PHYSICAL REVIEW D VOLUME 37, NUMBER 1 1 JANUARY 1988

Production of leptoquark bosons in ultrahigh-energy neutrino interactions

R. W. Robinett

The Department of Physics, The Pennsylvania State University, University Park, Pennsylvania 16803

(Received 27 July 1987)

We consider the resonant production of leptoquark bosons, especially those present in superstring-inspired E_6 models, in neutrino-nucleon interactions with $E_\nu > 1$ TeV. Such interactions might be probed in proposed large underwater detectors such as DUMAND using atmospheric or astrophysical neutrinos. We also compare neutrino-induced production of leptoquark bosons to the *e-q* fusion process available at *ep* colliders such as DESY HERA.

Leptoquark bosons (LQ's), particles which carry both lepton and baryon number and which can mediate direct lepton-quark transitions, are commonly present in many extensions of the standard model. The Pati-Salam unification scheme[1] which contains an $SU(4)_C$ group factor, for example, has gauge bosons with leptoquark-boson couplings. Because these bosons can mediate rare flavor-changing decays with a gauge coupling of strong-interaction strength, their masses are constrained[2] to be greater than ≈ 100 TeV and so cannot be produced in any foreseeable accelerator. Other models, however, such as technicolor schemes,[3,4] certain composite models,[5] left-right-symmetric models,[6] and the strongly coupled version of the standard electroweak model,[7] all allow for the possibility of "light" (<1 TeV) leptoquark bosons which might be accessible to planned or proposed hadron, e^+e^-, or *ep* colliders. More recently, superstring-inspired models based on E_6 grand unification have been much discussed[8] and seem to require the existence of "light," exotic color-triplet particles which can, in some cases, have leptoquark-boson couplings. In these models, the gauge group is $SU(3)\times SU(2)\times U(1)\times U(1)$ (Ref. 9) and requires an additional Z boson which, however, does not concern us. The matter fields of each generation belong to the fundamental 27-dimensional representation of E_6 which has the SO(10) (SU(5)) reduction:

$$\begin{aligned}27 = 16[10(Q,u^c,l^c)+5^*(L,d^c)+1(N^c)]\\ +10[5(H^c,D)+5^*(H,D^c)]+1(n)\end{aligned} \tag{1}$$

which displays the left-handed fermion content. Each such field also has its supersymmetric partner as well. In this notation, Q and L are the usual left-handed quark and lepton doublets, H and H^c are new SU(2) doublets (whose scalar partners act as Higgs bosons), and we wish to concentrate on the isosinglet, $Q=-\frac{1}{3}$ color-triplet D and especially its superpartners $\tilde{D}_R, \tilde{D}_L$. The gauge couplings of the 27-plet fields are completely determined but the decays of the new, exotic particles in the **10** are governed by unknown Yukawa couplings. The terms in the superpotential allowed by E_6 invariance involving the D fields are[10]

$$W \supset \lambda_1 LQ\bar{D} + \lambda_2 e^c u^c D + \lambda_3 QQD + \lambda_4 u^c d^c \bar{D} + \lambda_5 D d^c \nu^c \tag{2}$$

and there are three mutually exclusive choices of D couplings and quantum-number assignments [$B(L)$ = baryon (lepton) number] which allow for nucleon stability. They are (A) $\lambda_1=\lambda_2=\lambda_3=\lambda_4=0$ and $B(D)=\frac{1}{3}$, $L(D)=0$ in which case D acts as a quark,[11] decaying via mixing with the usual *d*-type quarks with a phenomenology similar to that of older "topless" models,[12] (B) $\lambda_1=\lambda_2=\lambda_5=0$, $B(D)=-\frac{2}{3}$, $L(D)=0$ and D acts like a diquark,[13] and (C) $\lambda_3=\lambda_4=\lambda_5=0$, $B(D)=\frac{1}{3}$, $L(D)=1$ and D (and $\tilde{D}$) have leptoquark-boson couplings and it is this case which we will study. [In a standard grand unified theory, all of the Yukawa couplings in (2) would be related by Clebsch-Gordan coefficients of order unity and nucleon decay would be a severe problem but superstring-inspired models offer the possibility of topological zeros[14] or more familiar, if less attractive, discrete symmetries[15] which can allow for the patterns of couplings above and for a phenomenologically acceptable light D.]

