

Remodeling the Pentagon After the Events of 2/23/06

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ABSTRACT: The meta-stable SUSY breaking mechanism of Intriligator Seiberg and Shih can be used to simplify the Pentagon model of TeV scale physics. The simplified model has only a single scalar field and no troublesome low energy axion. One significant signature is l^+l^-X plus missing energy, where X might be the two photons of gauge mediated models, but is likely to be different. There is a new strongly interacting sector with a scale around 1.5 TeV. The penta-hadrons of this sector have masses of order 6 TeV or more. Dark matter is probably the pseudo-goldstone boson of spontaneously broken penta-baryon number. This can be a viable dark matter candidate if an appropriate asymmetry in penta-baryon number is generated in the early universe. The pseudo-Goldstone particle has a mass of ~ 1 eV and is produced predominantly in flavor changing charged current decays of ordinary particles. The model solves the flavor problems of SUSY, but has two low energy CP violating phases, whose value is strongly constrained by experiment.

KEYWORDS: Cosmological SUSY Breaking.

Contents

1. Introduction	1
2. Known knowns	3
3. Known unknowns	8
4. Baryon number, lepton number, and flavor	11
4.1 B and L violating operators of dimension 4 and 5	11
4.2 Flavor and CP	13
5. Dark matter	14
6. Coupling constant unification	16
7. Anthropic considerations	17
8. Conclusions	18
9. Acknowledgments	20

1. Introduction

In a recent paper[1], I proposed an explicit model, which implemented the idea of Cosmological SUSY Breaking (CSB). Apart from the fields of the supersymmetric standard model (SSM), the model consisted of the Pentagon - a new strongly interacting $SU(5)$ super-QCD with 5 flavors of penta-quark, and three singlet fields, S, G, T with a variety of Yukawa couplings to the Pentagon and the SSM. The intricate pattern of singlets was required to motivate the possibility of a meta-stable SUSY breaking vacuum state of the flat space quantum field theory. It also caused a potential phenomenological problem - a low scale QCD axion. One could invoke higher dimension operators, which raised the axion mass and made it barely compatible with observation. This of course

removed the model's solution of the strong CP problem. It also introduced a fine tuning of the electroweak scale, of order 1%. This was required to raise the axion decay constant above the laboratory bounds.

The Pentagon Paper was written before the world changed on 02/23/06. The Neo-conservative¹ revolution in SUSY breaking, heralded by the paper of Intriligator, Seiberg, and Shih (ISS)[3] now provides us with a plethora of calculable SUSY breaking models, where SUSY is broken in a meta-stable state - exactly what is needed to solve the problems at the Pentagon.

ISS prove that when a mass term $m_{ISS}\text{str}P\tilde{P}$ is added to SUSY QCD with $N_C+1 \leq N_F \leq \frac{3N_C}{2}$, then that model has a SUSY violating meta-stable ground state with SUSY order parameter, $F \sim m_{ISS}\Lambda_{N_C}$. Λ_{N_C} is the confinement scale of the gauge theory, and the analysis is under control for $m_{ISS} \ll \Lambda_{N_C}$. The meta-stable state also breaks a vector-like sub-group of the $SU(N_F) \times U(1)$ flavor symmetry of the model, leading to a variety of pseudo-goldstone bosons. ISS also argued that a similar meta-stable state existed in the model with $N_F = N_C$. In terms of the moduli space of the $m = 0$ theory the vacuum was near the point $M_i^j = P_i^A \tilde{P}_A^j / \Lambda_{N_C} = 0$, $B = \tilde{B} = \Lambda_{N_C}$. B and \tilde{B} are the dimension one interpolating fields for penta-baryons and anti-baryons made of 5 penta-quarks. Note that these baryons are standard model singlets and that the only flavor symmetry which is spontaneously broken at this point in moduli space is the $U(1)$ penta-baryon number (axial symmetries are explicitly broken by the mass term).

For $N_F \geq N_C + 1$ there is a well controlled effective field theory of the meta-stable state for $m_{ISS}/\Lambda_{N_C} \ll 1$. This is not true for $N_F = N_C$. Furthermore, as we will see below, we will need to work in the region $m_{ISS} \geq \Lambda_5$ for phenomenological reasons.

The basic idea of this paper then, is to exploit the ISS meta-stable vacuum of the $N_F = N_C = 5$ theory to construct an effective theory for Cosmological SUSY Breaking (CSB). The basic CSB input is to fix the value of m_{ISS} in terms of the CSB ansatz for the gravitino mass, $m_{3/2} \sim \lambda^{1/4}$ (where little λ is the c.c.). This requires $m \sim \frac{\lambda^{1/4} m_P}{\Lambda_5}$. The factor of Λ_5 in the denominator of this formula, anathema to an effective field theorist, can be explained/excused in terms of the diagrams of [4], which mix up IR propagation through the bulk of space-time with UV interactions with de Sitter horizon degrees of freedom. One also adds a constant to the superpotential to guarantee that the true c.c. is in fact λ in the low energy effective theory. Both of these terms break a discrete R symmetry of the $\lambda = 0$ theory.

The result is a lean and mean, stripped down version of the Pentagon, suitable for

¹This term is motivated by the fact, pointed out to the author by N. Seiberg, that meta-stable SUSY breaking was advocated in unpublished work by M. Dine, which was done in the run-up to the Affleck Dine Seiberg [2] discovery of models of dynamical SUSY breaking.

rapid deployment to solve all² of the problems of the supersymmetric standard model. It involves a single scalar field S with discrete R charge 2. The only marginal/relevant couplings of S are encoded in a superpotential:

$$W_S = g_S S P_i^A P_A^j Y_j^i + g_\mu S H_u H_d + g_T S^3.$$

Y is the unique traceless $SU(1, 2, 3)$ invariant matrix in the fundamental representation of $SU(5)$. Note that the $SU(1, 2, 3)$ standard model gauge group is embedded in the obvious fashion into the vector $SU(5)$ flavor group of the Pentagon.

