

Discrete R Symmetries and Low Energy Supersymmetry

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Plan for Today: "New, Improved" Models of Dynamical Supersymmetry Breaking

It is often said that SUSY breaking is a poorly understood problem. But much has been known for many years; problem is that models were complicated. Stable, dynamical SUSY breaking requires chiral fields, other special features which are not particularly generic. Model building is hard. All of this changed with work of Intriligator, Shih and Seiberg (ISS): Focus on *metastable* susy breaking.

Metastable Supersymmetry Breaking

Quite generic. First, non-dynamical.

O’Raifeartaigh Model:

$$W = X(\lambda A^2 - f) + mAY \quad (1)$$

SUSY broken, can’t simultaneously satisfy

$$\frac{\partial W}{\partial X} = \frac{\partial W}{\partial Y} = 0. \quad (2)$$

E.g. $m^2 > f$ gives $\langle A \rangle = \langle Y \rangle = 0$, $\langle X \rangle$ undetermined. f is order parameter of susy breaking.

This model has a continuous "R Symmetry". In accord with a theorem of Nelson and Seiberg, which asserts that such a symmetry is required, generically, for supersymmetry breaking.. In components, using the same labels for the scalar component of a chiral field and the field itself:

$$X \rightarrow e^{2i\alpha} X \quad Y \rightarrow e^{2i\alpha} Y \quad A \rightarrow A \quad (3)$$

while the fermions in the multiplet have R charge smaller by one unit, e.g.

$$\psi_X \rightarrow e^{i\alpha} \psi_X \quad \psi_Y \rightarrow e^{i\alpha} \psi_Y \quad \psi_A \rightarrow e^{-i\alpha} \psi_A. \quad (4)$$

(For those familiar with superspace, this corresponds to $\theta \rightarrow e^{i\alpha\theta} \quad d\theta \rightarrow e^{-i\alpha} d\theta$.)

Under an R symmetry, the supercharges and the superpotential transform:

$$Q_\alpha \rightarrow e^{i\alpha} Q_\alpha \quad \bar{Q}_{\dot{\alpha}} \rightarrow e^{-i\alpha} \bar{Q}_{\dot{\alpha}} \quad W \rightarrow e^{2i\alpha} W. \quad (5)$$

We don't expect (exact) continuous global symmetries in nature, but discrete symmetries are more plausible. Take a discrete subgroup of the R symmetry, e.g. $\alpha = 2\pi/N$; a *discrete R* symmetry (Z_N) Allows

$$W = X(\lambda A^2 - f) + mAY + \frac{X^{N+1}}{M^{N-2}} \quad (6)$$

(We will assume $M \sim M_p$).

In this model, the continuous R symmetry is an accidental consequence of the discrete symmetries at low energies (the model can be the most general consistent with symmetries).

One expects that the model has supersymmetric vacua, and it does:

$$X = (fM^{N-2})^{1/N+1}. \quad (7)$$

But the minimum near the origin persists, with positive energy ($\approx f^2$), so the susy-breaking vacuum is *metastable*.

Retrofitting: Supersymmetry Breaking Made (too?) Easy

ISS: A beautiful dynamical example. But for a number of reasons (to which we will return) I will focus on models which are, at first sight, somewhat more ad hoc, but also simpler.

"Retrofitting".

Would like to generate the scale, f , dynamically.

Basic ingredient: dynamical generation of a scale, without susy breaking.

Candidate mechanism: gaugino condensation.

Gaugino Condensation

Pure susy gauge theory: One set of adjoint fermions, λ .
Quantum mechanically: Z_N symmetry.

$$\langle \lambda\lambda \rangle = \Lambda^3 e^{\frac{2\pi i k}{N}} \quad (8)$$

breaks discrete symmetry, but not susy.

Retrofitting the O'Raifeartaigh Model

Feng, Silverstein, M.D. Take our earlier model, and replace $f \rightarrow \frac{\Lambda^3}{M}$:

$$W = -\frac{1}{4} \left(1 + \frac{cX}{8\pi^2} \right) \frac{W_\alpha^2}{M_p} + XA^2 + mYA + \frac{X^{N+1}}{M_p^{N-2}}. \quad (9)$$

Calling

$$\langle \lambda\lambda \rangle = N\Lambda^3 e^{-\frac{cX}{NM_p}} \approx W_0 - fX \quad f = \frac{c\Lambda^3}{M_p} \quad W_0 = N\Lambda^3, \quad (10)$$

the low energy effective superpotential is (for $X \ll M_p$):

$$W = W_0 + X(A^2 - f) + XA^2 + mYA, \quad (11)$$

A skeptic can argue that this is all a bit silly:

- 1 We have introduced a new gauge interaction *solely* to generate an additional mass scale.
- 2 We still have a mass parameter M , put into the model by hand.
- 3 Anything else you might wish to complain about.

