



ELSEVIER

14 August 1997

PHYSICS LETTERS B

Physics Letters B 406 (1997) 309–313

Leptoquarks in SUSY unified models and the HERA events^{*}

S.F. King^a, G.K. Leontaris^b^a Department of Physics, University of Southampton, Southampton, SO17 1BJ, UK^b Theoretical Physics Division, Ioannina University, GR-45110 Ioannina, Greece

Received 21 April 1997; revised manuscript received 22 May 1997

Editor: P.V. Landshoff

Abstract

Motivated by the recent HERA events which are consistent with a possible leptoquark interpretation, we discuss the prospects for including additional light colour triplets and anti-triplets in the spectrum of supersymmetric unified theories. We focus on a particular string-inspired Pati-Salam model, and propose a simple mechanism by which a light colour triplet of charge $-1/3$ plus anti-triplet of charge $1/3$, may have a mass of order 200 GeV, with one of the new states having leptoquark couplings and with proton decay suppressed. We also discuss possible scenarios for gauge unification in such a model. © 1997 Elsevier Science B.V.

The recent HERA events [1,2] have been followed by much theoretical speculation about leptoquarks [3]. If we accept that the excess of events reported at high Q^2 is not a statistical fluctuation and future runs confirm their existence, it is clear that they are suggestive of new physics beyond the standard model (SM). In particular, assuming that the events occur at the s-channel, then the observed peak at definite large x -values is a distribution which corresponds to a mass determination of order $\mathcal{O}(200)$ GeV. The various theoretical explanations include contact interactions, R -parity violation and leptoquarks. In this letter, prompted by the above experimental findings at HERA, we discuss the prospects for incorporating leptoquarks into supersymmetric unified models.¹

^{*} Research supported in part by grant numbers GR/K55738, TMR contract ERBFMRX-CT96-0090 and IIENEΔ-15815/95.

¹ By leptoquarks we mean light colour triplets with leptoquark couplings. The introduction such states might be expected to destroy the unification of the three gauge couplings, however there are various ways to remedy this as discussed later. See also [4].

A). To set the notation we first present the R -parity conserving superpotential in the MSSM:

$$\mathcal{W} = \lambda_1 q u^c h_2 + \lambda_2 q d^c h_1 + \lambda_3 \ell e^c h_1 + \lambda_4 \phi_0 h_1 h_2 \quad (1)$$

where $q = (u, d) = (3, 2, \frac{1}{6})$, $u^c = (\bar{3}, 1, -\frac{2}{3})$, $d^c = (\bar{3}, 1, \frac{1}{3})$, $\ell = (\nu, e) = (1, 2, -\frac{1}{2})$, and $e^c = (1, 1, 1)$ are the left-handed quark and lepton superfields which transform under the standard model gauge group as shown and $h_{1,2}$ the standard higgses. ϕ_0 is a singlet which realises the higgs mixing.² In addition, one may add the following interactions

$$\mathcal{W}' = \lambda_5 \ell \ell e^c + \lambda_6 \ell q d^c + \lambda_7 u^c d^c d^c + \lambda_8 \phi_0 h_2 \ell \quad (2)$$

When both $\lambda_{5,6}$ couplings are present, there are graphs mediated by the scalar partners which lead to lepton number violation. On the other hand, the coexistence

² This is actually the next-to-minimal supersymmetric standard model (NMSSM). In the MSSM Higgs mixing is achieved by a $\mu h_1 h_2$ coupling.

of $\lambda_{6,7}$ couplings leads to fast proton decay, unless the couplings are unnaturally small [5]. A natural way to avoid such problematic couplings is to impose R -parity which forbids all the terms in (2), unless initial conditions on the couplings at the unification scale are assumed in order to allow only the desired terms at low energy (see for example [7]). Henceforth we shall assume such an R -parity, and turn instead to the possibility of leptoquarks.