In fact, we could consider a more general version of the model in which we require only that the linear combination of penta-quark bilinears to which S couples, is linearly independent of the combination to which m_{ISS} couples. The form we have written *may* have a group theoretic justification at the unification scale, which we will discuss below.

2. Known knowns

The full low energy Lagrangian of our model is

$$\begin{aligned} \mathcal{L} = & d^4\theta [P^* e^V P + Q^* e^V Q + L^* e^V L + (\bar{U})^* e^V \bar{U} + (\bar{D})^* e^V \bar{D} + (\bar{E})^* e^V \bar{E}] \\ & + [\int d^2\theta ((\sum \tau_i W_\alpha^i)^2 + P_i^A \tilde{P}_A^j (m_{ISS} \delta_j^i + g_S S Y_j^i) + g_\mu S H_u H_d + g_T S^3 \\ & + H_u Q_m (\lambda_u)_n^m \bar{U}^n + H_d Q_m (\lambda_d)_n^m \bar{D}^n + H_d L_m (\lambda_L)_n^m \bar{E}^n + \frac{1}{M_U} L_m L_n \lambda^{mn} H_u^2) + h.c.]. \end{aligned}$$

The scale of the neutrino seesaw operator is $M_U \sim 10^{14} - 10^{15}$ GeV. We will take this parameter to be the scale of all irrelevant corrections to the Lagrangian.

The gauge group of the model is $SU(5) \times SU(1, 2, 3)$, and the sum over gauge kinetic terms sums over simple factors of this group. When m_{ISS} , g_S and the standard model gauge couplings are turned off, the Lagrangian has an unbroken $SU_L(5) \times SU_R(5)$ global symmetry, acting on the small Latin indices of the penta-quarks P and \tilde{P} . The $SU(1, 2, 3)$ standard model is embedded in the usual way in the vector (diagonal) $SU(5)$ subgroup of this chiral flavor group. Thus, if we use $SU(5)$ notation to summarize standard model quantum numbers then the P is in a $[5, 5]$ under $SU(5) \times SU(1, 2, 3)$ while \tilde{P} is in a $[\bar{5}, \bar{5}]$.

²As is conventional in communications from the Pentagon, we are here indulging in a bit of hyperbole.

The parameter m_{ISS} is assumed to be induced by Cosmological SUSY Breaking, CSB, as in [4]. The *c.c.*, λ is a tunable parameter³, and m_{ISS} scales like $\lambda^{1/4}$ as $\lambda \rightarrow 0$. In this limit, the low energy Lagrangian has an $U(1)_R$ symmetry, which has no $SU_P(5)$ anomaly. P and \tilde{P} have R charge zero. A discrete Z_4 subgroup of this $U(1)$ is assumed to be an exact symmetry of the S-matrix when $\lambda = 0$. S has R charge 2. The R transformation properties of the SSM chiral multiplets can be chosen so that the only perturbative baryon or lepton number violating interaction of dimension ≤ 5 is the neutrino see-saw term,

$$\int d^2\theta \frac{(H_u L^m)(H_u L^n) S_{mn}}{M_U}.$$

The discrete R symmetry is also preserved by the 't Hooft interactions induced by standard model instantons.

The R charge of S does not permit the superpotential term S^2 . The linear term S can be forbidden by a variety of strategies. The simplest of these involves physics at the standard model unification scale. At that scale, we assume that the standard model is unified, perhaps in a way that involves extra compact dimensions, in a group containing the Georgi-Glashow group $SU(5)$. We further assume that S is the remnant of an $SU(5)$ adjoint, transforming like the hypercharge generator of $SU(1, 2, 3)$. All other members of this multiplet get mass at the unification scale. Finally, we assume that no $SU(5)$ violating superpotential couplings of S are induced by the tree level breaking of $SU(5)$. SUSY non-renormalization theorems then assure us that the terms

$$\int d^2\theta (aS + bSP_i^A \tilde{P}_A^i)$$

will not appear in the low energy effective Lagrangian at the TeV scale.

The fact that m_{ISS} produces SUSY breaking follows from the neo-conservative revolution fomented by ISS. These authors showed rigorously that in SUSY QCD with $3N_C/2 \geq N_F \geq N_C + 1$ a small mass term produces a meta-stable SUSY violating vacuum in Poincare invariant quantum field theory. For the indicated values of N_F , a systematic small m_{ISS}/Λ_{N_C} expansion of the properties of this state could be established. Giving a large mass to *one* $SU(N_C)$ fundamental when $N_F = N_C + 1$, ISS also argued that a similar meta-stable state existed for $N_F = N_C$, though its properties

³Actually it is discretely tunable. $\pi(RM_P)^2$ is the logarithm of an integer number of states. R is the dS radius. In a more ambitious model based on holographic cosmology, one gets a distribution of asymptotically dS universes with different λ , and λ can be anthropically selected. However, this model has no other testable consequences once the value of λ is chosen, so there is no point in discussing it here.

were not under analytic control. That state had a non-vanishing expectation value for the penta-baryon number violating operators

$$\begin{aligned} \langle \epsilon^{A_1 \dots A_{N_C}} P_{A_1}^{i_1} \dots P_{A_{N_C}}^{i_{N_C}} \rangle &= \Lambda_{N_C}^{N_C} \epsilon^{i_1 \dots i_{N_C}}, \\ \langle \epsilon_{A_1 \dots A_{N_C}} \tilde{P}_{i_1}^{A_1} \dots \tilde{P}_{i_{N_C}}^{A_{N_C}} \rangle &= \Lambda_{N_C}^{N_C} \epsilon_{i_1 \dots i_{N_C}}. \end{aligned}$$

By contrast, the meson operators $P_i^A \tilde{P}_A^j$ have vanishing expectation value in this state.

