O'Raifeartaigh models with spontaneous R-symmetry breaking

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Why O'Raifeartaigh models?

Interest:

- Historically: good models of stable SUSY breaking with $\langle F_X \rangle$
- Recent interest: ISS model (Intriligator,Seiberg,Shih)
  $\rightarrow$ Metastable non-SUSY vacua in $\mathcal{N} = 1$ SQCD!
  Low energy theory (Seiberg dual)

$$W = \tilde{q}_{i\alpha} M_{ij} q_j^{\alpha} + \mu^2 M_{ii} \quad i = 1 \dots N_F, \; \alpha = 1 \dots N_F - N_C$$

  $\rightarrow$ (Weakly gauged) O'Raifeartaigh-like model

Original O'Raifeartaigh model:

- Chiral superfields X, $\phi_{(2)}$, $\phi_{(0)}$
- Canonical Kahler potential
- Superpotential $W = f X + n X \phi_{(0)}^2 + m \phi_{(2)} \phi_{(0)}$
- R-symmetry $R(X) = R(\phi_{(2)}) = 2$, $R(\phi_{(0)}) = 0$

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O'Raifeartaigh models of SUSY breaking

- Fields X_n, ϕ_i with $n = 1 \dots n_X$, $i = 1 \dots n_\phi$
- R-charges

$$\boxed{R(X_n) = 2,\, R(\phi_i) = 0}$$

- Superpotential:

$$\boxed{W = \sum_n X_n\, g_n(\phi_i)}$$

- Vacuum equations $\quad g_n(\phi_i) = 0 \quad , \quad \sum_n X_n\, \partial_j g_n(\phi_i) = 0$
- SUSY spontaneously broken if $n_X > n_\phi$
- $(n_X - n_\phi)$-dimensional space of flat directions parametrized by $X_1 \dots X_{n_X - n_\phi}$. Complexified R-symmetry acts as a dilatation:

$$\boxed{X_n \to \alpha X_n \quad \alpha \in \mathbb{C}}$$

- Coleman-Weinberg 1-loop effective potential: true minimum at $X_n = 0$

SUSY breaking and R-symmetry

R-symmetry plays an important role in O'Raifeartaigh models

- Nelson-Seiberg argument:
  Generic superpotential and SUSY breaking $\Rightarrow$ R-symmetry

No R-symmetry	$\Rightarrow$	$\partial_i W = 0$ k equations in k variables	$\Rightarrow$	SUSY vacuum
R-symmetry	$\Rightarrow$	$\partial_i W = 0$ k equations in "$k - 1$" variables	$\Rightarrow$	If no solution SUSY broken

- ISS argument:
  Metastable SUSY breaking $\leftrightarrow$ *approximate* R-symmetry

Explicit and spontaneous R-symmetry breaking

Gaugino masses $\gtrsim$ 100 GeV $\Rightarrow$ R-symmetry must be broken

Two possibilities:

- Explicit breaking: vacuum metastability
- Spontaneous breaking: R-axion problem

How to achieve spontaneous breaking?

- Gauge interactions
- Perturbative dynamics of O'Raifeartaigh models (Shih model)

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The Shih model

Choose R-charges different from $R = 2, 0$

- Fields: X, $\phi_{(-1)}$, $\phi_{(1)}$, $\phi_{(3)}$
- R-charges: $R(X) = 2$, $R(\phi_{(k)}) = k$
- Superpotential

$$W = fX + NX\phi_{(1)}\phi_{(-1)} + M_3\phi_{(3)}\phi_{(-1)} + \frac{M_1}{2}\phi_{(1)}^2$$

- Vacuum equations $\Rightarrow$ SUSY breaking

$$f + N\phi_{(1)}\phi_{(-1)} = 0 \qquad \begin{aligned} M_3\phi_{(3)} + NX\phi_{(1)} &= 0 \\ M_1\phi_{(1)} + NX\phi_{(-1)} &= 0 \\ M_3\phi_{(-1)} &= 0 \end{aligned}$$

- For f small, there is a flat direction of non-SUSY minima at $\phi_{(-1)} = \phi_{(1)} = \phi_{(3)} = 0$ parametrized by X

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Coleman-Weinberg potential in the Shih model

Flat directions are lifted by 1-loop effective potential:

$$V_{eff}^{(1-loop)}(X) = \frac{1}{64\pi^2}\mathrm{Tr}\left(\mathcal{M}_B^4(X)\ln\frac{\mathcal{M}_B^2(X)}{\Lambda^2} - \mathcal{M}_F^4(X)\ln\frac{\mathcal{M}_F^2(X)}{\Lambda^2}\right)$$