Assuming the existence of light leptoquarks the basic question we wish to address is how they might naturally be incorporated within the framework of supersymmetric unified models. From this point of view leptoquarks correspond to new coloured states which are remnants of representations of a higher symmetry. For example in the context of a non-supersymmetric $SU(5)$ theory additional light states $Q = (3, 2, \frac{1}{6})$ and $\bar{Q} = (\bar{3}, 2, -\frac{1}{6})$ contained in the $10 + \bar{10}$ were introduced to adjust the wrong prediction of $\sin^2 \theta_W$ [8]. However tremendous fine-tuning is necessary to split apart the light Q state from the remaining components of the 10 which must remain superheavy. This is similar to the problem of splitting the Higgs doublet from the Higgs colour triplet in the 5 of $SU(5)$. From this example it would seem that light leptoquarks only serve to exacerbate the doublet-triplet splitting problem present in unified models, supersymmetric or not. However, as we shall see in the next section, there is a natural way to obtain a pair of light leptoquarks in supersymmetric unified models without any fine-tuning.

A further candidate for a light leptoquark, common to all grand unified models, are new left-handed representations $D^c = (\bar{3}, 1, \frac{1}{3})$ and $\bar{D}^c = (3, 1, -\frac{1}{3})$ where D^c has the quantum numbers of the down quark singlet d^c . There are two types of couplings which can exist in the low energy superpotential. These are,

$$\mathcal{W}_1 = \lambda_9 qq \bar{D}^c + \lambda_{10} u^c d^c D^c \quad (3)$$

$$\mathcal{W}_2 = \lambda_{11} D^c ql + \lambda_{12} \bar{D}^c u^c e^c + \lambda_{13} \bar{D}^c d^c \nu^c \quad (4)$$

where we have assumed that ν^c is the right handed neutrino. In order to avoid proton decay problems, with a suitable discrete symmetry we may prevent one of $\mathcal{W}_1, \mathcal{W}_2$. There are other exciting possibilities of exotic quark states [3,6], which create couplings that might interpret the HERA data. Thus, states like those described above, offer interesting possibilities for new phenomenology. Since all of these new states carry

colour, the new couplings should not lead to fast proton decay. In particular, symmetries imposed by hand in the above superpotential pieces are not always consistent with the unified gauge symmetry.

\mathcal{B}). After these rather general considerations we now specialise to a particular model in which it is possible to have light leptoquarks without inducing excessive proton decay, and to achieve this in a natural way without any fine tuning. This is the string-inspired Pati-Salam model [9,10]. Here we briefly summarise the parts of the model which are relevant for our analysis. The gauge group is

$$G_{PS} = SU(4) \otimes SU(2)_L \otimes SU(2)_R \quad (5)$$

The left-handed quarks and leptons are accommodated in the representations

$$F = (4, 2, 1) = (q, l)$$

$$\bar{F} = (\bar{4}, 1, \bar{2}) = (u^c, d^c, \nu^c, e^c)$$

The MSSM Higgs fields are contained in the following representations,

$$h_a^x = (1, \bar{2}, 2) = \begin{pmatrix} h_2^+ & h_1^0 \\ h_2^0 & h_1^- \end{pmatrix} \quad (6)$$

Under the symmetry breaking in Eq. (10), the Higgs field h in Eq. (6) splits into two Higgs doublets h_1, h_2 whose neutral components subsequently develop weak scale VEVs,

$$\langle h_1^0 \rangle = v_1, \quad \langle h_2^0 \rangle = v_2 \quad (7)$$

with $\tan \beta \equiv v_2/v_1$. The spectrum of the model is completed with four singlets $\varphi, \phi_i, i = 1, 2, 3$ where $\langle \varphi \rangle \sim \mu$ realises the higgs mixing and ϕ_i mix with the right handed neutrinos and participate in the higgs mechanism [10].