This model is merged with the hypothesis of CSB by making two assumptions. First the parameter m is determined so that the gravitino mass at the meta-stable SUSY violating vacuum is given by the CSB formula

$$m_{3/2} = \gamma \lambda^{1/4} (M_p / m_P),$$

where $M_P = \sqrt{8\pi} m_P$ is the Planck mass, and γ is an unknown constant, expected to be of order one. This means that

$$m_{ISS} \sim \gamma \frac{\lambda^{1/4} M_P}{\Lambda_5}.$$

Note that this is a term in the Lagrangian at a scale $\gg \Lambda_5$ where the Pentagon interactions are weak. From the point of view of standard effective field theory, it is extremely peculiar to have the IR scale Λ_5 appear in the denominator of this parameter. However, the diagrams contributing to the argument for the CSB formula that I presented in [4], combine infrared propagation in a single horizon volume, with UV dynamics in the vicinity of the horizon. It is plausible that they contain such inverse IR scales.

The second input from CSB is that we add a constant W_0 to the superpotential to tune the c.c. at the meta-stable minimum to λ . Again, there is no reason to do this in effective field theory, though in this case it would be the strategy of any effective field theorist who wanted the meta-stable vacuum to be of phenomenological relevance. The logic for adding W_0 in CSB is different. λ is viewed as a high energy input parameter determined by the number of quantum states in the asymptotic de Sitter space to which the system is converging. It cannot be renormalized, and the constants in effective field theory must be tuned to reproduce its input value.

It should be emphasized that from the point of view of low energy effective field theory, the model is defined without reference to CSB. Thus, the effective field theorist can simply take the mass term m_{ISS} to be a parameter of unknown provenance, or imagine that it arises as a consequence of the dynamics of another gauge group, not included in the Pentagon model. Our insistence on the origin of m_{ISS} in CSB is a strong constraint, because it bounds the scale of SUSY breaking in the model. We will see that this makes it more difficult to find a working version of the model.

One other place where CSB plays a role in our considerations is our decision to tune the c.c. (almost) to zero near a particular SUSY violating minimum of the effective potential of the flat space field theory. It would not be consistent with the hypothesis of CSB to perform this tuning at the SUSic minimum. We will in fact have to choose between two SUSY violating minima of the potential on phenomenological grounds. It is important to note that once we have done this tuning, the supersymmetric states no longer have anything to do with the theory. Our meta-stable SUSY violating world can tunnel to the negative c.c. region of the potential, but the resulting bubble is a low entropy, highly non-supersymmetric, Big Crunch geometry. These tunneling amplitudes are too small to be of any interest.

Before sailing for murkier waters, in which we will have to swim in order to get interesting phenomenological consequences of this model, I will list the approximate symmetries of the low energy Lagrangian. The pure $N_F = N_C = 5$ model has a $U(5) \times U(5)$ symmetry. The axial $U(1)$ is an R symmetry under which P and \tilde{P} have R charge 0. This is also a symmetry of the Yukawa couplings of the S field, if S has R charge 2 and the up and down Higgs fields have opposite R charge. On the other hand the mass term m_{ISS} breaks $U(1)_R$ and is required to be fairly large for phenomenological reasons. This term also breaks $SU(5) \times SU(5)$ to its diagonal subgroup. The Yukawa coupling g_S and the standard model gauge couplings break the diagonal $SU(5)$ down to $SU(1, 2, 3)$ of the standard model. The meta-stable ISS vacuum spontaneously breaks the remaining $U(1)$ Penta-baryon symmetry. The Goldstone boson is the field defined by

$$\langle B \rangle = \Lambda_5 e^{ib/\Lambda_5} = \langle \tilde{B} \rangle^*,$$

in the ISS vacuum. We call this the *penton* field, though a catchier name might be found, if one were willing to put in the effort to think about it.

In addition to these continuous low energy symmetries, the Pentagon has an anomaly free Z_5 subgroup of the axial symmetry which gives P and \tilde{P} charge one. The mass term m_{ISS} breaks this symmetry as well as the $U(1)_R$ but preserves a diagonal Z_5^R subgroup. This is inconsistent with the tenets of CSB, according to which the c.c. breaks all R symmetries. It would also prevent us from generating gaugino masses. The couplings g_S and g_T violate this Z_5^R if they are both non-zero. These couplings must therefore be large at low energy.

The usual chiral Lagrangian predictions for a Goldstone boson relate the emission amplitude for a single Goldstone boson in a transition between two final states to the change in the spontaneously broken quantum number in the transition. This would predict zero coupling to ordinary quarks and leptons since they do not carry penta-

baryon number. However, there are dimension 5 operators

$$\frac{c_B}{\Lambda_5} \partial_\mu b J_B^\mu + \frac{c_L}{\Lambda_5} \partial_\mu b J_L^\mu,$$

which are allowed by the symmetries of the low energy Lagrangian. These are in fact generated by the diagrams of Figure 1, involving standard model couplings at the scale Λ_5 . The nominal estimates for the coefficients are

$$c_B \sim \alpha_3^2(\Lambda_5), \quad c_L \sim \alpha_2^2(\Lambda_5),$$

where these are running gauge couplings, at the indicated scale.

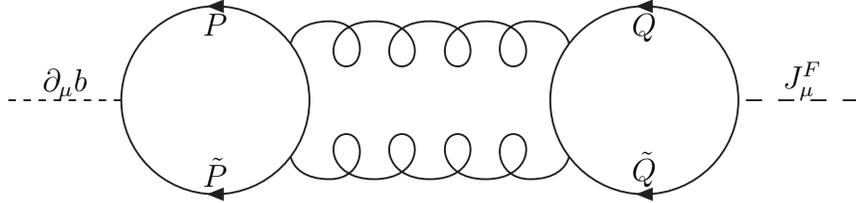


Figure 1: Diagrams leading to penton interaction with standard model currents. Gauge bosons are any charge and color neutral pair in $SU(1, 2, 3)$. The RHS loop could contain leptons.

These terms in the action are total derivatives if we neglect the violation of baryon and lepton number by electroweak instantons, but they will be important in the early universe if there are temperatures as high as the electroweak sphaleron mass.

