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Why is the supersymmetry breaking scale unnaturally high?

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ABSTRACT

Evidence is mounting that natural supersymmetry at the weak scale is not realized in nature. On the other hand, string theory suggests that supersymmetry may be present at some energy scale, and gauge coupling unification implies that energy scale may be relatively low. A puzzling question is then why nature would prefer a low, but not completely natural supersymmetry breaking scale. Here we offer one possible explanation, which simultaneously addresses also the strong CP and μ problems. We introduce an axion, and suppose that the Peccei–Quinn and supersymmetry breaking scales are connected. If we further assume that R-parity is not conserved, then the axion is required to be dark matter, and the Peccei–Quinn/supersymmetry breaking scale is required to be at least $\sim 10^{12}$ GeV. Gravity mediation then yields scalar superpartners with masses of at least ~ 100 TeV. The gauginos are likely to obtain loop-factor suppressed masses through anomaly mediation and higgsino threshold corrections, and thus may be accessible at the LHC. The axion should be probed at phase II of the ADMX experiment, and signs of R-parity violation may be seen in the properties of the gauginos.

1. Introduction

The lack of any observation of superpartners or new flavor violating effects, as well as the observed Higgs mass of 125 GeV, suggest that if supersymmetry (SUSY) is realized in nature, the SUSY breaking scale is likely appreciably higher than the weak scale. On the other hand, string theory suggests that supersymmetry may be realized at *some* scale in nature, and gauge coupling unification, naturalness and the presence of dark matter all point towards a low supersymmetry breaking scale. In fact, if the scalar superpartner masses are perhaps 100–1000 TeV, with gauginos obtaining lighter 100–1000 GeV masses automatically by anomaly mediation [1], then the resulting picture is remarkably consistent: The heavy scalars appropriately raise the Higgs mass through loop corrections, suppress flavor changing neutral currents, and allow for the avoidance of collider constraints. In such a scenario, supersymmetry breaking may be communicated by supergravity effects alone, without the need for additional structure.

In this picture – dubbed “Pure Gravity Mediation” (PGM) [2–4] – gauge coupling unification remains successful, naturalness is significantly improved compared to a case with a higher SUSY scale (or no SUSY at all), and the lightest superpartner – the wino – may still serve as dark matter. In spite of all of this, however, a crucial question nags: If nature prefers to solve the hierarchy problem and therefore has a relatively low SUSY breaking scale, then why does not it go all the way? There does not appear to be any fundamental physical constraint preventing the SUSY breaking scale from being lower, with a lighter dark matter particle and perfect naturalness. In a landscape picture, it is difficult to imagine why a region with a low, but not completely natural SUSY scale would be a likely place for us to find ourselves. A small number of other open questions remain in this scenario as well, such as the reason for a μ parameter at least as small as the SUSY breaking masses and the reason for the suppression of strong CP violation, amongst others.

In this Letter, we will show that the issues mentioned above – the μ problem, the strong CP problem, and the incomplete naturalness problem – may all be addressed simultaneously in a straightforward way. Our key assumptions will be as follows:

- The strong CP problem is solved by a Peccei–Quinn (PQ) symmetry [5] under which the standard model quarks are charged, with an associated axion.
- This same PQ symmetry forbids the presence of the μ term, and PQ symmetry breaking then leads to μ of an appropriate size.[1] Here we assume that the PQ charges are such that the μ parameter is suppressed by one power of the Planck scale.
- The breaking of PQ symmetry triggers supersymmetry breaking, so that the two scales are generated to be roughly equal.
- R-parity is not conserved.

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[1] See also for example [6].

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Our assumptions follow from a simple train of logic which begins with the hypothesis that an axion solves the strong CP problem. In such a case, PQ symmetry (assumed to be carried by the standard model quarks) automatically forbids the μ term, suggesting also a solution to the μ problem. We are then faced with the prospect of generating two new scales in nature – the PQ scale, and the SUSY scale. It is remarkable that the scale required for SUSY breaking in pure gravity mediation models $\Lambda_{\rm SUSY} \sim \sqrt{m_{3/2}M_{\rm pl}} \sim \sqrt{100~{\rm TeV} \times 10^{19}~{\rm GeV}} \sim 10^{12}$ GeV happens to coincide with the PQ breaking scale typically needed for axionic cold dark matter [7]. It is the simplest possibility then, that the scales are related, and moreover, that R-parity conservation is therefore not necessary in order to obtain a dark matter candidate.

Assuming that the fundamental theory violates R-parity, the PQ scale, and therefore also the SUSY breaking scale *must* be at least of order 10^{12} GeV in order to obtain a dark matter candidate, as seems required for structure formation [8]. We thus obtain a lower bound on the SUSY breaking scale of $\Lambda_{\rm SUSY} \gtrsim 10^{12}$ GeV, implying gravity mediated gravitino and scalar masses $\gtrsim 100$ TeV. While higher breaking scales are physically allowed, they are disfavored by a resulting increase in fine-tuning – both in the weak scale, and also in the initial displacement angle of the axion field to avoid dark matter over-production. Note that if we took R-parity to be conserved, it would open up the possibility for LSP gaugino dark matter, with a lower SUSY breaking (and PQ) scale, and the mystery of an incompletely natural weak scale would remain unsolved.[2] We also note that our picture tends to result in a supersymmetry breaking spurion charged under PQ symmetry, which is thus unable to give masses to the gauginos directly, implying the anomaly mediated (plus higgsino threshold corrected) spectrum which we consider.