The Pati-Salam gauge symmetry is broken at the scale M_{PS} by the following Higgs representations

$$\bar{H} = (\bar{4}, 1, \bar{2}) = (u_H^c, d_H^c, \nu_H^c, e_H^c)$$

$$H = (4, 1, 2) = (\bar{u}_H^c, \bar{d}_H^c, \bar{\nu}_H^c, \bar{e}_H^c) \quad (8)$$

The neutral components of the Higgs fields are assumed to develop VEVs

$$\langle \nu_H^c \rangle = \langle \bar{\nu}_H^c \rangle \sim M_{PS}, \quad (9)$$

leading to the symmetry breaking at M_{PS} :

$$G_{PS} \rightarrow SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \quad (10)$$

in the usual notation.

The high energy Higgs mechanism removes the H, \bar{H} components $u_H^c, e_H^c, \bar{u}_H^c, \bar{e}_H^c$ from the physical spectrum (half of these states get eaten by the heavy gauge bosons and gauginos and the other half will become massive Higgs bosons), leaving massless d_H^c, \bar{d}_H^c . In order to give these states a large mass one introduces a colour sextet superfield

$$D_6 = (6, 1, 1) = (D^c, \bar{D}^c)$$

where as before $D^c = (\bar{3}, 1, \frac{1}{3})$ and $\bar{D}^c = (3, 1, -\frac{1}{3})$. We take the gauge invariant superpotential to have the form (dropping all coupling constants)

$$\begin{aligned} \mathcal{W}_{422} \sim & \bar{F}Fh + \bar{F}H\phi_i + \varphi(hh + \phi_i\phi_j + D_6\bar{D}_6 + H\bar{H}) \\ & + FFD_6 + \bar{F}\bar{F}D_6 + \bar{H}\bar{H}D_6 + HHD_6 \end{aligned} \quad (11)$$

Now, the way the colour triplets receive superheavy masses is the following. Remember first that the decomposition of the sextet gives an antitriplet/triplet pair ($D_6 \rightarrow D^c + \bar{D}^c$). On the other hand \bar{H}, H fields contain also another such pair with the same quantum numbers: d_H^c, \bar{d}_H^c . To break the $SU(4) \times SU(2)_R$ the H, \bar{H} fields acquire vevs of $\mathcal{O}(M_{PS})$. Then from the terms of the second line in (11) one gets the following two mass terms

$$\langle H \rangle HD_6 + \langle \bar{H} \rangle \bar{H}D_6 \rightarrow \langle \bar{\nu}_H \rangle \bar{d}_H^c D^c + \langle \bar{\nu}_H \rangle d_H^c \bar{D}^c \quad (12)$$

From the point of view of proton decay the most dangerous colour triplets are those contained in the heavy sextet field D_6 . This is because of the terms in the second line of the superpotential which mix the families with them. Indeed, the following dangerous combinations of couplings appear

$$FFD_6 \rightarrow \lambda_9 qq\bar{D}^c + \lambda_{11} q\ell D^c \quad (13)$$

$$\bar{F}\bar{F}D_6 \rightarrow \lambda_{10} u^c d^c D^c + \lambda_{12} u^c e^c \bar{D}^c + \lambda_{13} d^c \bar{D}^c \nu^c \quad (14)$$

On the right hand side of the above equations we have inserted the same couplings used in Eqs. (3), (4) in

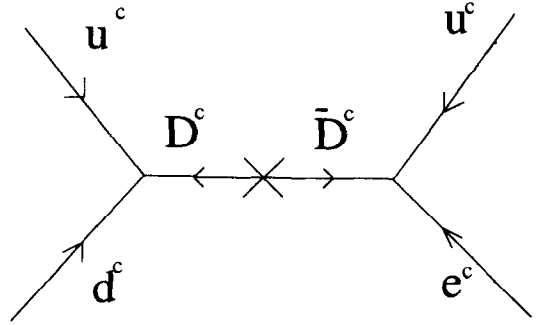


Fig. 1. A dimension-5 proton decay operator generated from terms in the operator $\bar{F}\bar{F}D_6$.

