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Constraints on leptoquark masses and couplings from rare processes and unification [*]

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Abstract

Motivated by the recent experimental H1 and ZEUS data at HERA, which have reported evidence for leptoquark production at $\sqrt{s} = 314$ GeV with a mass at $m_D = 200$ GeV we consider their implications in unified supersymmetric theories. We also present calculations for leptoquark production incorporating the existing limits from other exotic reactions on its couplings and other relevant parameters. © 1997 Elsevier Science B.V.

Recently, H1 [1] and ZEUS [2] experiments have reported an excess of e^+p deep inelastic scattering events at very high Q^2 and large x. In the past, there have appeared many suggestions which may interprete the high Q^2-events. For example, the reported excess could be explained with the existence of R-parity violating interactions [3] in supersymmetry. These data, could also be compatible with a narrow state suggestive of a new particle possessing both lepton and baryon quantum numbers (leptoquark) with a mass $m_D \sim 200$ GeV. This exciting possibility, at the time of writing this work, resulted in a number of very interesting theoretical considerations [4,5]. In the present work, we will attempt to describe the properties of such a state, in terms of isosinglet colour triplet superfields D, D^c by incorporating known limits from other exotic processes.

It is interesting that various extentions of the Minimal Supersymmetric Standard Model (MSSM) predict the existence of several kinds of new particles in addition to the known quarks and leptons. Among them, the leptoquarks as well could be proposed as a signal for new physics beyond MSSM. The intoduction of any new particle in the minimal theory has important implications which should not be overlooked. Two main concerns should be the following. New particles create new interactions in the theory which often lead to severe constraints on their masses and Yukawa couplings. Second, we know that the great and impressive success of the supersymmetric theories is intimately related to the unification of the fundamental forces at a large energy scale. Thus, the appearance of relatively light ($\mathcal{O}$(TeV)) states in the supersymmetric spectrum will have a significant effect on the gauge coupling running and therefore they might spoil the unification scenario.

In this note, we would like to address these two points in the context of unified theories whose low energy limit is a supersymmetric model which in addition to the MSSM spectrum has also a pair of leptoquarks D, D^c sitting in $(3,1,-\frac{1}{3})$ and $(\bar{3},1,\frac{1}{3})$ representa-

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tions of the standard model gauge symmetry. We will see that due to the possible existence of Yukawa couplings of the particles D, D^c with the ordinary matter, rare processes put rather stringent constraints on the related couplings. On the other hand, if we wish to retain the successful unification scenario, we find that we are forced to include in the spectrum new particles which become massive at some intermediate scale.

The basic superpotential couplings which result to the fermion masses in the MSSM are the following:

$$\mathcal{W} = \lambda_1 Q u^c h_1 + \lambda_2 Q d^c h_2 + \lambda_3 L e^c h_2 + \lambda_4 \phi_0 h_1 h_2 \tag{1}$$

where Q, u^c, d^c, L, e^c are the quark and lepton superfields and $h_{1,2}$ the standard higgses. ϕ_0 is a singlet which realises the higgs mixing. Now, we may assume in addition the existence of D, D^c particles. There are two types of couplings which can exist in the superpotential. These are

$$\mathcal{W}_1 = \lambda_5 QQD + \lambda_6 u^c d^c D^c \tag{2}$$

and

$$\mathcal{W}_2 = \lambda_7 D^c Q L + \lambda_8 D u^c e^c + \lambda_8' D d^c \nu^c \tag{3}$$

where we have assumed that ν^c is the right handed neutrino. If all terms of (2), (3) are present in the superpotential, the related Yukawa couplings should be unnaturally small in order to prevent fast proton decay [6,7]. With a suitable discrete symmetry [6] it is possible to prevent one of $\mathcal{W}_1, \mathcal{W}_2$. It is clear therefore, that the experimental findings at H1 and ZEUS, provided that they are not swept out in future runs, suggest that we retain $\mathcal{W}_2$. In this case D, D^c carry both lepton and baryon quantum numbers (leptoquarks).

