GRAVITATIONAL MEDIATION OF SUPERSYMMETRY 
BREAKING IN SUPERSTRING THEORY

TOMASZ R. TAYLOR
Department of Physics, Northeastern University
Boston, MA 02115 USA
E-mail: taylor@neu.edu

SUSY breaking and its mediation are among the most important problems of supersymmetric generalizations of the standard model. The idea of gravity-mediated SUSY breaking, proposed in 1982 by Arnowitt, Chamseddine and Nath, and independently by Barbieri, Ferrara and Savoy, fits naturally into superstring theory, where it can be realized at both classical as well as quantum levels. This talk is dedicated to Pran Nath on his 65th birthday.

1. History

In the summer of 1982, here at Northeastern University, Pran Nath, together with Richard Arnowitt and Ali Chamseddine, constructed the first SUGRA (supergravity) GUT (Grand Unified Theory) with supersymmetry breaking in a “hidden” sector, communicated to the electro-weak sector by gravitational interactions, so that

$$M_{E-W} \sim \frac{M^2_S}{M_{PLANCK}}, \quad (1)$$

with the supersymmetry mass scale $M_S \sim 10^{11-12}$GeV.

At the same time, on the other side of Atlantic Ocean, Riccardo Barbieri, Sergio Ferrara and Carlos Savoy, constructed very similar models.

Today, 22 years later, gravitational mediation of SUSY breaking remains as one of the basic model-building blocks “beyond the standard model.” This talk will celebrate Pran’s pioneering work by describing how his ground-breaking ideas are implemented in modern superstring theory.

The 1982 hidden sector contained just one chiral supermultiplet, which was a very modest proposal as compared to superstring theory in 2004; a generic superstring compactification is full of:
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- moduli: scalar fields whose vacuum expectation values (VEVs) determine the size and shape of the compactified dimensions
- gauge fields, in bulk and on D-branes: non-perturbative phenomena like gaugino condensation can lead to dynamical supersymmetry breaking in strongly-interacting gauge sectors.

Moduli stabilization together with the related SUSY breaking and its mediation are among the most important problems of superstring phenomenology. Here are some (at least partial) solutions...

2. SUSY Breaking and Moduli Stabilization

Historically, there had been two routes to low-energy SUSY breaking: a field-theoretical route and a string-theoretical one. The field-theoretical approach is based on a very reasonable expectation that low-energy SUSY breaking is indeed a low-energy phenomenon involving only the lowest (massless) superstring excitations, so that the heavy superstring modes are just passive spectators. In this case, a single, well-understood phenomenon like gaugino condensation could produce a non-trivial superpotential, stabilize moduli VEVs and break SUSY at the same time. This mechanism works very well in the heterotic superstring theory, up to a small, but often exaggerated problem of a “run-away” dilaton VEV. In fact, this run-away occurs only when the hidden gauge group is semi-simple; otherwise, individual gauge group factors create a “racetrack” that generically locks the dilaton in a semi-stable vacuum which can be either supersymmetric or non-supersymmetric, depending on the specifics of the model. The moduli freeze in a stable configuration, which in orbifold models often corresponds to a special, self-dual point in the moduli space. Moduli can also be stabilized in Type II compactifications by switching on fluxes related to some higher-dimensional fields. In either case, if the vacuum is non-supersymmetric, SUSY breaking is mediated by gravitational interactions already at the classical level and the soft supersymmetry breaking terms are generated in exactly the same way as described in the original papers.\(^1\)\(^2\)

Although phenomenologically viable, the field-theoretical approach is not suitable for including quantum gravitational effects which necessitate reintroducing string excitations just for the sole purpose of regulating ultra-violet divergences. This can be mimicked by using a good regularization scheme, for instance a Pauli-Villars procedure.\(^3\) Here, we will approach this problem in a more direct way, in the framework of ultra-violet finite string perturbation theory.
Any string theoretical mechanism that allows for an adjustable supersymmetry breaking scale is in one way or another equivalent to the Scherk-Schwarz (SS) breaking. It boils down to projecting out string states that are odd under simultaneous $2\pi$ spacetime rotation, i.e. $(-1)^F$ where $F$ is the fermion number, and a translation by the full length $2\pi R$ of an extra-dimensional circle, i.e. $(-1)^n$, where $n$ is the Kaluza-Klein momentum number. For this SS circle one can choose, for example, one of the cycles of $T^2$ in $K3 \times T^2$ compactifications. In this way, one creates a mass gap in the fermion spectrum, with the gravitino mass $m_{3/2} \sim 1/R$. All fermions from the closed string sector acquire similar masses. However, if the theory contains also an open string sector, with strings ending on D-branes, the corresponding fermions acquire tree level masses only if their D-brane world-volume encompass the SS direction. On the other hand, if the D-brane is perpendicular to the SS direction, the corresponding fermion spectrum is not affected by supersymmetry breaking, at least at the classical level. The latter case looks very interesting from both the phenomenological and theoretical viewpoints because it offers a simple setup for studying quantum mediation of supersymmetry breaking in the calculable framework of superstring theory.