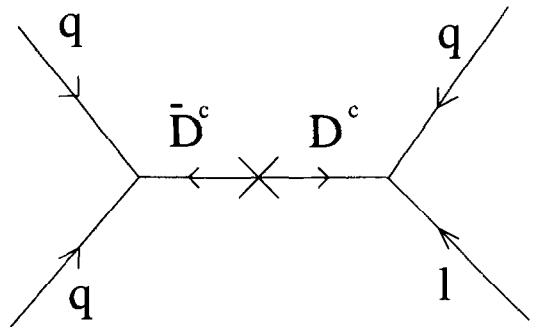


Fig. 2. A dimension-5 proton decay operator generated from terms in the operator FFD_6 .

order to emphasise the way that GUT models in general lead to couplings which can potentially generate proton decay.

C). The question we now ask is: can we somehow have a light colour triplet plus anti-triplet without inducing excessive proton decay? At first sight this would seem unlikely due to the dimension-5 operators generated by the colour triplet exchange diagrams in Figs. 1, 2.

Note that the dimension-5 proton decay diagrams rely on the mass mixing of the D^c and \bar{D}^c colour triplets, which is controlled by the term $\varphi D_6 \bar{D}_6$ in the superpotential whose adjustable coupling strength will dictate the proton decay rate. However there are also dimension-6 proton decay diagrams which do not involve the chirality-flipping mass mixing, which involve the exchange of D^c or \bar{D}^c only. Physically the dimension-5 operators correspond to spin-1/2 exchange, while the dimension-6 operators correspond to spin-0 exchange.

Let us first assume the existence of a symmetry which prevents the appearance of the term FFD_6 . However, this is not enough to prevent proton decay since $\bar{F}\bar{F}D_6$ contains two operators which are combined to a proton decay Feynman graph in Fig. 1. However we observe that if in addition one of the colour triplets D^c or \bar{D}^c were to remain heavy, then fast proton decay would be avoided at least at the dimension-5 level. How could this be achieved? The crucial observation is that the mass states in (12) are formed between $\bar{d}_H^c D^c$ and $d_H^c \bar{D}^c$. Thus if we extend the symmetry to forbid the term $\bar{H}\bar{H}D_6$ then there is only one allowed mass term for the two triplet pairs, namely $(\bar{\nu}_H)\bar{d}_H^c D^c$. When supersymmetry breaking takes place, the scalar part of the other pair receives a (mass)² $\sim m_{\text{soft}}^2$ i.e., of the order of the supersymmetry breaking scale. Thus fast proton decay is avoided, and a phenomenologically interesting light colour triplet \bar{D}^c and colour anti-triplet d_H^c pair occur in the spectrum.

Clearly, the general requirement is that one of the two operators FFD_6 or $\bar{F}\bar{F}D_6$ is forbidden and in addition one of the operators $\bar{H}\bar{H}D_6$ or HHD_6 is forbidden by the unspecified symmetry. What is the origin of such a symmetry? A situation typical of string constructions is to have a gauge group $G_{\text{PS}} \times U(1)$ where the various matter and higgs multiplets carry charges Q'_i under the $U(1)$ symmetry. As an example, if we assume the charges $Q'_F = Q'_H = -3Q'_F = -3Q'_H = -3/2$ and $Q'_h = Q'_{\phi_i} = -Q'_{D_6} = -Q'_{\bar{D}_6}/2 = 1$, ban the terms HHD_6 , FFD_6 as well as the mixings $\varphi(H\bar{H} + D_6\bar{D}_6)$. Similarly, making a different choice of the Q'_i s, we may ban the terms $\bar{H}\bar{H}D_6$, $\bar{F}\bar{F}D_6$.