The rest of this talk will be devoted to confronting these questions.

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- 1 The first failing is actually a major success.. When we consider the cosmological constant(!), retrofitting looks virtually inevitable.
- 2 Richer dynamics – a simple generalization of gaugino condensation – can account for both scales dynamically.
- 3 We will argue that in “gravity mediation”, R symmetries (discrete) are inevitably broken by Planck scale amounts and are not interesting. We will be lead to a general theorem about supersymmetry and R symmetry breaking (Festuccia, Komargodski, and M.D.).
- 4 In “gauge mediation” (lower scale breaking), R symmetries can play a role in suppressing proton decay and other rare processes.
- 5 The μ problem of gauge mediation is readily solved in this framework.

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Why Retrofitting is (Almost) Inevitable

Supergravity and the Cosmological Constant

In supergravity theories, the potential takes the form

$$V = e^{K(\phi, \phi^*)} \left[\left(\left| \frac{\partial W}{\partial \phi_i} + \frac{\partial K}{\partial \phi_i} \frac{W}{M_p} \right|^2 \right) - \frac{3}{M_p^2} |W|^2 \right] \quad (12)$$

This is not quite the most general form, but exhibits all essential features:

- 1 The generalization of the susy order parameter, $\frac{\partial W}{\partial \phi_i}$, of globally susy theories, is

$$F_i = \frac{\partial W}{\partial \phi_i} + \frac{\partial K}{\partial \phi_i} W.$$

- 2 If the cosmological constant is to be extremely small,

$$|\langle W \rangle| = \sqrt{3} |F| M_p \quad (13)$$

- 3 The gravitino mass is

$$m_{3/2} = e^{K/2} \langle W \rangle.$$

The Cosmological Constant in Gravity, Gauge Mediation

To obtain small cosmological constant, we need $\langle W \rangle \sim FM_p$. A traditional critique of gauge mediation (Banks): if breaking dynamical, $W \sim \Lambda^3$; $F \sim \Lambda^2 \leftrightarrow$ Need more interactions and another scale [think retrofitting!] or a big constant in W , unrelated to anything else.

"Supergravity" Models

In supergravity theories with supersymmetry broken at an intermediate scale, $F \approx (\text{TeV}) \times M_p \approx 10^{11} \text{ GeV}$, $\langle W \rangle$ is typically of the correct order of magnitude. E.g.

$$W = fZ + W_0. \quad (14)$$

("Polonyi model"). If $W_0 \sim fM_p$, one finds $Z \sim M_p$, so $W \sim FM_p$. At least plausible coincidence of scales. Perhaps in a dynamical model, W_0 generated by large vev for a pseudomodulus.

Our focus here is on discrete R symmetries, which would forbid W_0 ; canceling the cosmological constant would seem to require that the symmetry be spontaneously broken by a large amount. In the supergravity models, the R symmetry, because of the large breaking, is not useful to understand the structure of the low energy theory.

[If there were an approximate R symmetry, one would be able to analyze the theory as an approximately globally supersymmetric theory; there would then be an approximate R symmetry; but cancelation of the cosmological constant requires, then, a large breaking of the symmetry. This *could* happen in some separate sector; this will be the case in retrofitted models.]

Aside: A Theorem About the Superpotential

In theories with a continuous R symmetry,

$$|\langle W \rangle| < \frac{1}{2} f_a F \quad (15)$$

(Festucia, Komogordski, M.D.).

This is the subject of a separate seminar. For our problem, it makes rigorous the intuition from the simple model that canceling the *c.c.* requires Planckian breaking of the R symmetry (and then why was susy dynamically broken?)

[Various possible ways out.]

R symmetries and the Cosmological Constant

In the case of an unbroken R symmetry, $\langle W \rangle = 0$. So the breaking of any R symmetry is a requirement for obtaining small cosmological constant.

