Discrete R Symmetries: Macrophysics and Microphysics

String Phenomenology 2010, Paris

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March, 2010

Discrete R Symmetries: Why Might they be Important

Assuming supersymmetry (more about that later). Such symmetries can:

1. Give rise to accidental, continuous, R symmetries, as required by theorem of Nelson and Seiberg to account for supersymmetry breaking.
2. Account for smallness of $\langle W \rangle$ required for cosmological constant
3. Account for suppression of B and L-violating operators.

Discrete R symmetries are, at some sense, “typical" of string ground states. We will confront what we mean by “typical" shortly.

Macroscopic vs. Microscopic Questions

We will first consider how discrete R symmetries might be important in model building, i.e. in guessing the degrees of freedom and the structure of the effective action at scales far below the Planck or string scale. We will construct models of gauge mediation with

1. Supersymmetry dynamically broken; various scales of an appropriate order of magnitude.
2. W_0 automatically of the order of magnitude needed to cancel the supersymmetry-breaking contribution to the cosmological constant.
3. A simple solution to the μ problem of gauge mediated theories.

Varieties of R Symmetry Breaking: Generalizing Gaugino Condensation

Defining characteristic of gaugino condensation:

1. Breaking of a Discrete R Symmetry
2. Unbroken Supersymmetry
3. Dimensional Transmutation.

In pure gauge case, order parameter is $\langle \lambda\lambda \rangle \equiv W$, which has dimension three. Rather high dimension; problematic for certain types of model building. Interesting to write generalizations with lower dimension ops.

$\langle W \rangle$: Gaugino Condensation

W transforms under any R symmetry; an order parameter for R breaking.
Gaugino condensation: $\langle \lambda\lambda \rangle \equiv \langle W \rangle$ breaks discrete R without breaking supersymmetry.
Readily generalized (J. Kehayias, M.D.) to include order parameters of dimension one.
E.g. N_f flavors, N colors, $N_f < N$:

$$W = yS_{ff'}\bar{Q}_f Q_{f'} + \lambda \mathrm{Tr} S^3 \tag{1}$$

exhibits a $Z_{(3N-N_f)}$ symmetry, spontaneously broken by $\langle S \rangle$; $\langle \bar{Q}Q \rangle$; $\langle W \rangle$.

The dynamics responsible for this breaking can be easily understood. Suppose, for example, that $\lambda \ll y$. Then we might guess that S will acquire a large vev, giving large masses to the quarks. In this case, one can integrate out the quarks, leaving a pure $SU(N)$ gauge theory, and the singlet S. The singlet superpotential follows by noting that the scale, Λ, of the low energy gauge theory depends on the masses of the quarks, which in turn depend on S. So

$$W(S) = \lambda S^3 + \langle \lambda\lambda \rangle_S. \quad (2)$$

$$\langle \lambda\lambda \rangle = \mu^3 e^{-3\frac{8\pi^2}{b_{LE} g^2(\mu)}} \quad (3)$$

$$= \mu^3 e^{-3\frac{8\pi^2}{b_{LE} g^2(M)} + 3\frac{b_0}{b_{LE}} \ln(\mu/M)}$$

$$b_0 = 3N - N_F; \; b_{LE} = 3N \quad (4)$$

So

$$\langle \lambda\lambda \rangle = M^{\frac{3N-N_f}{N}} e^{-\frac{8\pi^2}{Ng^2(M)}} \mu^{\frac{N_f}{N}}. \quad (5)$$

In our case, $\mu = yS$, so the effective superpotential has the form

$$W(S) = \lambda S^3 + (yS)^{N_f/N} \Lambda^{3-N_f/N}. \quad (6)$$

This has roots

$$S = \Lambda \left(\frac{y^{N_f/N}}{\lambda} \right)^{\frac{N}{3N-N_F}} \quad (7)$$

times a Z_{3N-N_F} phase.
Consistent with our original argument that S large for small λ.
Alternative descriptions of the dynamics in other ranges of coupling.

Simple O'Raifeartaigh model

$$W = X_2(A_0^2 - f) + mA_0 Y_2 \qquad (8)$$

Exhibits a continuous R symmetry (subscripts are R charges) and a discrete ordinary symmetry ($A \to -A$, $Y \to -Y$) Breaks SUSY, consistent with theorem of Nelson-Seiberg theorem. R-symmetry unbroken, consistent with result of Shih. Simple model which breaks R symmetry (Shih):

$$W = X_2(\phi_1\phi_{-1} - \mu^2) + m_1\phi_1\phi_1 + m_2\phi_3\phi_{-1}. \qquad (9)$$

Desirable to generate the scales m, f dynamically.
Retrofitted Models (Feng, Silverstein, M.D.): OR parameter f from coupling

$$X(A^2 - \mu^2) + mAY \rightarrow \tag{10}$$

$$\frac{XW_\alpha^2}{M_p} + \gamma SAY.$$

Need $\langle W \rangle = fM_p = \Lambda^3$, $\langle S \rangle \sim \Lambda$, for example.

$$m^2 \gg \mu^2$$

SUSY breaking is metastable (supersymmetric vacuum far away).