In case C, the R parity of the color triplets is given by $R(D)=-1$, $R(\tilde{D}_R,\tilde{D}_L)=+1$ so that the $\tilde{D}_{L,R}$ are the true leptoquark bosons which couple directly to *l-q* pairs with interactions given by

$$-L = \lambda_1(\bar{\nu}^c d_L - \bar{l}^c u_L)\tilde{D}^*_R + \lambda_2(\bar{l} u^c_L)\tilde{D}_L + \text{H.c.} \tag{3}$$

and they can be produced singly in the interactions of "normal" matter unlike the fermions D, which must be pair produced. The D's couple to $\tilde{l}q, l\tilde{q}$ and so decay via $D \to lq\tilde{\chi}$ (where $\tilde{\chi}$ is the lightest neutralino, perhaps the photino $\tilde{\gamma}$), or $D \to \tilde{D}\tilde{\chi}$ (if kinematically allowed) and their possible production in accelerator experiments[16] has been discussed and we will not consider them further. The leptoquark-boson coupling in Eq. (3) is not specific to superstring models and is the most general $SU(3)\times SU(2)\times U(1)$-invariant interaction involving generations of scalar LQ's which conserves B and L so that our subsequent investigations will have applicability to a wider variety of models. It should also be noted that, in Eq. (3), generation indices are to be understood, i.e., $\lambda^{ijk} l_i u_j D_k$. In addition, the $\tilde{D}_L$ and $\tilde{D}_R$ will, in general, not be mass eigenstates in which case one should rewrite

(3) (for a one-generation model) in terms of $\phi_1 = \cos\theta\tilde{D}_R + \sin\theta\tilde{D}_L$, $\phi_2 = -\sin\theta\tilde{D}_R + \cos\theta\tilde{D}_L$ but we will ignore such mixing in what follows for simplicity.

Buchmüller and Wyler[17] and Campbell, Ellis, Gaillard, and Nanopoulos[18] have carefully analyzed the constraints that can be put on such SU(5) 5-plet leptoquark bosons by their possible contributions to familiar low-energy processes. For flavor-off-diagonal couplings, one typically has $\lambda < M(\mathrm{LQ})/100$ TeV but in theories where there is one leptoquark boson per generation, as in the E_6-motivated models we consider, flavor-diagonal couplings as large as gauge couplings are still allowed for light LQ's. Because of this, we will henceforth consider LQ-mediated interactions within a single generation only, i.e., consider the $(\nu_e d, eu)\tilde{D}_1$ and $(\nu_\mu s, \mu c)\tilde{D}_2$ couplings. Even for such flavor-diagonal couplings, one can still have strong constraints (for the first generation, at least) from helicity unsuppressed decays[17] such as $\pi^+ \to e^+\nu_e$ if the λ_1 and λ_2 terms couple to the same LQ, e.g., $(\lambda_1\lambda_2)^{1/2} < M(\mathrm{LQ})/10$ TeV. In our case, such decays can only occur if there is mixing between $\tilde{D}_L$ and $\tilde{D}_R$ and so can be naturally suppressed if such mixing is small. Thus, superstring-motivated leptoquark bosons naturally evade the most stringent low-energy constraints. That leaves constraints from quark-lepton universality in charged-current (CC) and neutral-current (NC) processes within a generation. For the first generation, constraints from β decay require[17] that $\lambda < M(\mathrm{LQ})/1.7$ TeV while constraints from precision atomic parity-violation experiments only provide the constraint $\lambda < M(\mathrm{LQ})/550$ GeV (Ref. 19). For simplicity, we will use the bound $\lambda < M(\mathrm{LQ})/2$ TeV for first-generation LQ's. For the second generation, the process $\nu_\mu s \to \tilde{D}_2 \to \nu_\mu s/\mu^- c$ can contribute to muon-neutrino charged- and neutral-current interactions but such contributions are suppressed by the smallness of the s-quark distribution in the nucleon and we find the relatively weak limit $\lambda < M(\mathrm{LQ})/400$ GeV which we will use for the second-generation LQ.