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 a pair of leptoquarks remaining massless down to the weak scale, in order that the idea of unification remains intact at some high scale (not necessarily the same as M_U), additional contibutions to the beta functions are needed to compensate for the leptoquark pair and yield a correct prediction for the weak mixing angle. In order to clarify this point let us assume that unification takes place at the scale M_U and assume in addition the existence of extra matter fields. Various kinds of exotic fields are present in unified theories, in particular in superstring derived models. In the present work however, we will assume only additional multiplets which carry quantum numbers like those of ordinary quarks and leptons. Thus, let us denote with n_D the number of the leptoquarks and $n_Q, n_{u^c}, n_\ell, n_{e^c}$ those of possible additional left and right handed type quarks, left leptons and right handed electrons respectively. For our purposes it is enough to consider only n_Q, n_{e^c}, n_D. Now, having in mind a unified model like flipped $SU(5)$ [8], the low energy measured quantities in terms of the extra matter fields and the scale M_U at the one-loop level, are [9]

$$\log \frac{M_U}{M_Z} = \frac{\pi}{10\alpha}\left(1 - \frac{8}{3}\frac{\alpha}{\alpha_3}\right) + \frac{1}{20\pi}(n_Q + n_D - n_{e^c}) \cdot \mathcal{L} \tag{4}$$

$$\sin^2\theta_W = \frac{1}{5} + \frac{7}{15}\frac{\alpha}{\alpha_3} + \frac{\alpha}{20\pi}(7n_Q - 3n_D - 2n_{e^c}) \cdot \mathcal{L} \tag{5}$$

where $n_r \cdot \mathcal{L} = \sum_I n_r^I \log(M_I/M_{I-1})$ takes into account the number of multiplets which remain massless at various possible intermediate scales M_I. It is clear from the formulae (4), (5) that if a leptoquark pair remains in the massless spectum this will alter both the unification scale and $\sin^2\theta_W$. Thus, for example, assuming $n_D = 2$, with no other extra multiplets ($n_Q = n_{e^c} = 0$), from Eq. (4) we find that $M_U \sim 7 \times 10^{17}$GeV. This is welcome as it is of the order of the string scale. However, in this simple case, the weak mixing angle form Eq. (5) does not have the right value ($\sin^2\theta_W(m_W) \sim 0.21$!). Thus, it is clear, that additional fields must coexist with the leptoquarks in order to cancel their contribution into the above equations and allow unification consistent with the correct value of $\sin^2\theta_W$. To pursue our argument further, let us consider two simple cases:

(i) The unification scale is the same as in the MSSM case, while the possible additional states remain massless also down to the elecroweak scale, or

(ii) we assume that the additional matter fields may receive a mass at some intermediate scale. We will see in this second case that a natural scenario implies a unification mass of the order of the String scale.

Table 1
The unification Scale and the mass of the vector quark multiplet for two values of α_3, and a leptoquark mass $m_D = 200$ GeV

α_3	$\sin^2\theta_W$	M_U (GeV)	M_I (GeV)	m_D (GeV)
0.110	0.2330	$4.9 \cdot 10^{17}$	$2.8 \cdot 10^8$	200
0.115	0.2317	$7.0 \cdot 10^{17}$	$3.3 \cdot 10^8$	200

Let us start with the analysis of case (i). Combining the above equations we may eliminate the scale M_U and express the deviation of the weak mixing angle from its MSSM value as follows:

$$\delta \sin^2\theta_W = \frac{7n_Q - 3n_D - 2n_{e^c}}{20 - n_Q - n_D + n_{e^c}} \tfrac{1}{10} \left(1 - \frac{8}{3}\frac{\alpha}{\alpha_3}\right) \quad (6)$$

From the fact that n_i are integers, it can be seen that $\delta \sin^2\theta_W$ can be within the accepted bounds only if the quantity $7n_Q - 3n_D - 2n_{e^c}$ is zero. For $n_D = 2$, this happens if $n_Q = 2, n_{e^c} = 4$. From Eq. (4) we also note that the scale M_U is the same as in the minimal case,

$$M_U = M_Z Exp\left(\frac{\pi}{10\alpha}\left\{1 - \frac{8}{3}\frac{\alpha}{\alpha_3}\right\}\right) \sim 10^{16}\ \text{GeV} \quad (7)$$

It is clear that the only contribution to the beta fuctions which has the potential to cancel the D, D^c effect comes from the vector like quark superfields $Q' + \bar{Q}'$ [9] as these are the only quantities entering with the opposite sign.