Under laboratory conditions, the dominant dimension 5 coupling of the penton to normal matter comes from similar dimension five couplings to non-conserved neutral hadronic currents like beauty, charm, and strangeness. They are suppressed by two powers of $\alpha_3(\Lambda_5)$ and are proportional to quark mass differences in units of the QCD scale (for light quarks). They are of the form

$$\alpha_3^2 \frac{m_F}{\Lambda_{QCD}} \frac{\partial_\mu b}{\Lambda_5} J_F^\mu,$$

where J_F^μ is a flavor current. Note that analogous couplings to axial currents are suppressed by further powers of electroweak gauge couplings, because the $SU(5) \times SU(3)$ gauge theory is invariant under parity. Thus pentons will be predominantly emitted in charged current weak decays, since the amplitudes are proportional to the divergence of the corresponding flavor current. As we will see in the section on dark

matter, pentons are very light, $.1 - 1$ eV, and will escape from the detector as missing energy.

Models with very low energy SUSY breaking cannot contain the usual SUSic candidates for dark matter. Even if R parity is conserved, the LSP is the gravitino, which is relativistic at the usual scale of matter domination. It is also relatively strongly coupled and so the NLSP is not cosmologically meta-stable. In previous attempts to construct a phenomenology based on CSB, I suggested that baryons of the new strong interactions (penta-baryons in the Pentagon model) would be the dark matter. This is not possible if penta-baryon number is spontaneously broken. Instead I will suggest that the dark matter is a condensate of pentons. I will show that this is reasonable if the early universe produces a sufficiently large penta-baryon asymmetry.

3. Known unknowns

We will accept the hypothesis of ISS that the Pentagon model has a meta-stable SUSY violating state with flat space vacuum energy of order $m_{ISS}^2 \Lambda_5^2$. ISS characterize this as a state which has vanishing expectation value for penta-meson operators. However, in the presence of m_{ISS} and the couplings g_S and g_T there is no symmetry which prevents the combinations $P_i^A \tilde{P}_A^j (\delta_j^i, Y_j^i)$ from getting non-zero VEVs. Thus, we expect these bilinears to have VEVs of order $K \Lambda_5^2$ at the SUSY violating minimum, where K involves powers of $g_{S,T}$ if these are small. We will tune the parameter W_0 in the SUGRA formula for the effective potential, so that the c.c. at this SUSY violating minimum is of order the observed c.c., λ .

Actually we must resolve one further ambiguity in choosing the SUSY violating vacuum. When $m_{ISS} = 0$ there are two solutions of the F and D term constraints for the Higgs fields and the singlet S :

$$h_{u,d} = 0, \quad g_S p_i^A \tilde{p}_A^j Y_j^i = -3g_T s^2,$$

and

$$s = 0, \quad g_S p_i^A \tilde{p}_A^j Y_j^i = -g_\mu h_u h_d,$$

where lower case letter represent the scalar components of chiral superfields. The Higgs VEVs in the second equation are oriented so that electromagnetism is unbroken and $\tan\beta$, the ratio of Higgs VEVs is one.

In the presence of the SUSY breaking parameter m_{ISS} there will be a similar ambiguity in the choice of VEVs at the SUSY violating vacuum. However, $s = 0$ is no longer a stationary point of the effective action since there are no unbroken symmetries which preserve it. On the other hand, the first minimum will still have $h_{u,d} = 0$. We

will choose to tune the c.c. to λ at the stationary point where $SU(2) \times U(1)$ is broken. The other SUSY violating stationary point of the flat space potential may then have either positive or negative c.c., while the erstwhile SUSic states will have negative c.c. None of the other stationary points of the potential represent long lived states of the universe once gravity is taken into account.

The Pentagon model thus has a stationary point of its effective potential with spontaneously broken SUSY ($F \sim m_{ISS}\Lambda_5$), and $SU(2) \times U(1) \rightarrow U(1)_{EM}$ with $|h_u| \sim |h_d| \sim \Lambda_5$, which we will take to represent the real world.

SUSY breaking is communicated to the standard model by two distinct mechanisms. Since s, h_u, h_d are all non-zero, the Higgs superfields have F terms which will contribute tree level masses to squarks and sleptons. In addition there are more or less conventional gauge mediated contributions. The latter are the dominant contributions for gaugino masses as well as the masses of squarks and sleptons, apart from the top squark. Gaugino masses are estimated from one loop standard model diagrams with pentaquark superfields in the loop, and arbitrary numbers of penta-gauge bosons. If we compare to conventional gauge mediated scenarios, these diagrams are enhanced by a factor of $5 \sum Y^2 \sim 16.7$ (where the sum is over the weak hypercharges in the 5 representation of $SU(5)_{GUT}$). As we will see, this means that the gaugino to squark or slepton mass ratios are larger by a factor ~ 4 than they are in conventional gauge mediated models.

The corresponding two loop contribution to *e.g.* the right handed charged slepton squared mass is enhanced by the same factor. Thus

$$m_{\tilde{e}_R} \sim 4 \frac{\alpha_1}{\pi} \frac{F}{\Lambda_5}.$$

In the standard model $\frac{\alpha_1}{\pi} \sim \frac{1}{250}$ so we need $F/\Lambda_5 > 6.25$ TeV in order to satisfy the experimental bounds on this mass. The CSB prediction for F is of order 10 TeV² so this implies $\Lambda_5 \sim 1.6$ TeV. The ISS mass parameter then satisfies

$$\frac{m_{ISS}}{\Lambda_5} \sim 4.$$

It is expected⁴ that when $m_{ISS} \gg \Lambda_5$, the meta-stable state of ISS disappears. One would expect to be able to integrate out the penta-quarks at a scale where the Pentagon gauge coupling was weak, leaving over the pure $SU(5)$ gauge theory and the supersymmetric standard model, coupled only by irrelevant operators. This theory does not have any meta-stable SUSY violating states. The ISS analysis itself was carried out in the limit where $m_{ISS} \ll \Lambda_5$.

⁴A proof of this fact has not yet been found.

