Supersymmetry Breaking and Higher Derivative Terms

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Overview

Introduction

- supersymmetric theories are one of the most promising candidates for physics beyond the Standard Model
- if supersymmetry exists it must be spontaneously broken
- various mechanisms and ideas have been proposed to achieve this
- mainly using chiral superfield, but that is not the only representation of supersymmetry
- under normal circumstances, complex linear superfield is equivalent to chiral superfield (chiral-complex linear duality)
- but not always! $\Rightarrow$ a new mechanism for SUSY breaking

Spontaneous SUSY Breaking

- If SUSY is realized in Nature, it must be broken.
- There are several mechanisms for SUSY breaking. [Fayet, Iliopoulos, '74] [O'Raifeartaigh '75]

When is SUSY broken?

- When $\langle F \rangle = f \neq 0$
  - $\delta\psi_\alpha \sim F\epsilon_\alpha + \cdots \ \rightarrow \delta\psi_\alpha \sim f\epsilon_\alpha$.
  - There exists Goldstone fermion.

The simplest example is

$$\begin{aligned}\mathcal{L} &= \int d^4\theta\ \bar{\Phi}\Phi - f\int d^2\theta\ \Phi + \text{c.c.} \\ &= \frac{1}{2}A\,\partial^{\alpha\dot{\alpha}}\partial_{\alpha\dot{\alpha}}\bar{A} + F\bar{F} - f\,F - f\bar{F} - i\psi_\alpha\partial^{\alpha\dot{\beta}}\bar{\psi}_{\dot{\beta}}\end{aligned}$$

- Equation of motion for F: $\bar{F} = f$
- Existence of Goldstone fermion $\psi_\alpha : \delta\psi_\alpha = \epsilon_\alpha f$
- Possitive vacuum energy: $H \sim P^0 \sim |Q|^2 \geq 0$

SUSY breaking for complex linear superfield

Recent work in 4D, $N = 1$ supersymmetry shows that superspace higher derivatives containing complex linear superfield may trigger supersymmetry breaking. For example

$$\mathcal{L} = -\int d^4\theta\ \bar{\Sigma}\Sigma + \frac{1}{8f^2}\int d^4\theta D^\alpha \Sigma D_\alpha \Sigma \bar{D}^{\dot{\beta}} \bar{\Sigma} \bar{D}_{\dot{\beta}} \bar{\Sigma}.$$

[Farakos, Ferrara, Kehagias, Porrati '14]

The main properties of this mechanism:

- it can not be captured by Kähler potential or superpotential
- it does not give rise to any instability (Ostrogradsky)

(2,2) Supersymmetry

In 2D, $(2,2)$ supersymmetry algebra is

$$\{\mathrm{D}_-, \overline{\mathrm{D}}_-\} = i\partial_= \,,$$
$$\{\mathrm{D}_+, \overline{\mathrm{D}}_+\} = i\partial_{\#} \,.$$

- The chiral superfield:
  $\overline{\mathrm{D}}_\pm \Phi = 0 = \mathrm{D}_\pm \overline{\Phi}\,.$
- The twisted chiral superfield:
  $\overline{\mathrm{D}}_+ \chi = \mathrm{D}_- \chi = 0 = \mathrm{D}_+ \overline{\chi} = \overline{\mathrm{D}}_- \overline{\chi}\,.$
- The complex linear superfield:
  $\overline{\mathrm{D}}_+ \overline{\mathrm{D}}_- \Sigma = 0 = \mathrm{D}_+ \mathrm{D}_- \overline{\Sigma}\,.$

[Gates, Hull, Roček '84]

$$P_{\alpha\dot{\alpha}} \to P_{\#},\ P_{=},\ K,\ L$$

$$\int d^4\theta \left[\mathrm{D}_+\Sigma\,\mathrm{D}_-\Sigma\,\overline{\mathrm{D}}_+\overline{\Sigma}\,\overline{\mathrm{D}}_-\overline{\Sigma}\right] \qquad \int d^4\theta \left[\overline{\mathrm{D}}_+\Sigma\,\overline{\mathrm{D}}_-\Sigma\,\mathrm{D}_+\overline{\Sigma}\,\mathrm{D}_-\overline{\Sigma}\right] \qquad 4D$$

$$\int d^4\theta \left[\mathrm{D}_+\Sigma\,\overline{\mathrm{D}}_-\Sigma\,\overline{\mathrm{D}}_+\overline{\Sigma}\,\mathrm{D}_-\overline{\Sigma}\right] \qquad \int d^4\theta \left[\overline{\mathrm{D}}_+\Sigma\,\mathrm{D}_-\Sigma\,\mathrm{D}_+\overline{\Sigma}\,\overline{\mathrm{D}}_-\overline{\Sigma}\right] \qquad 2D$$