This potential has the form

$$V_{eff}^{(1-loop)}(X) = V_0 + m_X^2|X|^2 + \lambda_X|X|^4 + \dots$$

where (for f small)

$$m_X^2 = \frac{f^2}{32\pi^2}\mathrm{Tr}\int_0^\infty dv\, v^3\left[\mathcal{M}_1(v)\mathcal{M}_1^\dagger(v) - \mathcal{M}_2(v)\mathcal{M}_2^\dagger(v)\right]$$

Note that m_X^2 is *not* positive-definite!

$$\mathcal{M}_1(v) = \frac{1}{\sqrt{v^2+\hat{M}^2}}\hat{N}\left(\frac{\sqrt{2}v}{v^2+\hat{M}^2}\right)\hat{N}\frac{1}{\sqrt{v^2+\hat{M}^2}}$$

$$\mathcal{M}_2(v) = \frac{1}{\sqrt{v^2+\hat{M}^2}}\hat{N}\left(\frac{2\hat{M}}{v^2+\hat{M}^2}\right)\hat{N}\frac{1}{\sqrt{v^2+\hat{M}^2}}$$

$$\hat{N} = \begin{pmatrix} 0 & 0 & 0 & 0 & N & 0 \\ 0 & 0 & 0 & N & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & N & 0 & 0 & 0 & 0 \\ N & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} , \quad \hat{M} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & M_3 \\ 0 & 0 & 0 & 0 & M_1 & 0 \\ 0 & 0 & 0 & M_3 & 0 & 0 \\ 0 & 0 & M_3 & 0 & 0 & 0 \\ 0 & M_1 & 0 & 0 & 0 & 0 \\ M_3 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

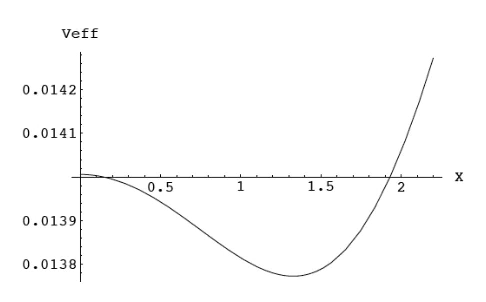
The two contribution to m_X^2 are of the same order $\rightarrow \not{R}$ if $m_X^2 < 0$

In usual O'Raifeartaigh models $\mathcal{M}_2 = 0 \quad \rightarrow$ No $\not{R}$

Spontaneous R-symmetry breaking

Choose the couplings such that $M_3 \lesssim 0.5\, M_1$

Coleman-Weinberg potential:



Minimum with $|\langle X \rangle| \sim M_3, M_1$

Non-hierarchical R-symmetry breaking

($\mathbb{Z}_2$ unbroken)

Runaway directions in the Shih model

Go back to the classical potential

$$V = \left|f + N\phi_{(1)}\phi_{(-1)}\right|^2 + \left|M_1\phi_{(1)} + NX\phi_{(-1)}\right|^2 + \left|M_3\phi_{(3)} + NX\phi_{(1)}\right|^2 + \left|M_3\phi_{(-1)}\right|^2$$

There is a *runaway direction*:

$$\phi_{(1)} = -\frac{f}{\lambda\phi_{(-1)}} \quad , \quad X = \frac{m_2 f}{\lambda^2\phi_{(-1)}^2} \quad , \quad \phi_{(3)} = \frac{m_2 f^2}{m_1\lambda^2\phi_{(-1)}^3} \quad , \quad \phi_{(-1)} \to 0$$

Along this direction $V \to 0$ (supersymmetric runaway vacuum)

- This direction corresponds to a complexified R-charge rescaling:

$$\boxed{\varphi(\epsilon) = \epsilon^{-R(\varphi)}\varphi \quad , \quad \epsilon \to 0}$$

- Vacua previously found are only metastable!