Other small mass parameters: μ-term, arise from dynamical breaking of discrete R symmetry. E.g.

$$W_\mu = \frac{S^2}{M_p} H_U H_D. \tag{11}$$

Because F_S small, μ generated without B_μ. Because of R symmetries, this structure natural.
Readily build realistic models of gauge mediation/dynamical supersymmetry breaking with all scales dynamical, no μ problem, and prediction of a large tan β.

Gauge Mediation and the Cosmological Constant

Gauge mediation: traditional objection: c.c. requires large constant in W, unrelated to anything else.

$$\langle W \rangle = \frac{1}{\sqrt{3}} F M_p \tag{12}$$

At the same time, R symmetries only *natural* mechanism to account for $W \ll M_p^3$.
Retrofitted models with discrete R symmetries: scales consistent with our requirements for canceling c.c. Makes retrofitting, or something like it, inevitable in gauge mediation.

Microscopics of R Symmetries

Up to now, we have adopted the conventional viewpoint in particle physics that symmetries are natural. Two justifications for this viewpoint:

1. Symmetry breaking radiative corrections suppressed as symmetric limit approached
2. Vague notion that symmetric configurations in some underlying theory are automatically stationary points of effective action.

Motivated by our “macroscopic" considerations, examine two types of symmetry:

1. Supersymmetry
2. R symmetries.

We will see that landscape poses a challenge to our beliefs that such symmetries are natural, and offer a *possible* explanation why they might be favored.

Most discussions of landscape involving finding “vacua", loosely defined as stationary points of some effective action. Expect many non-susy stationary points of the effective action. E.g. neighborhood of KKLT point typically small ρ, might include many stationary points with positive, negative c.c. Most not accessible to any sort of weak coupling or α' analysis. One might think that non-susy solutions more common (Douglas, Susskind). SUSY exceptional? Unlikely?

Here ask about stability. A putative low c.c. state typically surrounded by a large number of negative c.c. states. Tunneling to *every one* must be suppressed. E.g. if N a typical flux, and if $\exists$ h type fluxes, of order N^h states, mostly non-susy. Within ΔN flux units, of order ΔN^h “states", presumably half with c.c.

$$\Lambda \approx -M_p^4$$

Potential for rapid tunneling to big crunch cosmology.

What might account for stability?

Known features of string states with a generic character:

- Small Coupling
- Large volume
- Warping
- Supersymmetry

General scaling of tunneling amplitudes (IIB case):

1. Energies scale like N^2/V^2, so $\Delta E \sim N/V^2$ if volume is same in neighboring states (not realistic, but makes things worse)
2. Tensions scale like $1/V$.
3. Assuming scaling as in thin wall (scaling laws below are valid more generally), amplitude

$$A \sim e^{-T^4/\Delta E^3}$$

$$e^{-V^2/N^3}$$

So for large N, need large volume.

So it appears that (without other sources of suppression) one needs volume scaling like $N^{2/3}$ in both the initial and final state to suppress tunneling. Won't detail here, but warping, small coupling don't suppress tunneling.

Tunneling in Nearly Supersymmetric Theories

Supersymmetry is well-known to suppress tunneling (Witten, Hull, Deser and Teitelboim, Weinberg)
In flat space case, can understand by noting that there exist global supercharges, energy-momentum, obeying the usual susy algebra:

$$\{Q_\alpha, Q_\beta\} = P^\mu \gamma_\mu.$$

So no negative energy configurations (no bubbles can form, grow).
Small susy breaking?

Tunneling near the Supersymmetric Limit

Limit of small $m_{3/2}$. Suppose that the cosmological constant of the "false vacuum" is essentially zero. Then can distinguish three cases:

1. Lower energy AdS state is non-supersymmetric. In this case, the zero c.c. state is stable.
2. Lower energy AdS state is supersymmetric or approximately so, with $\langle W \rangle \gg m_{3/2} M_p^2$. In this case, the zero c.c. state is stable, or it is unstable, with decay amplitude given by a universal formula: $\mathcal{A} = e^{-2\pi^2 \left(\frac{M_p}{\mathrm{Re}\ m_{3/2}} \right)^2}$. (For special cases, this expression has been derived by Ceserole, Dall'Agata, Giryavets, Kallosh and Linde).
3. Lower energy AdS state is supersymmetric or approximately so, with $\langle W \rangle \sim m_{3/2} M_p^2$. This is the case of *metastable susy breaking*. Tunneling suppressed, but not as strongly; depends on details.

So SUSY states *might* be distinguished by stability.

Discrete Symmetries in the Landscape

Viewpoint: the large number of states in the landscape arise because of a large number of possible fluxes, each ranging over a large number of possible values.
Symmetric states are inevitably rare. In order to obtain a state with symmetries, it is necessary that

- All fluxes which transform under the symmetry vanish
- With vanishing of the asymmetric fluxes, minima of the potential for the moduli preserve the symmetry.

For interesting symmetries, one typically finds that 2/3 or more of the fluxes must be set to zero $\Rightarrow$ an exponential suppression. So symmetries uninteresting.