(2,2) Goldstini

The chiral Goldstino X:

$$X = \frac{G_- G_+}{\mathcal{F}} + \theta_+ G_- + \theta_- G_+ + \theta_+ \theta_- \mathcal{F}\,,$$

$$\mathcal{L} = \int d^4\theta X\overline{X} - \left\{ \int d^2\theta \left(f\, X + \mathcal{M}\, X^2 \right) + c.c. \right\}\,,$$

$$\begin{aligned} X^2 &= 0\,, \\ \overline{\mathrm{D}}_+ \overline{\mathrm{D}}_- \overline{X} &= -f - 2\,\mathcal{M}\, X\,. \end{aligned}$$

[Roček '78] [Lindström, Roček '79]

The twisted chiral Goldstino Y:

$$Y = \frac{G_+ \overline{G}_-}{\mathcal{F}} + \overline{\theta}_+ \overline{G}_- + \theta_- G_+ + \theta_- \overline{\theta}_+ \mathcal{F}\,,$$

$$\mathcal{L} = \int d^4\theta\, Y\overline{Y} - \left\{ \int d^2\theta^T \left(f\, Y + \mathcal{N}\, Y^2 \right) + c.c. \right\}\,,$$

$$\begin{aligned} Y^2 &= 0\,, \\ \mathrm{D}_- \overline{\mathrm{D}}_+ \overline{Y} &= -f - 2\,\mathcal{N}\, Y\,. \end{aligned}$$

Supersymmetry breaking in (2,2)

The model from 4D N=1 is

$$\mathcal{L} = \int d^4\theta \Big[-\overline{\Sigma}\Sigma - \frac{1}{2f^2}\, \mathrm{D}_+\Sigma\, \mathrm{D}_-\Sigma\, \overline{\mathrm{D}}_+\overline{\Sigma}\, \overline{\mathrm{D}}_-\overline{\Sigma} \Big] .$$

The bosonic sector

$$\begin{aligned}\mathcal{L}_{bos.} &= \partial_= A\, \partial_{+\!\!+} \overline{A} - P_{+\!\!+} \overline{P}_= - \overline{P}_{+\!\!+} P_= - F\overline{F} + K\overline{K} + L\overline{L} \\ &+ \frac{1}{2f^2} \Big[P_{+\!\!+} P_= \overline{P}_{+\!\!+} \overline{P}_= - \overline{K}\overline{L} P_{+\!\!+} P_= - KL \overline{P}_{+\!\!+} \overline{P}_= + F\overline{F} (\overline{P}_{+\!\!+} P_= + P_{+\!\!+} \overline{P}_=) \Big] \\ &+ \frac{1}{2f^2} \Big[- F\overline{F} (K\overline{K} + L\overline{L}) + K\overline{K} L\overline{L} + (F\overline{F})^2 \Big] ,\end{aligned}$$

has the following interesting solution

$$F = f \ , \ P_{+\!\!+} = P_= = K = L = 0 .$$

In a such vaccum we have

$$\mathcal{L}_{qua.} = \partial_= A\, \partial_{+\!\!+} \overline{A} + i\psi_- \partial_{+\!\!+} \overline{\psi}_- + i\psi_+ \partial_= \overline{\psi}_+ - \frac{f^2}{2} + \frac{i}{2} \lambda_+ \partial_= \overline{\lambda}_+ + \frac{i}{2} \lambda_- \partial_{+\!\!+} \overline{\lambda}_- ,$$

where the Goldstone fermions are

$$\langle \delta\lambda_\pm \rangle = \epsilon_\pm f .$$

Supersymmetry breaking in (2,2)

In superspace we have

$$\mathrm{D}_{\pm}\left(\Sigma - \frac{1}{2f^2}\left[\overline{\mathrm{D}}_{+}\left(\overline{\mathrm{D}}_{-}\overline{\Sigma}\,\mathrm{D}_{+}\Sigma\,\mathrm{D}_{-}\Sigma\right) - \overline{\mathrm{D}}_{-}\left(\overline{\mathrm{D}}_{+}\overline{\Sigma}\,\mathrm{D}_{+}\Sigma\,\mathrm{D}_{-}\Sigma\right)\right]\right) = 0.$$

