S, T, and Leptoquarks at HERA

E. Keith and Ernest Ma

Department of Physics
University of California
Riverside, California 92521

Abstract

If the recently discovered anomalous events at HERA are due to a scalar leptoquark, then it is very likely to have weak isospin $I = 1/2$. In that case, present precision measurements of the oblique radiative parameters $S$ and $T$ provide strong constraints on the mass of the other component of this doublet. If the standard model is extended to include such a doublet, a slightly better fit may in fact be obtained. However, in specific proposed models where this doublet comes from a larger symmetry, there are often additional large and positive contributions to $S$ from exotic heavy fermions which far exceed the present experimental limit. A way to improve the Tevatron exploration of leptoquarks is proposed.
Recently, two experiments at the HERA accelerator have observed some anomalous events in $e^+p$ scattering,[1, 2] which may be interpreted as due to a scalar leptoquark of mass about 200 GeV.[3] Assuming that a constituent quark of the proton is involved, then there are only four possibilities for this scalar leptoquark (call it $\eta$) according to what it is coupled to:

\begin{equation}
\begin{aligned}
(1) & \ e^+_L u_L, \\
(2) & \ e^+_L d_L, \\
(3) & \ e^+_R u_R, \\
(4) & \ e^+_R d_R.
\end{aligned}
\end{equation}

We find it more convenient to rewrite the last two cases in terms of their Hermitian conjugates:

\begin{equation}
\begin{aligned}
(3) & \ e^-_L \bar{u}_L, \\
(4) & \ e^-_L \bar{d}_L.
\end{aligned}
\end{equation}

It is thus obvious that $\eta$ has weak isospin $I = 1/2$ with $I_3 = 1/2, -1/2, -1/2, -1/2$ and weak hypercharge $Y = 7/6, 7/6, -7/6, -1/6$ respectively. The first two combine to form a doublet, whereas the last two have $I_3 = 1/2$ partners $\nu_L \bar{u}_L$ and $\nu_L \bar{d}_L$ respectively.

Let us assume that the standard $SU(3) \times SU(2) \times U(1)$ model of quarks and leptons is extended to include one such scalar leptoquark doublet. Its contribution to the oblique radiative parameters[4] $S$ and $T$ are easily calculated.[5] First, we have

$$
\Delta S = \frac{-Y}{2\pi} \log \frac{m_1^2}{m_2^2},
$$

where $m_{1,2}$ are the masses of the $I_3 = \pm 1/2$ components of $\eta$. Note that $\Delta S$ can be positive or negative, depending on $Y$ and $m_1^2/m_2^2$. This is in contrast to the well-known case of a fermion doublet in the standard model, because there the left-handed components form an $SU(2)$ doublet but the right-handed components are singlets, resulting in a positive value of $1/6\pi$ for each such doublet when $m_1 = m_2$. This fact is a very important constraint on models beyond the standard model and we will come back to it later.

Second, we have

$$
\Delta T = \frac{3}{16\pi} \frac{1}{s^2 c^2 M_Z^2} \left[ m_1^2 + m_2^2 - \frac{2m_1^2 m_2^2}{m_1^2 - m_2^2} \log \frac{m_1^2}{m_2^2} \right],
$$

2
where \( s^2 \equiv \sin^2 \theta_W \) and \( c^2 \equiv \cos^2 \theta_W \). As expected, \( \Delta T \) is necessarily nonnegative, and is zero only if \( m_1 = m_2 \). A recent analysis\[^{[3]}\] of all relevant experimental data obtained the following values for \( S \) and \( T \):

\[
S = -0.11 \pm 0.13 \quad -0.09 \quad +0.08, \quad T = -0.03 \pm 0.14 \quad +0.17 \quad -0.12, \tag{5}
\]

where \( m_t = 175 \text{ GeV} \), \( \alpha_S = 0.118 \), and the second set of uncertainties corresponds to the choice of the Higgs-boson mass: 1 TeV for the upper value, 300 GeV for the central value, and 100 GeV for the lower value. The standard-model contributions have been subtracted, so the above numbers represent how much new physics contributions are to be tolerated. Another recent analysis\[^{[7]}\] considers the parameters \( \epsilon_{1,2,3} \) with results consistent with the above.

The addition of a scalar doublet of leptoquarks to the standard model will in general shift \( S \) and \( T \). If the two components are degenerate in mass, the shifts do vanish in lowest order.\[^{[9]}\] This may well be the case with the HERA data. It means that for the \( Y = 7/6 \) interpretation, both components of the scalar leptoquark are produced, whereas for the \( Y = -7/6 \) or \(-1/6\) interpretation, there are also \( I_3 = 1/2 \) partners with the same mass (\textit{i.e.} 200 GeV) which decay into \( \nu_L \bar{u}_L \) and \( \nu_L \bar{d}_L \) respectively. Since all leptoquarks are also accessible at hadron colliders, these latter decay modes should also be searched for.