In the second possibility, case (ii), we may consider that the contribution of the leptoquarks in the beta function coefficients is compensated by new states which become massive at an intermediate scale. This scenario may be realised consistently if we assume for example that an equal number of left type quarks Q' and right handed electrons $e^{c'}$, i.e. $n_{e^c} = n_Q$, become massive at some intermediate scale M_I. We find that the mass scale M_I is

$$M_I \approx \left(\frac{m_D}{M_U}\right)^{\frac{3}{5}\frac{n_D}{n_Q}} M_U \quad (8)$$

For $n_Q = 2$, this gives $M_I \sim 10^8$ GeV. Table 1 shows the unification scale and the mass of the new states for two representative cases.

The terms in the superpotential of Eq. (3) lead to some very interesting phenomenology a major part of which has been explored in a previous paper [7]. Here we will review the essential conclusions of that paper and extend it to cover recent developments. Thus, the first term of Eq. (3) leads to quark lepton fusion into a leptoquark which for left handed fermions takes the form:

$$\mathcal{L}_{\text{eff}} = \lambda_7 D^c \bar{e} c_R u_L + \text{H.C.} \quad (9)$$

while for right handed fermions one obtains:

$$\mathcal{L}_{\text{eff}} = \lambda_8 D \bar{e} c_L u_R + \text{H.C.} \quad (10)$$

Both of them lead to $e^+\bar{u}$ and $e^- u$ fusion to a leptoquark. The first can occur via the sea antiquarks in the proton as we shall see below and is expected to proceed at a smaller rate compared to the second. For a proton target the electron beam is favored. Thus the leptoquarks generated from sea-antiquarks allow larger couplings than those generated in collisions with valence quarks.

Since the mass of the leptoquark has been constrained from the recent experiments we will attempt to constrain the flavor diagonal couplings λ_7 and λ_8. The ordinary β-decay leads to the bound [7]:

$$\lambda_7^2 \leqslant \sqrt{2} G_F m_{D^c}^2 \times 10^{-2}. \quad (11)$$

which for $m_{D^c} = 200$ GeV yields $\lambda_7 \leqslant 2.6 \times 10^{-2}$. The parameter λ_8 cannot be similarly constrained since now β-decay is the combined effort of λ_8, λ_8'. From the non-observation of β-decay involving right-handed currents one can set the following limit:

$$\lambda_8 \lambda_8' \leqslant \sqrt{2} G_F m_D^2 \times 10^{-2}. \quad (12)$$

If, however, we make the reasonable assumption that $\lambda_8 = \lambda_8'$ we obtain the same limit as above, namely $\lambda_8 \leqslant 2.6 \times 10^{-2}$. Additional constaints can be obtained from double beta decay once there is a coupling between $(\tilde{D}, \tilde{d})$ and/or $(\tilde{D}^c, \tilde{d}^c)$. This can arise out of the couplings λ_7 and λ_8' once the s-neutrinos acquire vacuum expectation values. Contrary to our previous work we will not assume here the mass of $\tilde{D}$ to be much larger than the mass of $\tilde{d}$. Thus the lepton violating parameter, since the gluino mediated process was found dominant [7], takes the form

$$\eta_{\tilde{D},\tilde{g}} = \frac{\pi \alpha_s m_p}{3 m_{\tilde{g}}} \left(\frac{\lambda_7 s_L c_L (m_{2L}^2 - m_{1L}^2)}{G_F m_{1L}^2 m_{2L}^2}\right)^2 \quad (13)$$