The outline of this Letter is as follows: In Section 2, we will briefly review some aspects of the pure gravity mediation scenario, before turning to discuss the details of our argument more thoroughly, as well as give an example of a simple model which can dynamically generate both the PQ and SUSY scales simultaneously. In Section 3, we will discuss the phenomenology of our scenario, including the requirements and constraints on the assumed R-parity violation. Dark matter axions have a good chance to be observed in upcoming experiments, and the gauginos may be observable at the LHC, or a future linear collider. The presence of R-parity violation may be suggested if the LSP is found to be a bino or gluino (since phenomenologically unacceptable contributions to the dark matter density would result without R-parity breaking). Moreover, it may be possible to directly observe R-parity violating decays of the LSP, providing an explicit check of our framework, especially if accompanied by an observation of axionic dark matter. We also point out that an interesting signal of our scenario would be to find a long lived wino LSP at a collider, but without a corresponding dark matter annihilation signal in cosmic rays. This discrepancy could be particularly acute for relatively light LSP masses of perhaps a few hundred GeV. We will summarize in Section 4.

2. Bound on the SUSY breaking scale

We will begin by reviewing the essential aspects of the pure gravity mediation scenario. After supersymmetry breaking by an F term vev $F_{\rm SUSY}$, the gravitino mass becomes

$$m_{3/2} = \frac{|F_{\rm SUSY}|}{\sqrt{3}M_{\rm pl}}, \tag{1}$$

with $M_{\rm pl} = 2.4 \times 10^{18}$ GeV. The scalar superpartners obtain masses at the same order. The μ parameter, and hence the scale of the higgsino masses, in general depends on the details of the solution to the μ problem, but has been taken in previous studies to be of order the gravitino mass as well. This will indeed be the case in the specific scenario that we consider here. The gauginos then obtain masses at 1-loop order through anomaly mediation and also through higgsino threshold corrections. After including renormalization group running effects as well, one obtains [4]

$$m_{\rm gluino} \simeq 2.5 \times (1 - 0.13\delta_{32} - 0.04\delta_{\rm SUSY}) \times 10^{-2} m_{3/2}, \tag{2}$$

$$m_{\rm wino} \simeq 3.0 \times (1 - 0.04\delta_{32} + 0.02\delta_{\rm SUSY}) \times 10^{-3} (m_{3/2} + L), \tag{3}$$

$$m_{\rm bino} \simeq 9.6 \times (1 + 0.01\delta_{\rm SUSY}) \times 10^{-3} (m_{3/2} + L/11), \tag{4}$$

where $\delta_{\rm SUSY} = \log[M_{\rm SUSY}/100~{\rm TeV}]$, with $M_{\rm SUSY}$ the scalar superpartner mass scale, here of order $m_{3/2}$. δ_{32} denotes $\delta_{32} = \log[m_{3/2}/100~{\rm TeV}]$ for the gluino, and $\delta_{32} = \log[(m_{3/2} + L)/100~{\rm TeV}]$ for the wino. The terms proportional to $m_{3/2}$ represent the anomaly mediated contributions, while those proportional to L are the higgsino threshold contributions, with L given by

$$L \equiv \mu \sin 2\beta \frac{m_A^2}{|\mu|^2 - m_A^2} \ln \frac{|\mu|^2}{m_A^2}. \tag{5}$$

m_A is the CP-odd Higgs mass and $\tan\beta$ is the ratio of Higgs vevs as usual. As discussed in Ref. [2], if μ is of the order of the gravitino mass along with the other soft mass parameters, then $L/m_{3/2}$ is generically of order 1. The wino mass therefore obtains comparable contributions from both anomaly mediated effects and those of the higgsino threshold corrections. Typically $L/m_{3/2}$ is required to be less than about 3 in order for the wino to be the LSP and provide a dark matter candidate, but since we will not assume gaugino dark matter in our discussions, this condition will not be necessary here.

We now assume the existence of a PQ symmetry under which the Higgs fields and quark fields of the minimal supersymmetric standard model (MSSM) are charged. We take the quark charges to be family universal for simplicity. In this case, an $H_U H_D$ superpotential term is necessarily forbidden by PQ symmetry, arising only after PQ symmetry breaking is communicated to the MSSM sector. We will choose PQ charges such that the μ term is generated via a term in the superpotential

$$W \supset \frac{\kappa}{M_{\rm pl}} Q^2 H_U H_D, \tag{6}$$

where Q^2 breaks PQ via an expectation value $\langle Q \rangle = \Lambda_{\rm PQ}/\sqrt{2}$. We assume that concurrent with PQ symmetry breaking, a superfield Z is triggered to obtain an F-term F_Z, breaking supersymmetry. We define $\Lambda_{\rm SUSY}^2 = F_Z = \lambda \Lambda_{\rm PQ}^2$. We take the SUSY/PQ breaking sector to not contain any small parameters which could lead to a significant hierarchy between $\Lambda_{\rm SUSY}$ and $\Lambda_{\rm PQ}$, so that λ and κ are of order 1.[3]

The strong anomaly of the PQ symmetry leads to an interaction

$$\frac{\alpha_{\rm QCD}}{8\pi}\left(\theta_0 + \frac{a}{f_a}\right) G\tilde{G}, \tag{7}$$

where a is the axion field, θ_0 is the strong CP parameter, G is the gluon field strength and $f_a = \frac{\Lambda_{\rm PQ}}{3N}$. Here $N = |\frac{q_{H_U} + q_{H_D}}{q_0}|$, where q_{H_U}

[2] Indeed, there does not appear to be any problem with, for example, mixed bino–wino thermal relic dark matter with mass of perhaps 5–10 GeV, and a few hundred GeV superpartner masses.

[3] Note that a fully strongly coupled theory would have λ of order 4π.