Available online at www.sciencedirect.com
ScienceDirect
Physics Letters B 661 (2008) 201–209
PHYSICS LETTERS B
www.elsevier.com/locate/physletb

Dynamical breaking of $U(1)_R$ and supersymmetry in a metastable vacuum

Steven Abel, Callum Durnford, Joerg Jaeckel *, Valentin V. Khoze

Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, United Kingdom

Received 15 August 2007; received in revised form 7 November 2007; accepted 28 January 2008

Available online 6 February 2008

Editor: A. Ringwald

Abstract

We consider the metastable $\mathcal{N}=1$ QCD model of Intriligator, Seiberg and Shih (ISS), deformed by adding a baryon term to the superpotential. This simple deformation causes the spontaneous breaking of the approximate R-symmetry of the metastable vacuum. We then gauge the flavour $SU(5)_f$ and identify it with the parent gauge symmetry of the Standard Model (SM). This implements direct mediation of supersymmetry breaking without the need for an additional messenger sector. A reasonable choice of parameters leads to gaugino masses of the right order. Finally, we speculate that the entire "ISS × SM" model should be interpreted as a magnetic dual of an (unknown) asymptotically free theory.

The issue of supersymmetry (SUSY) breaking has recently been reinvigorated by Intriligator Seiberg and Shih [1] (ISS). Their observation—that metastable SUSY breaking vacua can arise naturally and dynamically in the low-energy limit of supersymmetric $SU(N)$ gauge theories—has important implications for our understanding of how SUSY is broken in nature. Following this work there has been exploration of both the cosmological consequences [2–6], and the possibilities for gauge or direct mediation of the SUSY breaking to the visible sector [1,7–28]. On the cosmological side, the attractive feature of these models is that the metastable vacua are naturally long lived due to the flatness of the potential. Moreover, at high temperatures the SUSY breaking vacua are dynamically favoured over the SUSY preserving ones because they have more light degrees of freedom, so the early Universe would naturally have been driven into them.[1] On the phenomenological side, attention has focussed on a striking aspect of metastability, namely that the models do not have an exact $U(1)_R$-symmetry, and indeed the $U(1)_R$-symmetry is anomalous under the same gauge group that dynamically restores the supersymmetry in the supersymmetric global minima.

In principle this allows one to evade the theorem by Nelson and Seiberg that SUSY breaking requires R-symmetry in a generic model (i.e. one that includes all couplings compatible with the symmetries) [32]. R-symmetry is unwelcome because it implies that gauginos are massless, so the fact that it can be broken by metastability is an encouraging sign. In a more recent paper [18] it was emphasized that the relation between SUSY breaking and R-symmetry is a continuous one, in the sense that the lifetime of the metastable vacuum decreases in proportion to the size of any explicit R-symmetry breaking terms that one adds to the theory. This allows one to play the "approximate R-symmetry" game: add to the superpotential of the effective theory explicit R-symmetry breaking terms of your choosing, whilst trying to keep the metastable minimum as stable as possible. Such approximate R-symmetry models can then be motivated by appealing to (for example) higher-dimensional operators of the underlying high energy physics.

Clearly there is some tension in this procedure. For example the gauge mediation scenario explored in Refs. [12,17] invokes a messenger sector (denoted by f). The field f has to have an explicit R-breaking mass-term to give gauginos a mass, and conse-

* Corresponding author.
E-mail address: joerg.jaeckel@durham.ac.uk (J. Jaeckel).

[1] An additional cosmological development which is somewhat orthogonal to our discussion is the use of the models of ISS in supergravity to "uplift" supersymmetric models to small non-zero cosmological constant [29–31]. This possible phenomenon is relevant for larger SUSY breaking than that we will be considering here.

0370-2693
doi:10.1016/j.physletb.2008.01.065

quently a new SUSY restoring direction opens up along which f gets a VEV. One is then performing a rather delicate balancing act: in order to avoid disastrously fast decay of the metastable vacuum, large SUSY breaking scales must be invoked so that the R-breaking mass can be sufficiently small. It should also be noted that here the R-symmetry breaking responsible for the globally supersymmetric minima of ISS models plays no direct role in the generation of gaugino masses, and consequently this is expected to be a generic problem for gauge mediation of metastable SUSY breaking. This is also a problem for the models that were constructed to implement direct mediation [14], and again, in those cases certain operators had to be forbidden by hand, making the superpotential non-generic.