\mathcal{D}). Babu et al [6], observed that there are new kinds of colour particles which can distinguish between pe^+ and pe^- modes at HERA. In particular in addition to the D^c, \bar{D}^c fields considered above they also suggest the following SM representations.

$$U = (3, 1, \frac{4}{3}), \quad \bar{G} = (3, 2, -\frac{7}{6}) \quad (15)$$

These states have exotic charges. Both of them can be accommodated in representations of our gauge symmetry group. Indeed, assume the decomposition of the representation $\bar{\Sigma} = (15, 2, 2)$,

$$\begin{aligned} \bar{\Sigma} = & \bar{G} + \bar{U} + \bar{Q}' + \bar{Q}' + h' + \bar{h}' \\ & + (8, 2)_{\frac{1}{3}} + (8, 2)_{-\frac{2}{3}} \end{aligned} \quad (16)$$

However, if we stick to string motivated scenarios at $k = 1$ level [11], these representations are not possible since they only arise in the adjoint of $SU(4)$. Of course, at $k = 2$ Kac-Mody level they are possible. As an alternative, we may consider that such states may arise as bound states of smaller representations which bind together due to their properties under a hidden symmetry [12], however, in this letter we will not elaborate this further.

\mathcal{E}) We now briefly discuss the problem of unification. It is known that the particle content of the MSSM allows the three gauge couplings to attain a common value at a high scale, of the order $M_U \sim 10^{16}$ GeV. The introduction of massless states beyond those of the minimal spectrum change drastically the evolution of the gauge couplings. Thus, if we assume the existence of new (types of) quarks remaining massless down to the weak scale, in order that the idea of unification remains intact at some high scale additional contributions to the beta functions are needed to compensate for the leptoquark pair and yield a correct prediction for the weak mixing angle. It is clear that if a colour triplet plus anti-triplet pair remains in the massless spectrum this will alter both the unification scale and $\sin^2 \theta_w$. In the context of the present model, we desire gauge unification at the string scale, rather than at M_U , so some modification to the spectrum is required in any case. A complete exhaustive study is clearly required to determine all possible solutions to the unification question in this model.

Perhaps the simplest unification scenario is one in which we introduce in addition to the $D^c + \bar{d}_H^c$ or $\bar{D}^c + d_H^c$ pair a further pair of Higgs doublets at low energies contained in an extra $h' = (1, 2, \bar{2})$ (or perhaps $(1, \bar{2}, 2)$) representation of the Pati-Salam group. Then the low energy spectrum contains an extra two Higgs doublets h'_1, h'_2 giving four Higgs doublets in total. This would clearly have important implications for the electroweak symmetry breaking sector, which would be interesting to explore. The low energy spectrum would then contain in addition to the MSSM spectrum, extra states with the quantum numbers of an $SU(5)$ $5 + \bar{5}$ vector representation, and gauge unification is achieved in the usual way at around 10^{16} GeV. If this scale is identified with the Pati-Salam breaking scale M_{PS} then it is possible to maintain the equality of the coupling constants right up to the string scale by the addition of suitable extra

heavy Pati-Salam representations [13].

To summarise, motivated by a possible leptoquark interpretation of the HERA events, we have discussed the prospects for including additional light colour triplets and anti-triplets in the low energy spectrum of unified models. We have proposed a specific string-inspired Pati-Salam model which contains a mechanism for allowing low energy states which have leptoquark couplings, without inducing excessive proton decay, and outlined the kind of string symmetries which will forbid the correct combination of operators to allow this. There are two possible scenarios:

(1) HHD_6 allowed ($\bar{H}\bar{H}D_6$ forbidden) leading to a light $\bar{D}^c + d_H^c$,

(2) $\bar{H}\bar{H}D_6$ allowed (HHD_6 forbidden) leading to a light $D^c + \bar{d}_H^c$.