In retrofitted models, if the scale $M \sim M_p$, then

$$W \sim FM_p \sim \Lambda^3. \quad (16)$$

In other words, the scale of gaugino condensation is just what is required to obtain a small c.c.

From this point of view, retrofitting seems inevitable. From now on, focus on low energy breaking (gauge mediation).

Problems with our earlier model

- 1 Model has two scales. One attempt to avoid (related to ideas of Green, Wiegand.), is not compatible with the requirement of small c.c. (we would have to add still *other* interactions to cancel the c.c.
- 2 The model does not spontaneously break the R symmetry (once one performs the Coleman-Weinberg analysis; this is in accord with a theorem of D. Shih). Can be modified following constructions of Shih.
- 3 When developed into a model of gauge mediation, the model has other difficulties, such as the μ problem.

Many of these difficulties might be avoided if we had order parameters for the breaking of the R symmetry of lower dimension (e.g. gauge singlet chiral superfields).

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The Essence of Gaugino Condensation

Gaugino condensation is considered in many contexts, but its principal distinguishing feature is that it breaks a discrete R symmetry without breaking supersymmetry. Many other models, such as supersymmetric QCD with massive quarks, dynamically break such symmetries, but it would be helpful to have models like pure susy gauge theory, with scales generated by dimensional transmutation.

Models with Singlets

$SU(N)$ gauge theory with $N_f < N$ massless flavors, N_f^2 singlets, $S_{f,f'}$

$$W = y S_{f,f'} \bar{Q}_{f'} Q_f - \frac{1}{3} \gamma \text{Tr} S^3 \quad (17)$$

For convenience, we have taken the superpotential to respect an $SU(N_f)$ symmetry; γ and y can be taken real, by field redefinitions. Anomaly free discrete symmetry $Z_{2(3N-N_f)}$ R -symmetry,

$$\alpha = e^{\frac{2\pi i}{6N-2N_f}} \quad (18)$$

$$\lambda \rightarrow \alpha^{3/2} \lambda \quad S_{f,f'} \rightarrow \alpha S_{f,f'} \quad (Q, \bar{Q}) \rightarrow \alpha(Q, \bar{Q}). \quad (19)$$

(Special cases considered in the past by Yanagida)

For $N_f < N$, treating γ and y as small, we can analyze the system by including the familiar non-perturbative superpotential of $SU(N)$ QCD with N_f flavors

$$W_{dyn} = (N - N_f) \Lambda^{\frac{3N - N_f}{N - N_f}} \det(\bar{Q}Q)^{-\frac{1}{N - N_f}}. \quad (20)$$

In the $SU(N_f)$ symmetric limit, the $\frac{\partial W}{\partial \phi} = 0$ equations admit solutions of the form

$$S_{f,f'} = s \delta_{f,f'} \quad Q_f \bar{Q}_{f'} = v^2 \delta_{f,f'}. \quad (21)$$

with

$$v = \left(\frac{\gamma}{y^3} \right)^{\frac{N - N_f}{6N - 2N_f}} \alpha^k \Lambda; \quad s = \left(\frac{y^{N_f}}{\gamma^N} \right)^{\frac{1}{3N - N_f}} \alpha^k \Lambda. \quad (22)$$

Perturbing away from the symmetric limit, one can then check that there is no qualitative change in the solutions (e.g. the number is unchanged). For $N_f \geq N$, the theory has baryonic flat directions, and does not have a discrete set of supersymmetric ground states. Adding additional singlets and suitable (non-renormalizable) couplings, one can again spontaneously break the discrete symmetries. One can also consider generalizations to other gauge groups and to different matter content. (Under study by Kehayias).

New, Improved Models

In gauge mediated models, there are wide range of possible scales.

$$10^5 \text{ GeV} \leq M \leq 10^{14} \text{ GeV} \quad 10^5 \text{ GeV} \leq \sqrt{F} \leq 10^{8.5} \text{ GeV} \quad (23)$$

We revisit gauge-mediated model building using retrofitting and the enlargement of gaugino condensation.

We will consider two classes of models. The constructions will be *slightly* technical, so we state the main points first.

- 1 Models with a hierarchy of scales: In these, there is naturally a mass scale S (the scale of the microscopic R symmetry breaking), and a smaller scale, connected with susy breaking. The larger scale will be of order $10^{11.5}$ GeV, while the underlying susy breaking scale will be $\sqrt{F} \approx 10^8$ GeV. In this context, the μ problem is readily solved. The dynamics of susy breaking is not directly experimentally accessible.
- 2 Models with a single scale: here the underlying scale of susy breaking dynamics can be 100's of TeV (potential dramatic signatures; the scale of R symmetry breaking is larger). The μ problem, again, is readily solved.