3. Bulk-To-Brane SUSY Breaking Mediation

In Type I theory, open strings stretching between D-branes give rise to gauge bosons and scalars representing D-brane motion in the ambient space. After SUSY is broken in the bulk by SS mechanism, these fermions acquire masses as a result of quantum loop effects. In this talk, I will focus on gaugino mass generation.

When moving in spacetime, open superstrings sweep two-dimensional world-sheet surfaces bordered by D-brane positions. In order to couple to gauginos, at least one such a boundary is required. The computation of a particular mass correction amounts to integrating the two gaugino vertex operators over the boundary, followed by an integral over the moduli of the Riemann surface – a formidable task indeed for a general world-sheet. The “minimal” surface is restricted by $U(1)$ charge conservation of the underlying superconformal field theory:

$$g + \frac{h}{2} = \frac{3}{2},$$ (2)

where $g$ is the number of handles and $h$ is the number of boundaries. The solution with $h = 3$, $g = 0$ represents a disk with two holes that can be
interpreted as a two-loop open string diagram. Since open strings do not participate in SUSY breaking, this mass contribution is expected to vanish, or more precisely, to be suppressed in the large $R$ limit as $e^{-R^2/\alpha'}$, where $\alpha'$ is the string scale. Hence we are left with $h = 1$, $g = 1$, a surface with one boundary and one handle, shown on Figure 1. The spectrum of

![Figure 1. Genus 3/2 surface: two same-helicity gaugino vertex operators are inserted at the boundary.](image)

Kaluza-Klein excitations of closed strings propagating through the handle is non-supersymmetric, therefore such a diagram can indeed communicate SUSY breaking to open strings. We call it a “genus 3/2” surface, although more properly is should be called an “orientable genus 1 surface with Euler characteristics $-1$.” It can be thought of as a torus with a hole in its surface. It is characterized by one complex modulus $\tau$ which controls the “thickness” of the handle and one real modulus $l$ which determines the size of the hole, or more precisely, the width of the throat between the boundary and the handle. According to the standard power counting rules for the string coupling constant $g$, this diagram comes at order $g$, and since the gaugino kinetic terms are of order $1/g$, the mass will be of order $g^2$. Alternatively, one can replace the string coupling constant by the coupling constant $\lambda$ of the gauge group associated to the D-brane: then $g^2 = \lambda^4$.

For a generic SS radius $R$, the computation of the gaugino mass is very difficult. In the case of $K3$ orbifold compactifications however, all steps can be made very explicit. One finds that a very important role is played by orbifold symmetries. As an example consider a $T^4/\mathbb{Z}_2$ orbifold, with $\mathbb{Z}_2$ acting as a simultaneous reflection in the two complex planes of $T^4$. There is a residual symmetry with respect to interchanging these two complex planes. It turns out that the gaugino mass operator is odd under this symmetry, therefore the mass vanishes! Furthermore, SS compactifications are also symmetric with respect to reflections of the SS circle, with the
momentum number \( n \rightarrow -n \), and this symmetry is realized in effective field theory as a discrete subgroup of \( U(1) \) R-symmetry associated to the “third” complex plane. We conclude that one has to violate quite a few symmetries before generating a non-vanishing string loop correction the the gaugino mass. For instance, the orbifold symmetries can be eliminated by blowing-up the orbifold singularities with VEVs of some twisted fields. This amounts to inserting one additional vertex in the bulk of the world-sheet.