If the scalar leptoquark is not degenerate in mass, then \( \Delta T \) will be positive, but \( \Delta S \) can be either positive or negative. It is clear from the data that \( \Delta S < 0 \) is preferred. Now if we make the reasonable assumption that whereas the HERA leptoquark is 200 GeV in mass, its doublet partner ought to be heavier, then to obtain a negative \( \Delta S \), Case (2) should be chosen instead of Case (1). As for Cases (3) and (4), \( \Delta S < 0 \) implies that the missing partner should be lighter and decays into \( \nu_L \bar{u}_L \) and \( \nu_L \bar{d}_L \) as already mentioned. For Cases (2) and (3), it is in fact possible to have a slightly better fit to the data than with the standard model.
In Figure 1, we plot $\Delta T$ of Eq. (4) as a function of $m_1$, assuming $m_2 = 200$ GeV. Since this expression is symmetric with respect to the interchange of $m_1$ and $m_2$, it also applies to fixing $m_1$ at 200 GeV and varying $m_2$. The experimental upper limit on $T$ tells us that $|m_1 - m_2|$ cannot be too large. In Figure 2, we plot $\Delta S$ of Eq. (3) as a function of $m_1$, assuming $m_2 = 200$ GeV and $Y = 7/6$, i.e. Case (2). The experimental preference for a negative $S$ tells us that $m_1 > m_2$ is more likely in this case. Finally in Figures 3(a) and 3(b), we show the locus of points corresponding to Case (2) in the $S-T$ plane for $m_H = 100$ and 300 GeV respectively. In 3(a), the point on this curve closest to the center of the experimentally determined ellipse (defined by the sum of its distances to the two foci) corresponds to $m_1 \sim 200$ GeV, i.e. doublet degeneracy. The curve intersects the 90(99)% confidence-level (CL) ellipse at $m_1 \sim 140(120)$ GeV and 240(260) GeV. In 3(b), closest approach corresponds to $m_1 \sim 220$ GeV, and the limits on $m_1$ are 130(110) GeV and 270(280) GeV at the 90(99)% CL.

It is natural to expect $m_1 \neq m_2$ for the scalar leptoquark doublet $\eta \equiv (\eta_1, \eta_2)$ as shown below. The scalar potential here consists of the usual $\Phi \equiv (\phi^+, \phi^0)$ doublet of the standard model as well as $\eta$, i.e.

$$V = \mu^2 \Phi^\dagger \Phi + m^2 \eta^\dagger \eta + \frac{1}{2} \lambda_1 (\Phi^\dagger \Phi)^2 + \frac{1}{2} \lambda_2 (\eta^\dagger \eta)^2 + \lambda_3 (\eta^\dagger \eta)(\Phi^\dagger \Phi) + \lambda_4 (\eta^\dagger \Phi)(\Phi^\dagger \eta).$$

With $\langle \phi^0 \rangle = v$, it is easily obtained from the above that

$$m_1^2 = m^2 + \lambda_3 v^2, \quad m_2^2 = m^2 + (\lambda_3 + \lambda_4) v^2. \quad (7)$$

Hence $m_1^2 - m_2^2 = -\lambda_4 v^2$ and is in general nonzero and may be of either sign.

We are aware of two models which predicted scalar leptoquarks corresponding to one or more of the four cases being studied. One[10] is based on $SU(15)$ and essentially predicts all possible leptoquark combinations. If correct, many other scalar leptoquarks will be found, both in $e^+ p$ and $e^- p$ scattering. It also predicts dileptons and diquarks. The other[11] is
based on $SO(10) \times U(1)$ and predicts only one scalar leptoquark doublet corresponding to $Y = 7/6$. It also predicts a number of exotic particles, but none in the $e^-p$ channel. However, both models suffer from a large and positive contribution to $S$. In the former, because of the need for anomaly cancellation, there are three families of mirror fermions, hence $S$ receives a contribution of $2/\pi (= 0.64)$. In the latter, because the model is supersymmetric and there are two additional exotic families, the contribution is $4/3\pi (= 0.42)$. In the above, we have assumed doublet degeneracy so that $\Delta T = 0$. Relaxing that assumption only makes the disagreement with data worse.

A supersymmetric model based on $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ proposed recently\cite{12} assigns the HERA scalar leptoquarks to the representations $(3,2,2,4/3)$ and $(3^*,2,2,-4/3)$. Their fermion partners have gauge-invariant masses, hence they do not contribute to $S$. However, if these supermultiplets are embedded into a larger symmetry such as $SU(5) \times SU(5)$ proposed earlier\cite{13}, there will be in general positive contributions to $S$. For example, in the supermultiplets $(5,10) + (\bar{10},\bar{5})$, there are unpaired fermion multiplets $(6^*,2,1,1/3)$ and $(1,2,1,3)$ which would contribute $7/6\pi (= 0.37)$ to $S$.