To avoid these problems, the next option for generating non-zero gaugino masses would be to use the explicit R-breaking of the ISS model itself, associated with the metastability and the existence of a global supersymmetric groundstate. This is in fact a more difficult proposition than one might suppose for the following reason. At the metastable minimum there is an unbroken approximate R-symmetry (which is of course why it is metastable in the first place). The R-symmetry is explicitly (more precisely anomalously) broken only by the non-perturbative term,

$$W_{\rm np} \propto (\det_{N_f} \Phi)^{\frac{1}{N}} \sim \Phi^{\frac{N_f}{N}}, \tag{1}$$

where Φ is the meson field, $SU(N)_{\rm mg}$ is the gauge group of the magnetic theory, and $N = N_f - N_c$ with $SU(N_c)$ being the gauge group of the electric theory [1]. One might hope that this would induce (for example) R-symmetry breaking mass-terms that contribute to gaugino masses in perturbation theory. However such mass-terms will be typically of order $\frac{\partial^2 W}{\partial \Phi^2} \sim \Phi^{\frac{2N_c - N_f}{N}}$. Thus since ISS models are valid in the interval $N_c + 1 \leqslant N_f < \frac{3}{2}N_c$, they are exactly zero in the metastable minimum where $\langle \Phi \rangle = 0$.

We are led to an alternative—the focus of this Letter—which is to *spontaneously* break the approximate R-symmetry of the ISS model to generate gaugino masses. The explicit breaking of the model then ensures that any R-axions get a mass and are made safe. The natural avenue to explore is to gauge (part of) the $SU(N_f)$ flavour symmetry of the ISS model, identifying it with the Standard Model gauge groups. This would allow the quarks and mesons in the theory to mediate the SUSY breaking directly to the Standard Model, thereby avoiding the need for any messenger sectors which as we have seen are liable to destabilize the metastable vacuum. Once spontaneous R-breaking has been achieved, there is in principle nothing to prevent it being mediated via these fields to the rest of the model including the gaugino masses.[2] (Note that the non-perturbative explicit R-breaking can also now contribute to gaugino masses since Φ will get a VEV.)

In this Letter we demonstrate that perfectly viable direct mediation of SUSY breaking can indeed be implemented in this way, by making the simplest deformation to the ISS model that one can imagine, namely the addition of a baryon term to the superpotential. This "baryon-deformed" QCD model has a runaway direction to a non-supersymmetric metastable minimum of the ISS type, along a particular direction of field space which is lifted by the Coleman–Weinberg potential and stabilized. Along this direction the meson modes Φ_{ij} acquire a VEV, and the approximate R-symmetry is spontaneously broken. Importantly the diagonal ($U(1)$-trace) component of the pseudo-Goldstone modes (i.e. those modes of Φ_{ij} whose flavour indices correspond to SM gauge group) acquires a VEV at this point as well; the latter gives R-breaking masses to the magnetic quarks which are charged under the SM gauge groups. This enables them to act as messenger fields giving the gauginos masses at one-loop. We stress that all of this happens automatically upon adding a baryon. There is no need for any messenger sector outside the ISS model, and therefore no additional instability is induced. Moreover, we will show that the resulting gaugino masses can be naturally of the right order.

Let us begin by introducing our model which is based on the model of ISS with $SU(N_c)$ gauge symmetry and N_f flavours of quark/anti-quark pairs in the electric theory. The magnetic dual theory has a $SU(N)_{\rm mg}$ gauge symmetry, where $N = N_f - N_c$, N_f flavours of fundamental quark/anti-quark pairs, and is IR free if $N_c + 1 \leqslant N_f < \frac{3}{2}N_c$. The minimal values consistent with this equation and leading to a non-trivial magnetic gauge group are $N_f = 7$ and $N_c = 5$ giving $SU(2)_{\rm mg}$ in the magnetic dual theory. Now consider the following superpotential:

$$W = \Phi_{ij}\varphi_i \,.\, \tilde{\varphi_j} - \mu_{ij}^2 \Phi_{ji} + m\varepsilon_{ab}\varepsilon_{rs}\varphi_r^a \varphi_s^b, \tag{2}$$

where $i, j = 1, \ldots, 7$ are flavour indices, $r, s = 1, 2$ run over the first two flavours only, and a, b are $SU(2)_{\rm mg}$ indices (we set the coupling $h = 1$ for simplicity). This is the superpotential of ISS with the exception of the last term which is a baryon of $SU(2)_{\rm mg}$. Note that the 1, 2 flavour indices and the $3, \ldots, 7$ indices have a different status and the flavour symmetry is broken explicitly to $SU(2)_f \times SU(5)_f$. The $SU(5)_f$ factor will be gauged separately and will be identified with the parent $SU(5)$ of the SM.[3]

The baryon deformation is the leading order deformation of the ISS model that is allowed by R-symmetry (as well as the gauge and flavor symmetries discussed above). Terms quadratic in the mesons that could arise from lower dimensional irrelevant operators in the electric theory are forbidden by R-symmetry.

[2] Indeed the very same point was made in Ref. [10] which was presented in the language of retrofitting. There however, successful mediation required a messenger sector which, in general, may lead to new and unstable directions.

[3] Note that the breaking of $SU(5)$ is assumed to take place or be included explicitly in the SM sector.