$$\eta_{\tilde{D}^c,\tilde{g}} = \frac{\pi \alpha_s m_p}{3 m_{\tilde{g}}} \left(\frac{\lambda_7 s_R c_R (m_{2R}^2 - m_{1R}^2)}{G_F m_{1R}^2 m_{2R}^2} \right)^2 \tag{14}$$

where m_{1L}, m_{2L} are the $\tilde{D}, \tilde{d}$ eigenstates and m_{1R}, m_{2R} are the $\tilde{D}^c, \tilde{d}^c$ eigenstates, $m_{\tilde{g}}$ is the gluino mass and:

$$s_{L,R} = \sin\theta_{L,R}\,, \quad c_{L,R} = \cos\theta_{L,R} \tag{15}$$

where $\theta_{L,R}$ is the corresponding mixing angle. Since the effective four quark interaction is not of the $V-A$ type but of the S, P, T variety, there are ambiguities in going from the quark to the nucleon level [11]. Therefore, large ambiguities are expected in extracting limits from the non-observation of $\beta\beta_{0\nu}$-decay. In the spirit of [11,7,12], using the most recent experimental data on ^{76}Ge [11] we obtain:

$$\eta_{\tilde{D}^c,\tilde{g}} \leqslant 4 \times 10^{-7} \tag{16}$$

with a similar limit on $\eta_{\tilde{D},\tilde{g}}$. The limit (16) can be converted to a limit on the Yukawa coupling once the scalar quark and gluino mass eigenstates are known. Using renormalisation group analysis, for $\tan\beta \sim 10$ we find $m_{\tilde{d}} \sim 276$ GeV and $m_{\tilde{g}} \sim 272$ GeV which turns to a limit $\lambda_7 \leqslant 0.3$–0.06, for mixings 0.1–0.7. A similar bound is obtained for other consistent choices of the scalar mass spectrum in the allowed parameter space. It turns out that $\beta\beta_{0\nu}$-decay in this case does not improve the ordinary β-decay bound obtained previously.

We come now to the calculation of the cross section [10] in the case of a theory with a leptoquark coupling. The cross section of a leptoquark production in the spin zero case is equal to:

$$\begin{aligned} \sigma &= \frac{\pi}{2s} \frac{\lambda^2}{2} f\left(\frac{m^2}{s}\right) \\ &= 0.31\,\text{pb} \left(\frac{\lambda}{0.01}\right)^2 f\left(\frac{m^2}{s}\right). \end{aligned} \tag{17}$$

Using the quark distributions of Ref. [14], one obtains the fusion cross sections as a function of m_D, s and the leptoquark coupling λ. Representative computations for λ values respecting the β and $\beta\beta$-decay limits are shown in Table 2.

Table 2
$\sigma(e^+\bar{u})$ and $\sigma(e^-u)$ for three cases of m_D = 100, 200 and 250 GeV, for the indicated values of the Yukawa coupling λ ($\lambda = \lambda_7$ or $\lambda = \lambda_8$)

	λ	m_D (GeV)		
		100	200	250
$\sigma(e^+\bar{u})$	0.01	0.27	1.6×10^{-2}	3.3×10^{-5}
	0.02	1.10	6.4×10^{-2}	1.3×10^{-4}
$\sigma(e^-u)$	0.01	1.78	1.6×10^{-1}	1.8×10^{-2}
	0.02	7.20	6.4×10^{-1}	7.2×10^{-2}

In conclusion, we have shown that the introduction of the leptoquark superfields D, D^c and its superpotential couplings of the term $\mathcal{W}_2$ in Eq. (3) introduced to explain the experimental data, does not lead to any inconsistencies with the unification of gauge couplings provided there are additional left quark vector-like multiplets which become massive at some intermediate scale. Furthermore, utilizing the existing constraints on the leptoquark couplings from exotic reactions, recent experimental findings of H1 and ZEUS can be adequately explained.

Note added. As this work was being prepared, we have also noticed several new papers dealing with the interpretation of the HERA events [15].

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