In each case unification may be achieved with four low energy Higgs doublets, and in each case the proton decay constraint allows one of two possible options for the leptoquark couplings:

(A) FFD_6 allowed ($\bar{F}\bar{F}D_6$ forbidden) with couplings $\lambda_9 qq\bar{D}^c + \lambda_{11} q\ell D^c$,

(B) $\bar{F}\bar{F}D_6$ allowed (FFD_6 forbidden) with couplings $\lambda_{10} u^c d^c \bar{D}^c + \lambda_{12} \bar{u}^c e^c \bar{D}^c + \lambda_{13} d^c \bar{D}^c \nu^c$.

Possibility (1B) involves a light leptoquark coupling $\lambda_{12} \bar{u}^c e^c \bar{D}^c$, while possibility (2A) involves a light leptoquark coupling $\lambda_{11} q\ell D^c$. Clearly future HERA runs with electron/positron polarisers will decide which of these two operators is the relevant one. So far our discussion has been independent of family indices. Assuming HERA confirms the anomaly, and distinguishes between the two operators, then the task of theory will be to construct a complete theory of flavour along these lines. The main point of the present paper is to show that light leptoquarks may be elegantly incorporated into string-inspired supersymmetric unified models.

G.K.L. would like to acknowledge stimulating discussions with J. Rizos during the initial stages of this work.

References

- [1] C. Adloff et al., H1 collaboration, DESY 97-024, hep-ex/9702012.
- [2] J. Breitweg et al., ZEUS collaboration, DESY 97-025, hep-ex/9702015.
- [3] D. Choudhury and S. Raychaudhuri, CERN-TH-97-026, hep-ph/9702392;
H. Dreiner and P. Morawitz, hep-ph/9703279;
S.L. Adler, IASSNS-HEP-97-12, hep-ph/9702378;
G. Altarelli, J. Ellis, G.F. Giudice, S. Lola and M.L. Mangano, CERN-TH-97-040, CERN-TH-97-40, hep-ph/9703276;
J. Kalinowski, R. Rückl, H. Spiesberger and P.M. Zerwas, BI-TP-97-07, DESY-97-038, WUE-ITP-97-02, hep-ph/9703288;
J. Hewett and T. Rizzo, hep-ph/9703337;
Z. Kunszt and W.J. Stirling, hep-ph/9703288;
Tadashi Kon and Tetsuro Kobayashi, ITP-SU-97-02, hep-ph/9704221.
- [4] G.K. Leontaris and J.D. Vergados, hep-ph/9703338.
- [5] S. Dimopoulos et al., Phys. Rev. D 41 (1990) 2099;
H. Dreiner and G.G. Ross, Nucl. Phys. B 365 (1991) 597;
D. Brahmachari and P. Roy, Phys. Rev. D 50 (1994) 39;
Y. Nir and V. Ben-Hamo, Phys. Lett. B 399 (1994) 77;
A.Yu. Smirnov and F. Vissani, 9506416;
S. Babu and S. Barr, Phys. Lett. B 381 (1996) 137.
- [6] K.S. Babu, Christopher Kolda, John March-Russell and Frank Wilczek, IASSNS-HEP-97-04, hep-ph/9703299.
- [7] Riccardo Barbieri, Alessandro Strumia and Zurab Berezhiani, IFUP-TH-13-97, INFN-FE-03-97, hep-ph/9704275.
- [8] H. Murayama and T. Yanagida, Mod. Phys. Lett. A 7 (1992) 147.
- [9] J. Pati and A. Salam, Phys. Rev. D 10 (1974) 275.
- [10] I. Antoniadis and G.K. Leontaris, Phys. Lett. B 216 (1989) 333;
I. Antoniadis, G.K. Leontaris and J. Rizos, Phys. Lett. B 245 (1990) 161.
- [11] For a review see K. Dienes, hep-ph/9602045.
- [12] K. Babu and J. Pati, Phys. Rev. D 48 (1993) 1921;
P. Dimopoulos et al., hep-ph/9604265, to appear in Zeit. Phys. C.
- [13] S.F. King, Phys. Lett. B 325 (1994) 129.