Models with a Hierarchy of Scales

We will retrofit a model which spontaneously breaks a continuous R symmetry. Perhaps the simplest example is provided by a theory with fields $\phi_{\pm 1}, \phi_3, X_2$, where the subscripts denote the R charge, and with superpotential:

$$W = X_2(\phi_1\phi_{-1} - f) + m_1\phi_1\phi_1 + m_2\phi_{-1}\phi_3. \quad (24)$$

Motivated by this model, consider a theory with fields $X_0, S_{2/3}, \phi_0, \phi_{2/3}, \phi_{4/3}$, where the subscript denotes the discrete R charge ($\phi_q \rightarrow \alpha^q \phi_q$, where α is a root of unity). $S_{2/3}$ is a field with a large mass and an R symmetry breaking vev,

$$W = \frac{1}{M_p} X_0 S_{2/3}^3 + y X_0 \phi_{2/3} \phi_{4/3} + \lambda_1 S_{2/3} \phi_{2/3} \phi_{2/3} + \lambda_2 S_{2/3} \phi_{4/3} \phi_0 \quad (25)$$

(up to terms involving higher dimension operators).the resulting low energy effective theory is that of eqn. 24, with

$$m_1 = \lambda_1 S_{2/3} \quad m_2 = \lambda_2 S_{2/3} \quad f = -\frac{S_{2/3}^3}{M_p}. \quad (26)$$

Below the scale $S_{2/3}$, the theory possesses an accidental, (approximate) continuous R symmetry which is spontaneously broken.

$m_i^2 \gg f$. If X couples to some messenger fields, the scale for gauge mediated masses is set by Λ_m :

$$W_{mess} = X\bar{M}M \quad \Lambda_m = \frac{F_X}{X} \approx \frac{S^2}{M_p}. \quad (27)$$

If $\Lambda_m \sim 10^5$ GeV, for example, then we have $S \sim 10^{11.5}$ GeV.

It is also not difficult to write down models with a lower scale of supersymmetry breaking with many similar features (i.e. where $\langle X \rangle^2 \sim F_X \sim 10^5 \text{ GeV}$).

The μ Problem

Generating a μ term in gauge mediation has long been viewed as a challenging problem.

Retrofitting has been discussed as a solution to the μ problem (Yanagida, Thomas, Dine and Mason, Green and Wiegand). If the source of the μ term is a coupling of the gaugino condensate responsible for the hidden sector F term,

$$W_\mu = \frac{W_\alpha^2}{M_p^2} H_U H_D \quad (28)$$

the resulting μ term is very small; it would seem necessary to introduce still *another* interaction, with a higher scale. Not only does this seem implausibly complicated, but it is once more problematic from the perspective of the c.c.

Models with singlets, on the other hand, allow lower dimension couplings and larger μ terms. In the hierarchical model, for example, if the product $H_U H_D$ has R charge $4/3$, it can couple to S^2/M_p with coupling λ .

$$W_\mu = \lambda \frac{S_{2/3}^2}{M_p} H_U H_D. \quad (29)$$

Then

$$\mu = \Lambda_m \quad (30)$$

The F component of S is naturally of order $m_{3/2}^2$, so this does not generate an appreciable B_μ term; the B_μ term must be generated at one loop. A rough calculation yields $\tan \beta \sim 30$. Alternative structures lead to different scaling relations (more detailed analysis in progress with John Mason).

We can similarly solve the μ problem in the single-scale models. Again, W_{μ} , for a range of F 's and λ 's, yields a μ term of a suitable size.

Roles for Discrete R Symmetries

- 1 Account for structure of susy breaking sector
- 2 Account for structure of messenger sector (segregation from visible sector; stability (or not) of messengers.
- 3 Suppression of B,L Violating Dimension Four and Five Operators

For the third point, don't have time for details here, but we see that cosmological constraint provides a (lower) bound on the extent of R symmetry breaking.

One, arguably (Yanagida) should, impose a variety of constraints. E.g.

- 1 Absence of anomalies.
- 2 μ term forbidden in the superpotential
- 3 Kahler potential terms permitted which give rise to a μ term of order the supersymmetry breaking scale.

