc. In addition, lack of mass degeneracy in the scalar spectrum can change the renormalization group analysis and SU(5) predictions [27,28,29]. To

illustrate the latter effect, I first give the $SU(3)_c \times SU(2)_L \times U(1)$ decomposition of the above multiplets and assign their components arbitrary masses m_i, $i = 1,2,\ldots 21$.

$$\underline{5} = \underbrace{(1,2,1)}_{m_1} + \underbrace{(3,1,-2/3)}_{m_2}$$

$$\underline{10} = \underset{m_3}{(1,1,2)} + \underset{m_4}{(\bar{3},1,-4/3)} + \underset{m_5}{(3,2,1/3)}$$

$$\underline{15} = \underbrace{(1,3,2)}_{m_6} + \underbrace{(3,2,1/3)}_{m_7} + \underbrace{(6,1,-4/3)}_{m_8}$$

$$\underline{45} = \underbrace{(1,2,1)}_{m_9} + \underbrace{(3,1,-2/3)}_{m_{10}} + \underbrace{(3,3,-2/3)}_{m_{11}} + \underbrace{(\bar{3},1,8/3)}_{m_{12}} + \underbrace{(\bar{3},2,-7/3)}_{m_{13}}$$
$$+ \underbrace{(\bar{6},1,-2/3)}_{m_{14}} + \underbrace{(8,2,1)}_{m_{15}}$$

$$\underline{50} = \underbrace{(1,1,-4)}_{m_{16}} + \underbrace{(3,1,-2/3)}_{m_{17}} + \underbrace{(\bar{3},2,-7/3)}_{m_{18}} + \underbrace{(6,1,8/3)}_{m_{19}} + \underbrace{(\bar{6},3,-2/3)}_{m_{20}}$$
$$+ \underbrace{(8,2,1)}_{m_{21}}$$

Some of these scalars can mediate proton decay, hence they must be rather massive [13] ($m_2, m_{10}, m_{11}, m_{12}, m_{17} > 10^{10}$ GeV). The other masses are more or less arbitrary. In the "great desert" scenario one would assume $m_1 \approx m_W$ while all other scalar masses $\approx m_X$, then the results in Section 1 follow. Allowing arbitrary m_i, one finds [30]

$$\sin^2\theta_W(m_W) = 0.210 - 7 \times 10^{-5}$$
$$\times \ln\left[\frac{m_1^2\, m_5^4\, m_6^7\, m_7^4\, m_9^2\, m_{11}^{24}\, m_{10}^{33}}{m_2^2\, m_3\, m_4^3\, m_8^{11}\, m_{10}^2\, m_{12}^7\, m_{13}^4\, m_{14}^9\, m_{15}^4\, m_{16}^4\, m_{17}^2\, m_{18}^4\, m_{19}^{19}\, m_{21}^4}\right] \qquad (14a)$$

$$\tau_p = 1 \times 10^{30\pm1.7} \left(\frac{m_1\, m_3\, m_6^5\, m_9\, m_{11}^3\, m_{12}^4\, m_{13}^7\, m_{16}^4\, m_{18}^7\, m_{19}^4}{m_2\, m_5\, m_7\, m_8^4\, m_{10}\, m_{14}^6\, m_{15}^8\, m_{17}\, m_{20}^6\, m_{21}^8}\right)^{2/33} \text{ yr.} \qquad (14b)$$

Predictability is lost; however, some general features can be seen: 1) Relatively light color singlets decrease τ_p. 2) Light m_5, m_7, m_{20} lead to increases in both $\sin^2\theta_W(m_W)$ and τ_p. 3) Assuming a hierarchy condition $0.1 \le m_i/m_j \le 10$, $i,j = 2,\ldots 21$ and $m_1 = m_W$, one finds a maximum increase of a factor of 150 in τ_p while correspondingly $\Delta\sin^2\theta_W(m_W) = +0.001$. Uncertainty in the Higgs sector provides additional motivation for pushing up the bound on τ_p and continuing the search for $p \to e^+\pi^0$.

2.2 PROTON DECAY VIA HIGGS SCALARS

Proton decay can be mediated by the following $SU(3)_c \times SU(2)_L \times U(1)$ Higgs scalar multiplets [13]: (3,1,-2/3), (3,3,-2/3), ($\bar{3}$,1,8/3) Assuming only Higgs 5-plets, Golowich [30] found that the (3,1,-2/3) induced proton decay amplitudes have the following ratios due to couplings alone

$$p \to K^+\bar{\nu}_\mu, \quad K^0\mu^+, \quad \pi^0\mu^+, \quad K^0e^+, \quad \pi^0e^+$$
$$m_s m_d : \quad m_s^2\sin^2\theta_c : \quad m_s m_d \sin\theta_c : \quad m_s m_d \sin\theta_c : \quad m_d^2 : \tag{15}$$

where θ_c is the Cabibbo angle ($\sin^2\theta_c \simeq 0.05$). Phase space suppresses the K modes by $\simeq 1/2$, in addition one expects 3 quark fusion to enhance the π^0 and K^+ decay modes but not the K^0 (because the $pK^0\Sigma^+$ coupling is small [31]). Incorporating these effects with Golowich's results [30], I expect

