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Supersymmetry, Flavour and Vacuum Selection

Zygmunt Lalak*
CERN Physics Department, Theory Division, CH-1211 Geneva 23, Switzerland
Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, Hoża 69, 00-681 Warsaw, Poland
E-mail: Zygmunt.Lalak@fuw.edu.pl

We discuss the structure and basic properties of supersymmetric flavour sectors which are needed to realize horizontal flavour symmetries at the microscpic level. It is found that the desired thermal evolution favours heavy mass scales in hidden flavour sector.

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*Speaker.

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1. Introduction

Supersymmetry, although under pressure from severe exclusion limits coming from the LHC experiments, remains a chief candidate for a perturbative extension of the Standard Model and a prime solution to the big hierarchy problem. However, supersymmetry doesn't answer all puzzles of the Satandard Model. One problem that becomes even more accute in the presence of supersymmetry is the observed suppression of the flavour changing neutral currents. The point is that the superparters of known particles introduce new contributions to the low energy flavoured observables and the new contributions are suppressed only by the inverse powers of the superpartner masses i.e. by the supersymmetry breaking scale m_s. That scale shouldn't be to large in order not to spoil naturalness in the electroweak setor. Thus there should exist an additional mechanism suppressing flavour transitions in the supersymmetric extensions of the SM. An obvious candidate are horizontal symmetries, abelian or nonabelian, see [1]. Then the hierarchical structure of quark Yukawa matrices and suppression of the off-diagonal terms in squark mass matrices can be explained with the help of a small parameter $\varepsilon =< \phi > /M$, which is the ratio of a vacuum expectation value of a flavon charged under a horizontal symmetry and certain large scale M characterizing the decoupled (heavy) flavour sector. Microscopic models which realize such scenarios necessary include new vector-like fields charged under the SM gauge group. They may have quantum numbers of the SM quarks or of the SM Higgs fields, see [2]. They need to couple to themselves and to one or more flavons to reproduce correctly the low energy masses and mixings. Hence, in models with horizontal symmetries there may exist a separate flavour hidden sector. It turns ot that this hidden sector is often very similar to the hidden sectors responsibe for the supersymmetry breakdown. It may suffer similar problems and in fact it may participate in the supersymmetry breakdown. In the rest of this note we shall summarize basic features of simple flavour hidden sectors from the point of view of their possible interference with the supersymmetry breakdown mechanism.

2. Fermionic flavour messenger sector

For definiteness we shall assume a flavour messenger sector consisting of heavy fermions - triplets under $SU(3)_c$ and doublets or singlets under $SU(2)_w$ and concentrate on the case of an abelian horizontal $U(1)$ symmetry. The new couplings between light generations and new states are of the form

$$W_f = X_f \bar{\Psi}\Psi + a^{ij}\bar{\Psi}_i \psi_j \phi + H\bar{\Psi}\psi, \tag{2.1}$$

where $\Psi, \bar{\Psi}$ are heavy quarks, ψ denotes light quarks and $X_f = M + F_f \theta^2$ is a flavour spurion whose scalar vev sets the mass M of the heavy quarks. The F-term of X_f could be nonzero, depending on the dynamics which stabilises this superfield. We shall come back to this issue later. With the couplings written above one can form tree-level chain diagrams, [2], which reconstruct, upon integrating out heavy fields, the effective Yukawa couplings of the form

$$\bar{Q}^i_L \left[a_{ij} \frac{< \phi >}{M} \right]^{|u_j + q_i|} U^j_R, \tag{2.2}$$

where u_j and q_i are horizontal charges of the light quarks. One should note, that the actual light quarks are mixtures of original "light" states and the new heavy states, obtained upon diagonalisation of the full fermionic mass matrix. For the complete analysis of the current constraints on

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the scale M see the papers [2, 3]. The model independent lower bound on the messenger mass turns out to be $M > 20\,\text{TeV}$, which can be reuced down to a few TeV in non-abelian models or in a model-dependent manner with the help of suitably arranged small couplings inside the flavour sector.

3. Dynamics of the hidden flavour sector

One can easily spot the striking similarity between the superpotential 2.1 and a superpotential describing the spurion/messenger sector of the simple gauge mediation models. The complete superpotential describing both sector should take the form

$$W = X_f \bar{\Psi}\Psi + a^{ij}\bar{\Psi}_i \psi_j \phi + H\bar{\Psi}\psi + \mu_f^2 X_f + \mu^2 X + XQq, \tag{3.1}$$