The constraint of $S$ on unpaired fermion doublets is important in other models as well. For example, in a specific $SO(10) \times SO(10)$ model,\cite{14} there is an extra $(16,1)$ supermultiplet, hence $S$ receives a contribution of $2/3\pi (= 0.21)$. On the other hand, in supersymmetric $E_6$ models, the 27 representation is safe in this respect because it contains no additional unpaired doublet beyond those of the standard model.

If the HERA anomalous events are due to scalar leptoquarks, then they can be produced in proton-antiproton collisions at Fermilab. However, preliminary reports\cite{15} from the CDF and D0 experiments at the Tevatron indicate that they are excluded up to 210 and 225 GeV in mass respectively. Since such a leptoquark should be a member of a doublet and according to the constraints from $S$ and $T$, if one mass is 200 GeV, the other should be close to it,
both should be produced at the Tevatron. For example if $m_1 = m_2$, then both $\eta_1$ and $\eta_2$ should be produced, thereby doubling the putative cross section, resulting in an even more stringent bound on the leptoquark mass.

In conclusion, if a scalar leptoquark is responsible for the anomalous $e^+p$ events at HERA, then it is very likely to have weak isospin $I = 1/2$. The constraints from precision measurements at the $Z$ pole tells us that if one component of this doublet is at 200 GeV, the other cannot be too far away. This allows for a very stringent test of leptoquarks at the Tevatron. At present, assuming the production of a single scalar leptoquark, preliminary lower limits of 210 and 225 GeV are being reported by the CDF and D0 collaborations. If one assumes the production of two scalar leptoquarks, then a lower limit can be placed upon their masses in a two-dimensional plot. This can be done by assuming a fixed ratio of $m_1/m_2$ with $m_1 > m_2$, then determining the lower limit on $m_2$. If $m_1/m_2$ is large, the present bounds for the production of a single scalar leptoquark are recovered. In Cases (1) and (2), the decays of both components of the doublet are into $e^+ q$ (or $e^- \bar{q}$). In Cases (3) and (4), one component decays into $\bar{\nu} q$ (or $\nu \bar{q}$) which would involve large missing energy. Such an analysis will improve the present Tevatron bounds and may help to rule out (or confirm) the leptoquark hypothesis.

ACKNOWLEDGEMENT

We thank Paul Frampton, Seiji Matsumoto, and Peter Renton for correspondence. This work was supported in part by the U. S. Department of Energy under Grant No. DE-FG03-94ER40837.
References

[1] H1 Collaboration, C. Adloff et al., Z. Phys. C74, 191 (1997).

[2] ZEUS Collaboration, J. Breitweg et al., Z. Phys. C74, 207 (1977).

[3] Many theoretical papers have appeared since the HERA experimental announcements. For a short summary, see for example P. H. Frampton, hep-ph/9706220.

[4] M. E. Peskin and T. Takeuchi, Phys. Rev. Lett. 65, 964 (1990).

[5] See for example C. D. Froggatt, R. G. Moorhouse, and I. G. Knowles, Phys. Rev. D45, 2471 (1992).

[6] K. Hagiwara, D. Haidt, and S. Matsumoto, hep-ph/9706331.

[7] P. Renton, Oxford Univ. Report OUNP-97-01, Int. J. Mod. Phys. A, to be published.

[8] G. Altarelli, R. Barbieri, and S. Jadach, Nucl. Phys. B369, 3 (1992); B376, 444(E) (1992).

[9] J. L. Hewett and T. G. Rizzo, hep-ph/970337. See also J. K. Mizukoshi, O. J. P. Eboli, and M. C. Gonzalez-Garcia, Nucl. Phys. B443, 20 (1995).

[10] P. H. Frampton, Mod. Phys. Lett. A7, 559 (1992).

[11] V. Barger and E. Ma, Phys. Rev. D51, 1332 (1995).

[12] B. Dutta, R. N. Mohapatra, and S. Nandi, hep-ph/9704428.

[13] R. N. Mohapatra, Phys. Lett. B379, 115 (1996); Phys. Rev. D54, 5728 (1996).

[14] E. Ma, Phys. Rev. D51, 236 (1995).

[15] See for example Fermi News (June 20, 1997).
Figure Captions

Fig. 1. Contribution to $T$ from the scalar leptoquark doublet given by Eq. (4) as a function of $m_1$ for $m_2 = 200$ GeV.

Fig. 2. Contribution to $S$ from the scalar leptoquark doublet given by Eq. (3) as a function of $m_1$ for $m_2 = 200$ GeV and $Y = 7/6$, i.e. Case (2).

Fig. 3. (a): Parameteric plot of the Case (2) ($m_2 = 200$ GeV and $Y = 7/6$) $T$ and $S$ values of Fig. 1 and Fig. 2 for the range $100$ GeV $< m_1 < 300$ GeV together with the experimentally determined 90\% (inner) and the 99\% CL (outer) ellipses for $T$ and $S$ from new physics when it is assumed that $m_t = 175$ GeV and $m_H = 100$ GeV according to Ref. [6]. (b): Same as (a) but the ellipses correspond to $m_H = 300$ GeV.
Fig. 1

Fig. 2
Fig. 3