O'Raifeartaigh models with general R-charges

Class of models with SUSY breaking

$$W = fX + \frac{1}{2}N^{ij}X\phi_i\phi_j + \frac{1}{2}M^{ij}\phi_i\phi_j \left(+\frac{1}{2}Q_a^{ij}Y_a\phi_i\phi_j\right)$$

Conditions: $R(X) = R(Y_a) = 2, \quad M^{ij}, N^{ij}, Q_a^{ij}$ symmetric, $\quad \det M \neq 0$

$M^{ij} \neq 0 \Rightarrow R(\phi_i) + R(\phi_j) = 2 \qquad N^{ij}, Q_a^{ij} \neq 0 \Rightarrow R(\phi_i) + R(\phi_j) = 0$

Vacuum equations: $\quad (M^{ij} + XN^{ij} + Y_aQ_a^{ij})\phi_j = 0 \quad , \quad f + \frac{1}{2}N^{ij}\phi_i\phi_j = 0$
$\det(M + XN + Y_aQ_a) = \det M \neq 0 \quad \Rightarrow$ SUSY broken

For f small, non-SUSY flat directions at $\phi_i = 0$ parametrized by pseudomoduli X, Y_a

Spontaneous R-symmetry breaking

Quadratic part of 1-loop potential (for small f):

$$V_{quad}(X, Y_a) = \frac{f^2}{32\pi^2}\mathrm{Tr}\int_0^\infty dv\, v^3 \left[\mathcal{M}_1(v)\mathcal{M}_1^\dagger(v) - \mathcal{M}_2(v)\mathcal{M}_2^\dagger(v)\right]$$

$$\mathcal{M}_1(v) = \frac{1}{\sqrt{v^2+\hat{M}^2}}\left(\hat{N}\frac{\sqrt{2}v}{v^2+\hat{M}^2}\hat{Y}\right)\frac{1}{\sqrt{v^2+\hat{M}^2}}$$

$$\mathcal{M}_2(v) = \frac{1}{\sqrt{v^2+\hat{M}^2}}\left(\hat{N}\frac{\hat{M}}{v^2+\hat{M}^2}\hat{Y} + \hat{Y}\frac{\hat{M}}{v^2+\hat{M}^2}\hat{N}\right)\frac{1}{\sqrt{v^2+\hat{M}^2}}$$

$$\hat{M} = \begin{pmatrix} 0 & M^\dagger \\ M & 0 \end{pmatrix}, \hat{N} = \begin{pmatrix} 0 & N^\dagger \\ N & 0 \end{pmatrix}, \hat{Y} = \begin{pmatrix} 0 & (NX+Q^aY_a)^\dagger \\ NX+Q^aY_a & 0 \end{pmatrix}$$

$\longrightarrow$ Spontaneous R-symmetry breaking in a range of couplings

Symmetries

Flavor and gauge symmetries needed for ultraviolet completion, SUSY-breaking mediation...
No relevant changes in Coleman-Weinberg potential

- Easy to introduce *real representations* in the Shih model, for example SO(N) fundamentals:

$$W = fX + NX\phi^{\alpha}_{(1)}\phi^{\alpha}_{(-1)} + M_3\phi^{\alpha}_{(3)}\phi^{\alpha}_{(-1)} + \frac{1}{2}M_1\phi^{\alpha}_{(1)}\phi^{\alpha}_{(1)}$$

- The simplest model with *complex representations*, for example U(N) fundamentals:

$$\begin{aligned} W \quad = \quad & fX + XN_5\phi^{\alpha}_{(5)}\phi_{(-5)\alpha} + XN_3\phi^{\alpha}_{(3)}\phi_{(-3)\alpha} + \\ & + M_7\phi^{\alpha}_{(7)}\phi_{(-5)\alpha} + M_5\phi^{\alpha}_{(5)}\phi_{(-3)\alpha} + M_3\phi^{\alpha}_{(3)}\phi_{(-1)\alpha} \end{aligned}$$

This model also shows spontaneous R-symmetry breaking

Runaway directions

Many models $W(\varphi_j)$ with generic R-charges have runaway directions

- Vacuum equations $\partial_i W(\varphi_j) = 0$ can be classified by R-charges:

$$\begin{array}{ll} \partial_i W = 0,\ R(\varphi_i) < 2 & R > 0 \\ \partial_i W = 0,\ R(\varphi_i) = 2 & R = 0 \\ \partial_i W = 0,\ R(\varphi_i) > 2 & R < 0 \end{array}$$