$$p \to K^+\bar{\nu}_\mu, \quad K^0\mu^+, \quad \pi^0\mu^+, \quad K^0e^+, \quad \pi^0e^+$$
$$0.75 : \quad 0.18 : \quad 0.07 : \quad 0.007 : \quad 0.004 : \tag{16}$$

for Higgs (3,1,-2/3) mediated proton decay. Although the $K^+\bar{\nu}_\mu$ mode is dominant, the more easily observable $K^0\mu^+$ and $\pi^0\mu^+$ decay rates are significant. Already the IMB experiment has given the bound [15]

$$1/\Gamma(p \to K^0\mu^+) > 1.4 \times 10^{31}\ \text{yr}. \tag{17}$$

In the case of the neutron, a similar analysis suggests that $n \to K^0\bar{\nu}_\mu$ dominates and $\Gamma(n \to \pi^-\mu^+) \simeq \Gamma(p \to K^0\mu^+)$. In this scenario $m_2 \simeq 10^{10}$ GeV corresponds to Higgs mediated decay lifetimes $\simeq 10^{30}$ yr

($\tau_p \propto m_2^4$); however, there is no compelling reason for introducing a 10^{10} GeV mass scale in the SU(5) model.

3.1 SUPERSYMMETRIC SU(5)

The basic idea of supersymmetry [32] is that each known boson (fermion) has a fermion (boson) partner. Assuming that all such partners of light particles have mass $\simeq m_W$ while partners of superheavies have mass m_X (i.e. retaining the "great desert" idea), one obtains the predictions [33,34] illustrated in Table III. Notice that the predictions are very sensitive to the number of light Higgs isodoublets, N_H. In this scenario proton decay is still mediated by the X and Y; so the branching ratios in Section 1 hold.

N_H	m_X (GeV)	τ_p (yr)	$\sin^2\theta_W(m_W)$	m_W (GeV)	m_Z (GeV)
2	7.7×10^{15}	3×10^{35}	0.236	79.3	90.8
4	4.2×10^{14}	5×10^{30}	0.259	75.7	88.0

TABLE III. Supersymmetric SU(5) predictions for $\Lambda_{\overline{MS}} = 0.16$ GeV.

The most striking supersymmetry modification is that $\sin^2\theta_W(m_W)$ increases. That appears to be ruled out by the results in Eq. (4); however, the definitive test lies in the measurement of m_W and m_Z. There are of course ways to lower $\sin^2\theta_W(m_W)$. One popular idea [35] involves adding Higgs $\underline{10} + \underline{\overline{10}}$ multiplets containing light color singlets such that $\sin^2\theta_W(m_W)$ and τ_p are both reduced.

3.2 DIMENSION 5 OPERATORS AND PROTON DECAY

It was noted by Weinberg and Sakai and Yanagida [36] that dimension 5 (fermion-fermion-scalar-scalar) B and L violating operators are induced by Higgsino mixing in supersymmetric GUTS. Through loop effects, these operators give rise to dimension 6 four-fermi amplitudes which lead to proton decay at a rate proprotional to $1/m_X^2$ rather than $1/m_X^4$. Subsequent analyses [37] found that such effects lead to $\tau_p \simeq 10^{30}$ yr through the dominant decay mode $p \to \bar{\nu}_\tau K^+$ (for the neutron, $n \to \bar{\nu}_\tau K^0$). Such short lifetimes appear to be in conflict with the bound

$$\tau_p > 3 \times 10^{31} \text{ yr} \quad (\mu^+ \text{ in final state}) \tag{18}$$

obtained by the Homestake experiment [38]. (64% of the K's should produce a μ^+.) However, there are uncertainties in the theoretical analysis. I should note that the dimension 5 operators can be exorcised by symmetries [36].

3.3 HIGGS SCALARS AND PROTON DECAY

It has been noted that the geometric mass scale $(m_W m_P)^{1/2} \approx 10^{10}$ GeV arises quite naturally in locally supersymmetric models [39]. (m_P is the Planck mass $\approx 10^{19}$ GeV.) Such a mass scale in the Higgs sector can lead to scalar mediated decays with $\tau_p \approx 10^{30}$–10^{32} yr. In that case the analysis of Section 2.2 regarding branching ratios is applicable.

4. COMMENTS

The initial results of the IMB experiment [15] appear to be in conflict with minimal SU(5) and the "great desert" hypothesis. To be more definite, we need better determinations of $\Lambda_{\overline{MS}}$, $\sin^2\theta_W(m_W)$, m_W and m_Z. In any case, a variety of possibilities can populate the desert. They range from new fermions and scalars to additional gauge bosons which occur in larger symmetry groups. All things considered, it is worth pushing the bound on $p \to e^+\pi^0$ as far as possible.

Higgs mediated proton decay exists at an arbitrary rate in the SU(5) model. Some supersymmetric models naturally suggest a lifetime of $\tau_p \approx 10^{30}$–10^{32} yr. from such decays. In such scenarios the decays $p \to K^+\bar{\nu}_\mu$, $K^0\mu^+$, $\pi^0\mu^+$ and $n \to K^0\bar{\nu}_\mu$, $\pi^-\mu^+$ tend to dominate. All should be searched for. I must remark that if supersymmetric partners exist at mass scale m_W, they will be quite easily discovered and studied at CBA. Underground and accelerator experiments are clearly complementary probes of the fundamental laws of nature.

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