where X is the supersymmetry breaking spurion, Q, q are supersymmetry messengers and μ_f, μ are coefficients of the terms linear in the spurion fields which determine the scale of their F-terms. The two sectors could be completely independent, so in first approximation one can analyse the vacuum structure of the flavour sector independently of the details of the dominant supersymmetry breakdown. It is well known, that to stabilise all the fields one needs quantum corrections which can be included as non-canonical terms in the Kähler potential. There exist supersymmetric minima with $F_f = 0$, but at these minima the expectation values of the scalar component of heavy quark superfields are non-zero, causing the spontaneous breakdown of colour or electroweak interactions. This is avoided in the meta-stable minimum with both $< X_f > \neq 0$ and $F_f \neq 0$. However, non-vanishing F_f has interesting consequences. The point is that it contributes to the full fermionic mass matrix which includes also the ψs. There appear mixings which cause the lowest eigenvalue of the tree-level mass matrix squared to be negative. One includes then loop induced supersymmetry breaking masses, but if they are fed by F_f only, they tur out to be to small to make the negative eigenvalue become positive. Barring more sophisticated and less natural solutions, this means that the dominant contribution to soft terms must be given by a spurion X which is different than X_f. All this favours general gauge mediation (GGM) scenarios. A specific realisation can be found for instance in [4].

4. Thermal dynamics of the flavour sector

One can adopt the analysis of the thermal evolution of the hidden sector of gauge mediation given in [5, 6] to follow the evolution of the flavour sector 2.1. Let us consider a model

$$W = \lambda X_f \bar{\Psi}\Psi + \mu_f^2 X_f, \tag{4.1}$$

where $\bar{\Psi}$ and Ψ are heavy fermions charged under the Standard Model gauge group and order 4 or order 6 (in X_f) corrections to the Kähler potential are present, see [5, 6]. Thermal evolution of such a system is characterized by two critical temperatures

$$T_{cr}^q = \left(\frac{\lambda F_f}{8g_s^2 + 4\lambda^2} \right)^{1/4} \tag{4.2}$$

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and

$$T_X^2 = \frac{8}{5} \frac{F_f}{\lambda\sqrt{3}M_P} \left(\frac{F_f}{\lambda}\right)^{1/2}, \tag{4.3}$$

where g_s is the SM gauge coupling, we assume that the strong interactions give the dominant effect. Let the universe cool down from a very high initial temperature T_{ini}. The first critical temperature T_{cr} corresponds to opening up of the directions towards the supersymmetric minima, with nonvanishing vevs of the heavy sfermions. Below the second critical temperature, T_X, the possibility of the transition to the non-supersymmetric minimum opens up. The obvious constraint on the model is the demand, that $T_X > T_{cr}^q$, since otherwise the system lands in the wrong minimum when the universe cools down during expansion. The above relation can be fulfilled if the coupling λ is sufficiently small

$$\lambda < \left(\frac{10^{-3}\sqrt{F_f}}{2.5\sqrt{3}M_P}\right)^{2/5}. \tag{4.4}$$

It is easily seen, that to make λ large one would need to take F_f to be of the order of the squared Planck scale, which contradicts the assumption that the flavour sector supersymmetry breaking is subdominant. Let us take as an example a value of F_f which gives a sub-TeV contribution to the soft masses, $\sqrt{F_f} = 2.4\,10^9$ GeV. This gives $\lambda < 1.2\,10^{-5}$. Taking into account the experimental limits on the messenger masses derived in [2, 3], $m_\Psi > 20$ TeV, one finds the lower limit on the new physics scale $\Lambda_{NP} =< X_f >$:

$$< X >> \frac{20\,\mathrm{TeV}}{\lambda} > 20 \times 10^5\,\mathrm{TeV}. \tag{4.5}$$

Of course, for smaller values of the coupling λ this lower limit becomes more severe. Such scales go beyond the reach of the direct probe in existing and future accelerators.

5. Summary

Supersymmetry brings new contributions to flavour observables which are only mildly suppressed by the powers of the soft masses. An additional mechanism is needed tu suppress the supersymmetry-induced flavour changing operators and a simple solution is offered by horizontal symmetries, abelian or non-abelian. To realize this mechanism at a microscopic level one needs to introduce new states charged under the SM gauge group - heavy fermions or new Higgs fields. This means that in the context of supersymmetric extensions of the Standard Model new flavour "hidden" sector needs to be introduced in addition to the one which is responsible for the spontaneous breakdown of supersymmetry. It turns out that the structure of couplings in the flavour sector is very similar to that of the O'Raifeartaigh hidden sectors used in the context of models with gauge mediation. One may ask the question whether the two sectors cannot be replaced by a single one. This idea is difficult to realize, because of the necessary mixing between the light and heavy interaction eigenstates. This mixing results in negative mass squared eigenvalues in the effective scalar potential for the would-be supersymmetry breaking solutions. One can check that in simple versions of the hidden flavour sector radiative corrections are insufficient to lift the unstable directions. This points towards more general models, with more than one supersymmetry breaking

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spurion in the hidden sector. In addition to constraints coming from the requirement of the correct low energy vacuum, one can also analyse the thermal evolution of the system to find out the conditions necessary for the system to land in the correct vacuum at low temperatures. The evolution to the realistic supersymmetry breaking minimum can occur provided the coupling between spurion and heavy flavour messenger is sufficiently weak (as compared to gauge couplings) and the mass scale of the flavour messenger sector is sufficiently high.

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