Perhaps this is too naive. We are accustomed to the idea that finite temperature favors symmetries. Perhaps other cosmological considerations might be relevant.

Might symmetric states be attractors? To address this question, we need both a model for states and a model for cosmology.

The Bousso Polchinski Model

E.g., Bousso-Polchinski model.

$$E_0 = \frac{1}{2} N_i^2 q_i^2 - \Lambda_0. \tag{13}$$

The q_i's are constants, independent of N_i. They are assumed to be small enough that all tunneling amplitudes are small. This requires that the internal manifold be large, with volume scaling as a positive power of the flux. This model is extremely useful, first, for illustrating the idea of a discretuum: the model exhibits a nearly continuous distribution of energies for large fluxes. It also provides a model for eternal inflation.

A Cosmological Model

Goal: establish whether there is any reason to think that the rare states in a landscape exhibiting symmetries are somehow favored.

Burden (for now) not to establish conclusively that this is the case in an underlying, complete theory of gravity, but simply to establish some general conditions under which symmetries might plausibly be favored.

- Postulate a landscape with a large number of (very) metastable de Sitter states,
- Take as “initial condition" universe starts in one such state. Ask whether, for a non-negligible fraction of possible starting points, the system finds its way to the symmetric state.
- Suppose that the antecedents of the symmetric state are short lived and do not experience long periods of exponential growth.

The Neighborhood of the Symmetric States

As part of our *model*, we adopt (Douglas; Kachru) *continuous flux approximation*.
Consider a state which is symmetric or approximately symmetric under an ordinary discrete symmetry. Some subset of fluxes, N_i, $i = 1, \ldots, B$, respect the symmetry (they are neutral under the symmetry), and there are minima of the resulting potential in which only fields neutral under the symmetry have expectation values. The rest, n_a, $a = 1, \ldots, A$, break the symmetry. Putative, low cosmological constant, symmetric state, $\vec{N}^o$.

$$|n_a| < |N_i - N_i^0| \tag{14}$$

defines the neighborhood of the symmetric point.

States exhibiting discrete symmetries are rare in the flux landscape. But the fraction of states lying nearby such symmetric points need not be small.

Following BP, model vacuum energy by:

$$E_0 = \sum_{i,J=1}^{I} f_{IJ} N_I N_J + \sum_{a,b=1}^{A} g_{ab} n_a n_b \quad (15)$$

Two cases:

1. g_{ab} has only positive eigenvalues. Starting in the neighborhood of the symmetric state, those transitions which change the n_a's will tend towards the symmetric state.
2. g_{ab} has some negative eigenvalues. The corresponding n's will tend to grow, and the system will not tend towards the symmetric state.

Problem: even if all eigenvalues of g positive there is nothing particularly special about $\vec{N}^0$. If eigenvalues of g, f, are all similar, if $n_a \ll N_i$

$$\frac{S_b(\delta n_a = 1)}{S_b(\delta N_i = 1)} \sim \frac{N^3}{n^3} \tag{16}$$

Transitions which change n are much slower than those which change N. Notion of a neighborhood is not relevant to the tunneling process. One may reach a state $(\vec{N}_0, \vec{n}_a)$, but then one will transition to big crunches with negative cc.
If elements of g, in addition to being positive, were far larger that those of f, then some possibility. We will a phenomenon of this sort in the case of R symmetric vacua.

R Symmetric States

Working assumption is that in these states, R symmetry breaking and susy breaking are small, non-perturbative effects. Then changes in N, in the symmetric limit, are not associated with changes in energy, so they are potentially highly suppressed.

Transition rates in the R-symmetric Neighborhood

Crucial difference with the non-R states: the energy in the symmetric state is naturally small.
To compare tunneling rates for processes with changes in N with those with changes in n, we need to understand how the energies of these states depend on n. Expect (examining field theory models) quite weak, n^4/N^2. Dependence of bubble tension also weak, so

$$\frac{S_b(\Delta N = 1)}{S_b(\Delta n = 1)} = \frac{N^9}{n^9}! \tag{17}$$

Transitions towards the symmetric point are likely to be much faster than other transitions.

Lessons

This analysis establishes that in a class of *model* landscapes and *model* cosmologies:

- Non-R symmetries are unlikely to be attractors
- R symmetries may be attractors

The model assumptions are strong; whether they hold in “real" landscapes is an open question. But it is hard to see how things could be much better than this.

Conclusions: Macroscopic/Microscopic Reasoning

Macroscopic considerations, and conventional ideas about naturalness, point to a role for low energy supersymmetry, with discrete R symmetries and gauge mediation playing a central role.

More microscopic considerations challenge this picture. In a flux landscape, non-supersymmetric states seem likely to overwhelm supersymmetric ones; within (approximately) supersymmetric states, states exhibiting discrete symmetries seem rare.

We have argued:

- Questions of stability may lead to a preponderance of supersymmetric states, especially among states with hierarchies of mass scales.
- States with R symmetries may be cosmological attractors, favoring low energy supersymmetry.

These questions seem not nearly so hard as asking why the gauge group is what it is, or the specific values of Yukawa couplings. They have immediate importance for the physics of the LHC. Perhaps we can make more definitive statements?