The phenomenologically preferred value for m_{ISS}/Λ_5 is not in the perturbative regime. For example, a corresponding ratio in QCD would correspond to quark masses of order 600 MeV. Thus, it is not implausible that the meta-stable state exists in the phenomenologically required region. Note also that the additional hypercharged states in the Pentagon model might make the coupling α_1 , which appears in the estimate for the slepton mass, slightly larger, and consequently loosen the bound on F/Λ_5 . Nonetheless, these considerations suggest that the lightest charged sleptons in the Pentagon model of SUSY breaking cannot be significantly heavier than the current experimental lower limits. Thus, we expect to see these sleptons produced at LHC. Since the LSP is the light gravitino, with couplings of order $1/F$, slepton pair production will result in spectacular final states with two hard leptons, other hard particles, and missing energy, a classic signal for low energy SUSY breaking[5]. It is however likely that the NLSP in this model is not a gaugino, because of the extra factor of 4 in gaugino masses. The other hard particles in the final state depend on the nature of the NLSP, which we cannot determine at this time.

It is worth pointing out that these estimates of the scale of SUSY breaking give a gravitino mass of order 5×10^{-3} eV. Such gravitinos are perfectly consistent with Big Bang Nucleosynthesis, in sharp contrast to conventional gauge mediated models. They are light enough, and their longitudinal components strongly coupled enough, that one might imagine finding them in experiments probing for short distance modifications of gravity. It has also been suggested that they might be found at the LHC[6].

Another difference between the Pentagon model and conventional gauge mediated models is that the $SU(2) \times U(1)$ violating top squark mass generated by the F term of H_u is comparable to or larger than the gauge mediated mass. This is because our model effectively generates a sizable effective μ term, from the VEV of S .

Unfortunately, the strong coupling physics at the scale Λ_5 prevents us from making very precise statements about the spectrum of superpartner masses. In particular, there are three potentially worrisome tuning problems that I have not had the calculational skill to address. First, our estimates of gaugino and right handed slepton masses depended on the assumption that the couplings g_S and g_T were strong enough that there is no further loop suppression of gaugino masses (recall that these couplings broke the discrete R symmetry left over by m_{ISS}). In particular one may worry that g_T is not asymptotically free (it would appear to be renormalized only by wave function renormalization of the gauge invariant S field) so that a large value at low energy may lead to a Landau pole well below the unification scale.

The second potential tuning is the ratio of the electroweak scale, 250 GeV to Λ_5 . For g_S of order 1, this is of order 1/6. It scales like g_S for small g_S , since the VEV of the bilinear $PY\tilde{P}$ is of order g_S , but small g_S would alter our estimates for gaugino

and charged slepton masses in an unpleasant fashion. Finally, one may worry about the “little hierarchy problem”. Precision electroweak measurements seem to prefer a Higgs mass below 200 GeV, and this may also be a little tuned in the current model. It is hard to tell whether one should take factors of 6 – 10 seriously in a model where it is so hard to make precise calculations.

One thing that appears safe is direct interference of the Pentagon degrees of freedom with precision electroweak measurements. These would primarily affect the Peskin-Takeuchi S-parameter, but with our estimates of Λ_5 and m_{ISS} the effects seem to be small⁵. These same estimates suggest that the expected rich “penta-hadron” spectrum may be beyond the discovery reach of the LHC. Scaling up from QCD we might expect penta-mesons in the 6 – 10 TeV range. Penta-baryons will probably be unstable to decays into penta-mesons and pentons, with life-times of order Λ_5^{-1} . The penton itself is the only light remnant of the penta-hadron spectrum. As discussed above, it should be produced in association with ordinary charge changing weak decays and can be searched for in low energy experiments, rather than the LHC.

4. Baryon number, lepton number, and flavor

4.1 B and L violating operators of dimension 4 and 5

A central element in CSB is the discrete R symmetry which guarantees Poincare invariance in the the limiting model. This can be put to other uses. In [7] I showed that it can eliminate all unwanted dimension 4 and 5 baryon and lepton number violating operators in the supersymmetric standard model. This is sufficient to account for experimental bounds on baryon and lepton number violating processes. The interaction $\int d^2\theta H_u^2 L^2$, should not be forbidden by R. I will adopt the philosophy of a previous paper and insist that the texture of quark and lepton Yukawa couplings, as well as neutrino masses, are determined by physics at the unification scale.

We will choose the R charge of SSM fields to be independent of quark and lepton flavor, and denote it by the name of the corresponding field. All R charges are to be understood modulo N , where Z_N is the R symmetry group. In the remodeled Pentagon model, we must choose $N = 4$ in order to accommodate the $g_T S^3$ term in the superpotential. We will also impose anomaly freedom for the discrete R symmetry. That is, the 't Hooft interactions generated by all instantons should be invariant. This leads to the three constraints (all equations in this section are equalities mod 4):

$$5(P + \tilde{P}) = 0 \tag{4.1}$$

⁵I would like to thank H. Haber for conversations about this point.

$$6Q + 3\bar{U} + 3\bar{D} + 5(P + \tilde{P}) = 0 \quad (4.2)$$

$$H_u + H_d + 9Q + 3L + 5(P + \tilde{P}) = 0 \quad (4.3)$$

In writing these equations, we have taken into account the gaugino charges, and dropped terms that are explicitly zero mod 4. Using the first anomaly equation and dropping more terms which vanish mod 4, the second two equations can be simplified to:

$$6Q + 3(\bar{U} + \bar{D}) = 0, \quad (4.4)$$

$$3Q + L = 0. \quad (4.5)$$

The condition that the standard Yukawa couplings are allowed by R symmetry is

$$L + H_d + \bar{E} = Q + H_d + \bar{D} = Q + H_u + \bar{U} = 2. \quad (4.6)$$

The coupling SH_uH_d requires

$$H_u + H_d = 0. \quad (4.7)$$

Note that these conditions forbid the standard μ term $\int d^2\theta H_uH_d$. We will also impose $2L + 2H_u = 2$ to allow the dimension 5 F term which can generate neutrino masses. The renormalizable dynamics of the Pentagon gauge theory preserves all flavor symmetries of the standard model. This forbids the generation of the neutrino seesaw term with coefficient $\frac{1}{\Lambda_5}$. As emphasized in [7], we imagine the neutrino seesaw term, and the texture of the quark and lepton mass matrices, to be determined by physics at the scale M_U , probably via a Froggat Nielsen mechanism.