- R-symmetry $\Rightarrow$ this set of equations cannot be solved ...
  ... but it can be possible to solve the *subset* with $R \geq 0$
- The form of the potential $V = V_{R<0} = \sum_{R(\varphi_i)>2} |\partial_i W|^2$ does not change under complex R-symmetry transformations
- Rescaling $\varphi(\epsilon) = \epsilon^{-R(\varphi)}\varphi$ corresponds to a runaway direction:

$$V(\varphi(\epsilon)) \to 0 \quad , \quad \epsilon \to 0$$

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Models with a single pseudomodulus

$$W = fX + \frac{1}{2}N^{ij}X\phi_i\phi_j + \frac{1}{2}M^{ij}\phi_i\phi_j$$

Vacuum equations with $R > 0$:

$$\begin{aligned} NX\phi_{(k-2)j} + M\phi_{(k)j} &= 0 \\ NX\phi_{(k-4)j} + M\phi_{(k-2)j} &= 0 \\ \ldots \\ NX\phi_{(-1)j} + M\phi_{(1)j} &= 0 \end{aligned}$$

Equations with $R > 0$ can be solved if $\det M \neq 0$ ($\leftarrow$ SUSY breaking condition)
Then the $R = 0$ equation $f + N^{ij}\phi_i\phi_j = 0$ can be solved by rescaling all ϕs.

$\Rightarrow$ Runaway directions exist in *all* generic models of this class

Models with more pseudomoduli

Most models have SUSY or non-SUSY runaway directions. Example:

$$W = fX + (\lambda X + \eta Y)\phi_{(1)}\phi_{(-1)} + m_1\phi_{(3)}\phi_{(-1)} + \frac{1}{2}m_2\phi_{(1)}^2$$

Here no SUSY runaway vacua, because $R = 0$ equations cannot be solved:

$$f + \lambda\phi_{(1)}\phi_{(-1)} = 0 \qquad \eta\phi_{(1)}\phi_{(-1)} = 0$$

However, there is a *non-SUSY* runaway direction: $\lambda' \equiv \frac{|\lambda|^2+|\eta|^2}{\bar{\lambda}}$

$$\phi_{(1)} = -\frac{f}{\lambda'\phi_{(-1)}},\ X + \frac{\eta}{\lambda}Y = \frac{m_2 f}{\lambda'^2\phi_{(-1)}^2},\ \phi_{(3)} = \frac{m_2 f^2}{m_1\lambda'^2\phi_{(-1)}^3},\ \phi_{(-1)} \to 0$$

by *minimizing* $V_{R=0}$ and *solving* $R > 0$ equations

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Metastability and remnants of SUSY vacua

ISS argument

Small explicit R-symmetry breaking terms restore supersymmetry:

$$W_\varepsilon = W + \varepsilon_r W_r^{\not R} \qquad R(\varepsilon_r) \neq 0$$

SUSY vacua are pushed to infinity as $\varepsilon_r \to 0$

$$V(\tilde\varphi_a(\varepsilon)) = \sum_b |\partial_b W(\tilde\varphi_a(\varepsilon))|^2 = \sum_b |\varepsilon_r \partial_b W_r^{\not R}(\tilde\varphi_a(\varepsilon))|^2$$

Usually no control because $\varphi \sim 1/\varepsilon^k$, but for some R-breaking terms $\varepsilon_r \to 0$ can be thought of as an R-charge rescaling:

Runaway directions	$\longleftrightarrow$	Positions of SUSY vacua for $\varepsilon_r \neq 0$
Runaway vacuum	$\longleftrightarrow$	SUSY vacuum pushed to infinity

Example: $W^{\not R} = \sum_{R(\phi_j)>2} \varepsilon_j \phi_j$

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Conclusions

- Spontaneous R-symmetry breaking often occurs in O'Raifeartaigh models with general R-charge assigment
- Flavor symmetries can be easily introduced
- These models often have runaway directions (both SUSY and non-SUSY)

Recent developments (last month):

Existence of runaway directions is welcome, because they can be lifted by 1-loop effects leading to metastable vacua with broken R-symmetry (*pseudo-runaway*) (Essig,Sinha,Torroba)

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Recent developments

- Essig,Sinha,Torroba: next talk

$$W = \Phi \mathrm{tr} M + \mathrm{tr} q M \tilde{q} + \Phi \mathrm{tr} P \bar{P} + \left(\det P \bar{P}\right)^{-\frac{1}{N_c' - N_f'}}$$

  SUSY runaway direction lifted by CW potential

- Cho,Park: ISS + singlets
  Same as Shih model

- Abel,Durnford,Jaeckel,Khoze: ISS + baryonic term

$$W = \tilde{q}_{i\alpha} M_{ij} q_j^{\alpha} + \mu^2 M_{ii} + m \epsilon^{rs} \epsilon^{\alpha\beta} q_{r\alpha} q_{s\beta}$$

  Non-SUSY runaway direction lifted by CW potential

$\Rightarrow$ Spontaneous R-symmetry breaking more generic than expected!