Superstring computations can be simplified by focusing on the large SS radius behavior of the mass. The reason is that in the \( R \rightarrow \infty \) limit, the spectrum of Kaluza-Klein states propagating through the handle becomes almost supersymmetric, with fermion contributions canceling bosons unless they propagate for a proper time sufficiently long to allow the whole Kaluza-Klein tower to contribute. This corresponds to \( \tau \rightarrow \infty \), a “pinching” limit of the handle in which our surface degenerates to a disk radiating and reabsorbing a massless closed string excitation, see Figure 2. As shown on

![Figure 2](image-url)

Figure 2. \( \tau \rightarrow \infty \) limit of genus 3/2 and its further degeneration to a gravitational loop.

Figure 2, by a further shrinking of the disk, that is by throwing away all except for the lightest “virtual” open strings, one can distort the world-sheet to a standard one-loop Feynman diagram representing a radiative gravitational correction! The result of the full string computation is:

\[
m_{1/2} \propto \lambda^4 m_{3/2}^3
\]

This can be explained in the following way. The Feynman diagram shown on Figure 2 contains two powers of the gravitational coupling that bring the factor \( M_{\text{PLANCK}}^{-2} \), and it is quadratically divergent in the ultra-violet regime, so one expects

\[
m_{3/2} \propto m_{3/2} \frac{\Lambda_{\text{UV}}^2}{M_{\text{PLANCK}}^2}
\]

where \( \Lambda_{\text{UV}} \) is the ultra-violet cutoff. With supersymmetry broken at \( m_{3/2} \) one expects \( \Lambda_{\text{UV}} \sim m_{3/2} \) and \( m_{1/2} \propto m_{3/2}^3 \). Indeed, one can reproduce
Eq.(3) by using Pauli-Villars regularization. Hence the string loop correction can be understood as quantum-gravitational mediation at the one-loop level.

The string derivation of Eq.(3) contains a very interesting subtlety which caused some confusion in the original version of Ref.[5]. In fact, there is another way of viewing Figure 1: in the limit $l \to 0$, the genus $3/2$ surface splits into a torus and a disk connected by a narrow tube, as shown in Figure 3. This region of moduli space cannot be interpreted as gravitational mediation. In principle, it could yield contributions as large as $m_{1/2} \propto \lambda^4 m_{3/2}$. The reason why we do not find such an “anomalously” large mass is that there are no massless particles propagating between the disk and the loop. This is related to the puzzling absence of anomaly mediation, which is believed to be a universal mass generation mechanism in spontaneously broken SUGRA models.

Anomaly mediation is an important ingredient in many supergravity-based generalizations of the standard model. There are several, equally confusing ways of explaining it, but the idea is that once SUSY is broken in the gravitational sector, the same loop corrections that give rise to superconformal anomaly, generate also some mass terms for gauginos. It would be very nice to see this mechanism at work in a model with a sensible ultraviolet completion. In particular, superstrings with Scherk-Schwarz SUSY breaking provide a natural testing ground for these ideas. If one looks, however, more carefully at the “anomaly-mediated” formulas, one finds an unpleasant surprise that this mechanism does not yield a mass in no-scale supergravity models, which is exactly in the case of SS breaking. It is quite disappointing that anomaly mediation does not operate even at higher, $\lambda^4$ order in string loops.

Figure 3. $l \to 0$ limit of genus $3/2$. 
4. Conclusions

22 years later, we are still struggling to understand SUSY breaking, now in superstring theory. The minimal SUGRA model will be soon tested at LHC. Just wait three or four more years to see the gravity-mediated spectrum of gauginos, squarks and sleptons... Congratulations, Pran, on your great ideas!

5. About Pran

When I came to CERN, on my first postdoc straight from Poland, where a tough winter of 1981 was coming up, I noticed very interesting preprints coming from Northeastern University in a faraway Boston. They were co-authored by Arnowitt, Chamseddine and Nath, and there were so many of them! It was quite intriguing that the order of author’s names kept changing in an unpredictable pattern. So naturally, I started wondering who Pran Nath was. Little did I know that few years later, I would come to Northeastern to join Pran as a faculty colleague.

I have enormous respect for Pran. He truly deserves to be called a scholar: he believes in physics as an important part of human civilization and forcefully defends research in fundamental theory. He takes every idea seriously and works very, very hard, pursuing his own dream of a theory of everything. Happy Birthday, my friend! We are looking forward to hundreds more of your papers.

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Note Added

After this paper was submitted to the Pran Nath Festschrift, the discussion of Ref.[5] has been extended and improved in Ref.[8]. A new type of non-gravitational mediation of SUSY breaking between open string sectors has been discussed in Ref.[9].
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