Dimension 4 baryon and lepton number violating operators in the superpotential will be forbidden in the limiting model by the inequalities

$$2L + \bar{E} \neq 2 \quad (4.8)$$

$$2\bar{D} + \bar{U} \neq 2, \quad (4.9)$$

$$L + Q + \bar{E} \neq 2. \quad (4.10)$$

Absence of dimension 5 baryon number violating operators requires

$$3Q + L \neq 2 \quad (4.11)$$

$$3Q + H_d \neq 2 \quad (4.12)$$

$$\bar{E} + 2\bar{U} + \bar{D} \neq 2, \quad (4.13)$$

The condition that there be no baryon number violating dimension 5 D-terms is that none of $Q + \bar{U} - L$; or $U + E - D$, vanishes.

We can solve for all of the R charges in terms of L and H_d :

$$\begin{aligned} Q &= -3L \\ \bar{E} &= 2 - L - H_d \\ \bar{D} &= 2 + 3L - H_d \\ \bar{U} &= 2 + 3L + H_d. \end{aligned}$$

In addition we have the relation

$$2L = 2H_d + 2.$$

The inequalities which forbid dangerous operators are all satisfied if and only if L is odd and H_d is even. Any choice satisfies the last constraint, so we have four solutions $L = \pm 1, H_d = 0, 2$.

4.2 Flavor and CP

The Pentagon shares with generic gauge mediated models the property that the only terms in the low energy Lagrangian that are not invariant under the $SU(3)_Q \times SU(3)_{\bar{U}} \times SU(3)_{\bar{D}}$ flavor group of the standard model, are the quark and lepton Yukawa couplings, and the neutrino seesaw term. As a consequence it has a GIM mechanism, and flavor changing neutral currents are suppressed below experimental upper bounds. Similarly, lepton flavor changing processes like $\mu \rightarrow e + \gamma$ are within experimental limits. Quark and lepton flavor changing processes, in addition to those induced by the neutrino seesaw term, will come from dimension 6 operators. We can assume that they are scaled by the same operator $M_U \sim 10^{15}$ GeV as the neutrino seesaw. Note that the restriction to dimension 6 operators is non-trivial and depends on the fact that dimension 5 superpotential terms like $Q^2 \bar{U} \bar{D}$ (with various flavor combinations) are forbidden by the Z_4 R symmetry, although they conserve baryon and lepton number. Flavor violation comes predominantly through SSM loop graphs.

The remodeled Pentagon thus solves most of the problems of generic SUSic models. However, it does have CP violating phases in addition to the usual CKM parameter. To see this, perform the following sequence of transformations.

- A $U_A(1)$ transformation on quarks, to eliminate the QCD θ angle, θ_3 .
- A similar $U_AP(5)$ transformation on penta-quarks to eliminate θ_5 .
- An anomaly free $U_R(1)$ transformation, to eliminate $\text{arg}m_{ISS}$.

- A common phase rotation on $H_{u,d}$ to eliminate $\arg\det\lambda_u\lambda_d$.
- A phase rotation of S to eliminate $\arg g_\mu$.

We are left with the phases of $g_{S,T}$ (as well as phases in the neutrino see-saw term and CKM matrix) as physical CP violating parameters. When we integrate out scales $\gg \Lambda_{QCD}$, these phases will infect the determinant of the renormalized quark mass matrix and are likely to give rise to an electric dipole moment for the neutron which is incompatible with experimental bounds. The upside of this result is that the potentially troublesome axion, which roamed the halls of the old Pentagon, no longer exists.

Counting one of these two phases as a stand in for θ_3 we see that the Pentagon model has six new physical parameters, the absolute values of m_{ISS} , Λ_5 , $g_{S,T,\mu}$ and one combination of the phases of $g_{S,T}$ in addition to the parameters in the standard model Lagrangian. Of these, $|m_{ISS}|$ is roughly determined by the rules of CSB. The three Yukawa couplings of the S field are required to be reasonably large. We will discuss the consequences of this assumption in the section on unification of couplings.

5. Dark matter

CSB, like any model with a maximum SUSY breaking scale of order < 100 TeV, does not have a cosmologically stable massive LSP. Even if R-parity is preserved, the LSP is the gravitino, and its longitudinal components are so strongly coupled that the NLSP will decay to it rapidly, probably in typical particle detectors, and certainly with non-cosmological lifetimes. In previous discussions of CSB, I have suggested baryons of the new strong gauge group as dark matter candidates and in [8] we showed that this was a viable option if a sufficiently large penta-baryon asymmetry is generated in the early universe. The meta-stable ISS SUSY breaking state also breaks penta-baryon number spontaneously, so penta-baryons are no longer cosmologically stable.

Instead, I want to show that with a sufficiently large penta-baryon number asymmetry, the penta-baryon can be the dark matter. Assume a penta-baryon asymmetry to entropy ratio ϵ is generated in the early universe at or after inflationary reheating, and that there is no significant entropy production thereafter. The universe is radiation dominated and the penta-baryon density at temperature T will be

$$n_{PB} = \epsilon GT^3,$$

where G counts the effective number of massless degrees of freedom in the plasma. Once T drops below Λ_5 the penta-baryon density can be written in terms of the penta-baryon

field b

$$n_{PB} = \Lambda_5 \dot{b},$$

so we get the equation of motion

$$\dot{b} = \epsilon G \frac{T^3}{\Lambda_5}.$$

So far we have not taken explicit penta-baryon number violation into account. The leading gauge invariant supersymmetric penta-baryon number violating interactions are the dimension six F terms $\frac{1}{M_U^2} \int d^2\theta (aP^5 + b\tilde{P}^5)$. We will take the mass scale in these interactions to be the same order of magnitude, $\sim 10^{15}$ GeV, as that which enters the dimension 5 operator that leads to neutrino masses and mixings. Below the scale Λ_5 these interactions will give rise to a potential for b of order

$$\frac{\Lambda_5^6}{M_U^2} V(b/\Lambda_5),$$

where V is a periodic function. This gives a penton mass of order $\frac{\Lambda_5^2}{M_U} \sim 2eV$.