Or equivalently

$$\Sigma - \frac{1}{2f^2}\left[\overline{\mathrm{D}}_{+}\left(\overline{\mathrm{D}}_{-}\overline{\Sigma}\,\mathrm{D}_{+}\Sigma\,\mathrm{D}_{-}\Sigma\right) - \overline{\mathrm{D}}_{-}\left(\overline{\mathrm{D}}_{+}\overline{\Sigma}\,\mathrm{D}_{+}\Sigma\,\mathrm{D}_{-}\Sigma\right)\right] = \overline{\Phi}\,, \quad \overline{\mathrm{D}}_{+}\overline{\mathrm{D}}_{-}\overline{\Phi} = 0\,.$$

The solution in components can be described in superspace as

$$\Sigma = \overline{\Phi} + X,$$

X is the chiral Golstino

$$\begin{aligned} X^2 &= 0\,, \\ \overline{\mathrm{D}}_{+}\overline{\mathrm{D}}_{-}\overline{X} &= -f - 2\,\mathcal{M}\,X\,. \end{aligned}$$

The distribution of components is

$$A, \psi_{+}, \psi_{-} \in \overline{\Phi}\,,$$
$$\lambda_{-}, \lambda_{+}, f \in X\,.$$

Supersymmetry breaking in (2,2)

We study the Lagrangian

$$\mathcal{L} = \int d^4\theta \Big[-\Sigma\overline{\Sigma} + \frac{1}{2f^2}\,\mathrm{D}_+\Sigma\,\overline{\mathrm{D}}_+\overline{\Sigma}\,\overline{\mathrm{D}}_-\Sigma\,\mathrm{D}_-\overline{\Sigma}\Big]\,.$$

The bosonic sector

$$\mathcal{L}_{bos.} = \partial_= A\partial_{\#}\overline{A} - P_{\#}\overline{P}_= - \overline{P}_{\#}P_= - F\overline{F} + K\overline{K} + L\overline{L}$$
$$+ \frac{1}{2f^2}\Big[F\overline{F}L\overline{L} - (L\overline{L})^2 + L\overline{L}P_{\#}(\overline{P}_= + i\partial_=\overline{A}) + L\overline{L}\overline{P}_{\#}(P_= - i\partial_= A)\Big]$$
$$- \frac{1}{2f^2}P_{\#}\overline{P}_{\#}(P_= - i\partial_= A)(\overline{P}_= + i\partial_=\overline{A})\,,$$

has the following interesting solution

$$F = K = 0 = P_{\#} = P_= \,,$$
$$L = f\,, \quad \partial_= A = \partial_=\overline{A} = 0\,.$$

In a such vaccum we have

$$\mathcal{L}^{(2)}_{ferm.} = i\psi_+\partial_=\overline{\psi}_+ - i\psi_-\partial_{\#}\overline{\psi}_- - \frac{i}{2}\lambda_+\partial_=\overline{\lambda}_+\,,$$

where the Goldstone fermions are

$$\langle\delta\psi_-\rangle = -\epsilon_- f\,,$$
$$\langle\delta\lambda_+\rangle = \overline{\epsilon}_+ f\,.$$

Supersymmetry breaking in (2,2)

In superspace we have

$$\mathrm{D}_\pm \left(\Sigma - \frac{1}{2f^2} \left\{ \overline{\mathrm{D}}_+ (\mathrm{D}_- \overline{\Sigma}\, \mathrm{D}_+ \Sigma\, \overline{\mathrm{D}}_- \Sigma) - \mathrm{D}_- (\overline{\mathrm{D}}_+ \overline{\Sigma}\, \mathrm{D}_+ \Sigma\, \overline{\mathrm{D}}_- \Sigma) \right\} \right) = 0 \,.$$

The solution in components can be described in superspace as

$$\Sigma = Y + \overline{\Phi}_L \,,$$

where $\overline{\Phi}_L$ is the chiral lefton

$$\overline{\mathrm{D}}_\pm \Phi_L = 0 \,,$$
$$\mathrm{D}_- \Phi_L = 0 \,,$$

[Siegel '84] [Gates, Siegel '88]
and Y is the twisted chiral Goldstino

$$Y^2 = 0 \,,$$
$$\mathrm{D}_- \overline{\mathrm{D}}_+ \overline{Y} = -f - 2\mathcal{N}\, Y \,.$$

The distribution of components is

$$A, \psi_+ \in \overline{\Phi}_L \,,$$
$$\psi_-, \lambda_+, f \in X \,.$$

Summary

- superspace higher derivatives may trigger supersymmetry breaking
- it can not be captured by Kähler potential or superpotential
- these new mechanism could open up new directions for constructing realistic models
- how are these results modified by couplings to other fields?

Thank you for your attention!