Very restrictive (Yanagida, Private Communication)

Imposing anomaly constraints requires making plausible – but not strictly necessary – assumptions on the form of the microscopic theory. E.g. messengers, other fields, can mass at the (large) scale of R symmetry breaking. Fields in the same $SU(5)$ multiplet need not transform in the same way. But the limited solutions subject to these restrictions are interesting and give pause. [Thanks to Professor Yanagida for his comments on these issues].

In any case, such symmetries, we have seen, are necessarily broken by significant amounts. If order parameters include gauge singlet chiral fields, suppressing dangerous dimension four operators is challenging and constrains the symmetries. Other interesting issues [again raised by Professor Yanagida] include domain walls and inflation.

Conclusions

If I were giving this talk 15 years ago, I would be very optimistic about the imminent discovery of susy, given the ease with which one can construct relatively simple models of dynamical supersymmetry breaking and gauge mediation. [If I am at all hesitant, this is because of the "little hierarchy", but this is for another talk.]

- 1 Retrofitting allows construction of broad classes of viable models.
- 2 The scales required for retrofitting are precisely those required to account for a small cosmological constant.
- 3 "Gaugino Condensation" is one realization of a broad phenomenon, which permits models with a range of possible scales (and accounts for dimensional transmutation).
- 4 Within these frameworks, the μ problem is not a problem, and one anticipates a large $\tan \beta$.
- 5 Discrete R symmetries seem likely to play a role in accounting for many of the features of low energy susy; in gauge mediation (but not in gravity mediation) they might account for the proton lifetime and suppression of other rare processes.

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THE END

On the Other Hand, In Case you Want More:

Discrete R Symmetries and Proton Decay

Most supersymmetric model building seeks to suppress dangerous dimension four lepton and baryon number violating operators by imposing R parity. R parity is not really an R symmetry at all (it is an ordinary symmetry times a 360° rotation). Unlike the R symmetries we are focussing on in this paper, there is no requirement that it be broken; this leads, most strikingly, to stable dark matter.

Discrete R symmetries might forbid dangerous dimension four *and* dimension five operators. Must be broken; the size of this breaking, and the transformation properties of the fields, will control the size of B and L violating effects (e.g. Yanagida et al, Banks).

In model building with discrete symmetries, one would seem to have a great deal of freedom in both the choice of symmetry group and in the transformation properties of the fields. One, arguably (Yanagida) should, impose a variety of constraints. E.g.

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Imposing anomaly constraints requires making plausible – but not strictly necessary – assumptions on the form of the microscopic theory. E.g. messengers, other fields, can mass at the (large) scale of R symmetry breaking. Fields in the same $SU(5)$ multiplet need not transform in the same way. But the limited solutions subject to these restrictions are interesting and give pause. [Thanks to Professor Yanagida for his comments on these issues]. Other interesting issues [again raised by Professor Yanagida] include domain walls and inflation.

Most discussions of the use of R symmetries to suppress proton decay are framed in the context of gravity mediation, and we have seen that once one requires a small cosmological constant, this is problematic.

R Symmetries in Gauge Mediation

Symmetry which forbids dimension four and five operators (for purposes of illustration): *Conventional R parity*, and an R symmetry, under which all quark and lepton superfields are neutral, while the Higgs transform like the superpotential. This forbids all dangerous dimension four and dimension five operators. Once R symmetry breaking is accounted for, dimension five operators may be generated, but they will be highly suppressed.

We can contemplate more interesting symmetries, which do not include R parity, and for which the Higgs, quarks and leptons have more intricate assignments under the R symmetry. Given that the R symmetry is necessarily broken, dangerous dimension four operators will be generated.

Consider, first, the case where the R symmetry is broken by a gaugino condensate in a pure gauge theory. Suppose that B and L -violating operators of the form

$$\delta W_{b,l} \sim \frac{W_\alpha^2}{M_p^3} \Phi \Phi \Phi \quad (31)$$

are permitted by the symmetries. Even if \sqrt{F} is as large as 10^9 GeV, $W/M_p^3 \approx 10^{-18}$, more than adequately suppressing proton decay.

In the presence of a singlet field such as S , the constraints are more severe. Even in the low gravitino mass case, the small parameter, S/M_p , is of order 10^{-9} . So suppression of dangerous operators by a single factor of S is not adequate. One requires that many operators be suppressed by two powers of S .