The potential will begin to affect the cosmological evolution of the penton when the kinetic energy generated by the asymmetry is of order the potential. This happens at a temperature T^* given by

$$\epsilon^2 G^2 (T^*)^6 = \frac{\Lambda_5^8}{M_U^2}.$$

Unless $\epsilon G < \frac{\Lambda_5}{M_U} \sim 10^{-12}$, this temperature is below Λ_5 and so our description of the effects of the explicit symmetry breaking is valid. We will see that ϵ has to be quite large if we want the penton to be dark matter.

Indeed, below the scale T^* the penton density will grow relative to the radiation energy density by a factor $\frac{T^*}{T}$.

$$\frac{\rho_p}{\rho_\gamma} = \epsilon^2 G \left(\frac{T^*}{\Lambda_5}\right)^2 \frac{T^*}{T}.$$

Note that

$$\left(\frac{T^*}{\Lambda_5}\right)^3 = \frac{\Lambda_5}{\epsilon G M_U},$$

so that

$$\frac{\rho_p}{\rho_\gamma} = \epsilon \frac{\Lambda_5}{M_U} \frac{\Lambda_5}{T}.$$

Matter radiation equality occurs at $T \sim 10$ eV in the real world, and we can achieve this if $\epsilon \sim 5$. Values of ϵ this large can probably only be achieved via coherent classical processes analogous to Affleck-Dine baryogenesis, but are certainly not implausible in that context.

We remarked in the second section of this paper that there is a coupling between the penta-baryon and baryon number currents induced by QCD interactions above the scale Λ_5 . In the presence of the asymmetry we have postulated here, this gives rise to a time dependent chemical potential for baryon number in the early universe. It would be remarkably interesting if, when combined with ordinary electro-weak sphaleron processes, this could give rise to the observed baryon asymmetry, thus tying together the baryon asymmetry and dark matter densities of the universe. This would be a form of *spontaneous baryogenesis*, as first envisaged by Cohen and Kaplan[9] . We hope to report on this interesting possibility in the near future⁶.

6. Coupling constant unification

The extra matter in the Pentagon model consists of the $SU_P(5)$ gauge multiplet, the $SU(1, 2, 3)$ singlet S and the the penta-quarks, which are in complete multiplets of the $SU(5)$ GUT group. One loop gauge coupling unification will not be affected by these new states, but the value of the unified gauge coupling is considerably enhanced. Indeed, the beta function for the $SU(2)$ coupling above the scale m_{ISS} is

$$\frac{d\alpha_2^{-1}}{dt} = -\frac{6}{2\pi},$$

which gives a value of α_2^{-1} slightly less than 8 at the unification scale. The Landau pole in this one loop running coupling comes at $\sim 7 \times 10^{19}$ GeV, so we seem to be just within the perturbative regime . Two loop calculations make the unified coupling even larger and one may be skeptical of the perturbative expansion. Nonetheless, it appears reasonable to claim that this model predicts coupling unification. The large size of the unified coupling suggests that dimension six operators may give proton decay within range of future experiments.

A more troubling problem is posed by the Yukawa couplings $g_{S,T}$. These are required to be large at the scale Λ_5 in order to provide sufficiently large gaugino masses. While it is possible that the physical (as opposed to holomorphic) g_S is asymptotically free (since it has a large negative term in its one loop β function coming from Pentagon gauge interactions), this is not true for g_T . It is thus likely that the value of g_T that we need for acceptable gaugino masses will lead to a Landau pole below the unification scale. Further investigation is required to determine whether the prediction of coupling unification can be salvaged.

⁶Preliminary analysis and further work on this problem have been done in collaboration with S.Echols and J.Jones[10].

7. Anthropic considerations

Viewed as an effective field theory, the Pentagon model has a coincidence of scales, $m_{ISS} \sim 4\Lambda_5$, which is forced on us by phenomenology. One might try to explain this coincidence by anthropic arguments. I will discuss only the version of this argument that follows from the principles of CSB, in which only the parameter m_{ISS} , which is determined in terms of the c.c., is allowed to vary. The whole structure of the Pentagon model, determined as it is by discrete R symmetries, does not fit in well with the String Landscape[11], in which we would have to assume that all parameters are anthropically scanned. Within the context of CSB, Weinberg's anthropic bound on the c.c takes on its full force, and one does not have to worry about varying other parameters.

However, if the c.c. is an input parameter, governing the number of states in the quantum theory, it is no longer safe to assume that the probability distribution determining it is flat near $\Lambda = 0$. For example, a flat distribution in the number of states corresponds to a strong preference for very small Λ . Weinberg's argument that we observe a typical value for the c.c. that allows galaxies to exist is no longer so obvious. A meta-physical model, which introduces an *a priori* preference for large Λ [12] could solve this problem.

It is however interesting that the qualitative low energy physics of our model changes drastically as soon as $\sqrt{\lambda^{1/4}M_P} \sim 100$ GeV rather than ~ 3 TeV. This corresponds to reducing m_{ISS} by a factor of 30 so that $m_{ISS}/\Lambda_5 \sim .1$. When this dimensionless parameter is small the low energy theory has a large set of degrees of freedom charged under the standard model and the QCD coupling does not become asymptotically free until a scale of order 100 GeV. We should imagine that its short distance value is fixed, so that $\alpha_3(100\text{GeV})$ is much smaller than its experimental value. With a very crude estimate, we find that this reduces the QCD scale by a factor of 200. Note that the scale Λ_5 , and thus the scale of electroweak interactions is unchanged, while the value of the electroweak couplings $g_{1,2}$ is slightly reduced. Quark and lepton masses are not changed significantly. It is clear that these changes will have dramatic effects on nuclear physics and stellar evolution, and bring the scales of atomic and nuclear physics closer together. Such changes make life of our type impossible. More work would be necessary to determine precisely what the anthropic lower bound on λ is in this framework, but it is clear that it is within a few orders of magnitude of the observed value.

One might also ask whether an improved *upper* bound on λ would follow from a similar argument. This seems unlikely, since the physics of the Pentagon model depends only on the fourth root of λ . However, there is one way in which a tight upper bound on λ might arise from the Pentagon. Suppose that the phenomenologically required value

of m_{ISS}/Λ_5 , which appears to be ~ 4 , were close to the value at which the meta-stable ISS state of the Pentagon model disappears. If *e.g.* the critical value of this ratio were 10, then increasing λ by a factor of $(2.5)^4 \sim 40$ would completely change the low energy world.

Indeed, whether or not it gives us a strong anthropic bound on λ , the existence of a critical value of $r \equiv m_{ISS}/\Lambda_5$ raises an interesting conundrum for CSB. The basic idea of CSB is that the finite λ theory is described by a finite number of fermionic oscillators, which represent quantized pixels on the cosmological horizon of dS space[13]. This finite system has an approximate S matrix, which converges to the S matrix of a super-Poincare invariant theory of quantum gravity in the $\lambda \rightarrow 0$ limit. Low energy matrix elements of this approximate S matrix are supposed to be calculable from the Pentagon model for sufficiently small λ . If there is a critical value of r above which the Pentagon model does not break SUSY, then, above this value of r , the low energy Pentagon model is not a good approximation to the underlying theory of pixels. That model certainly does not have exact SUSY, and certainly does have a finite number of states. On the other hand, since the critical value of λ is $\ll m_P$, one would imagine that there is a valid low energy Lagrangian for the system even above the critical value. What is it? and how can we understand the transition between the two descriptions in low energy terms?

8. Conclusions

The remodeled Pentagon is a much more robust structure than its predecessor. The existence of a meta-stable SUSY violating state is on fairly firm footing and the complicated singlet sector of the previous model has been replaced by a single field. This eliminated the troublesome low scale axion. Elimination of an approximate residual Z_5 R symmetry seems to restrict the fundamental R symmetry group of the model to be Z_4 . The model has no problems with FCNC or unwanted baryon and lepton number violating interactions of dimension less than six. Its unification scale couplings are large enough that dimension six proton decay might occur at observable rates. Precision electroweak measurements also seem to pose no problems for the Pentagon, since the particles in the new sector (apart from the neutral penton) are in the 6-10 TeV range.

The Pentagon model predicts relatively light charged sleptons, which will be produced at LHC and have the spectacular decay signals of sleptons in all SUSY breaking scenarios with a very light gravitino. The final state includes opposite sign hard leptons plus missing transverse energy plus X . It is possible, but unlikely since gauginos appear to be heavy in our models, that X is the two photon signal of standard gauge mediation. The nature of X is determined primarily by the identity of the NLSP in

the Pentagon model and our ability to calculate the details of the sparticle spectrum in the Pentagon model is limited. One should also note that, as a consequence of the low SUSY breaking scale, decays to gravitinos will be prompt in our model and there will be no displaced vertices.

The Pentagon gives a pattern of SUSY breaking similar to but distinct from conventional gauge mediated models. The typical squark or slepton mass ratio is enhanced by a factor ~ 4 (but this only effects the determination of the scales of the model in terms of experimental quantities). However, the typical gaugino to squark or slepton mass ratio is also enhanced by a factor ~ 4 . Top squarks have relatively large $SU(2) \times U(1)$ breaking masses coming from the F terms of the Higgs fields, which may be comparable to or larger than their gauge mediated masses. Electroweak symmetry breaking occurs naturally, with the right pattern and $\tan\beta \sim 1$.

Dark matter consists of the penton, a scalar pseudo-Goldstone boson of penta-baryon number. This requires a penta-baryon asymmetry of order 5 to be generated in the early universe, and suggests a new mechanism for understanding the dark matter to baryon ratio. The penton mass is in the single eV range. Its dominant couplings to ordinary matter come through flavor violation. It will be emitted in flavor changing charged current decays of ordinary hadrons and leptons. The hadronic processes are enhanced by two powers of the ratio of strong and weak fine structure constants, but even these hadronic branching ratios for associated penton production are quite small. There is additional chiral suppression for processes involving only light quarks.

Gravitinos are extremely light in the Pentagon model and have no dangerous cosmological consequences. It is conceivable that double gravitino exchange might be observed in short distance gravity experiments, and that light gravitino signals can be seen at LHC.

Possible problems with the model arise in the Higgs and Singlet sectors. It is not clear that the VEV of the singlet, S , is large enough to play the role of the μ term of the MSSM. It may be inconsistent with perturbative unification to take the Yukawa couplings g_S and g_T to be as large as they must be in order to have acceptably large gaugino masses. It is not clear whether the nominal factor of 6 between the value of electroweak VEVs and the scale $\Lambda_5 \sim 1.5$ TeV, constitutes a fine tuning or little hierarchy problem. The small Higgs mass preferred by precision electroweak data might also appear problematic. The value of the electroweak VEV obtained by setting $F_S = 0$ (which is not the correct thing to do, since SUSY is violated) is of order $g_S \Lambda_5$, so we might try to attribute the ratio $\langle H_u \rangle / \Lambda_5$ to a small value of g_S . However, setting $g_S = 0$ restores the Z_5 R symmetry of the ISS state in the pure Pentagon gauge theory, and gaugino masses will vanish in this limit. It seems clear that we must develop more reliable methods for computing properties of the strongly coupled Pentagon theory, in

order to assess the severity of these tuning problems.

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