Limits on LQ masses that are relatively independent of the unknown Yukawa couplings can be derived from production processes at higher energies mediated by their gauge interactions. Leptoquark bosons can be pair produced in e^+e^- collisions via their electromagnetic coupling and a DESY PETRA search[20] has placed a lower limit of ≈ 20 GeV on their mass. They might also be produced in Z^0 decays at the Stanford Linear Collider or CERN LEP (Ref. 21) but limits on their masses which are, in principle, derivable from $p\bar{p}$ collider data may well make such decays kinematically impossible. The spinless, color-triplet $\tilde{D}$ can be pair produced at hadron colliders via gluon fusion and then decay via $\tilde{D} \to q\nu$ which leads to a jet(s) plus missing energy signature which is exactly the same as for the production and subsequent decay of ordinary scalar quarks $(p\bar{p} \to \tilde{q}\,\tilde{q}, \tilde{q} \to q\tilde{\gamma})$. Thus, the analyses of UA1 monojet/dijet events[22] which can be used to bound $M(\tilde{q})$ could also be applied to leptoquark bosons to imply $M(\mathrm{LQ}) > 40-50$ GeV, but no detailed analyses along these lines have appeared. Limits from $p\bar{p} \to$jet-jet-l^+-l^- events would give similar or even more stringent limits and future hadron colliders (Fermilab Tevatron or the Superconducting Super Collider) would be able to extend the search even further. (The virtual effects of third-generation LQ's, whose Yukawa couplings are very poorly constrained, may still be quite sizable in the decays of t-quarkonium.[21])

Because of their direct quark-lepton coupling, the first-generation LQ could be produced resonantly in ep collisions via eq fusion and several groups[23] have analyzed the prospects for their discovery at DESY HERA and at hypothetical, higher-energy ep machines.[24] The resonant nature of the eq production mechanism can easily be made clear even at a fixed energy machine by the appropriate binning[23] of various kinematic variables. Another possible resonant production mechanism involving leptoquark bosons would be νq fusion in νN interactions as could be probed in ultrahigh-energy (UHE) neutrino interactions. Studies of such UHE νN reactions, initiated by atmospheric neutrinos or even ν's from astrophysical point sources, would be one of the major physics goals of the proposed large underwater detectors [such as DUMAND (Ref. 25) or perhaps an enhanced Kamiokande[26]] and it is this possibility that I wish to discuss in this paper.

The suggestion to search for resonant production of heavy particles in high-energy cosmic-ray (anti)neutrino interactions is not new. Glashow[27] suggested long ago the process $\bar{\nu}_e e^- \to W^-$ (where e is an atomic electron) as a possible W production mechanism and Wilczek[28] has recently updated this notion. This process requires $E_\nu = M_W^2/2m_e \approx 6.6 \times 10^6$ GeV neutrinos and is likely unobservable in any proposed detector because of the small neutrino flux at these energies. More recently, resonant production of scalar quarks[29,30] by the lightest supersymmetric particle (LSP, e.g., the photino $\tilde{\gamma}$, or scalar neutrino[31]), i.e., $\tilde{\gamma}q \to \tilde{q}$, due to a LSP flux produced by gluino production and decay in the atmosphere[29] or from some astrophysical point source[32] has been considered. In this case, the required LSP energy is (naively) given by $E(\mathrm{LSP}) = M(\tilde{q})^2/2m_q$ which can be much lower than that required for neutrino-induced W production since $m_q \approx 600m_e$ for a constituent-quark mass $m_q \approx 300$ MeV (see more below). Because the atmospheric (or astrophysical) flux of light, neutral, weakly interacting particles is often a steep function of energy [for example, $d\Phi(\nu)/dE \propto E^{-3.8}$ for atmospheric neutrinos (Ref. 33)] such a lower resonance energy can result in dramatically increased event rates (or, equivalently, much improved limits on particles with heavier masses or smaller couplings) than for processes requiring large resonant energies. Such supersymmetric processes, however, require light (< 8 GeV) gluinos and may be irrelevant due to accelerator bounds on the gluino mass,[34] but the idea of resonant production on nucleon targets is still a useful lesson. [Berezinskii,[35] in fact, has very briefly considered the production of leptoquark bosons in UHE neutrino interactions but did so for Pati-Salam-type vector-gauge-boson LQ's ($M > 10$ TeV) with universal gauge strength coupling, used somewhat older distribution functions, and did not discuss the resonant process we will find and so came to rather pessimistic conclusions.] Because the LQ's will have fewer decay channels open than W's and have smaller couplings,[28] they will be somewhat narrower and, therefore, perhaps, easier to produce.

We feel that there are several motivating factors that may make the UHE neutrino LQ production process complimentary to searches at HERA. (i) Direct production of leptoquark bosons at HERA ($\sqrt{s}=314$ GeV) will be possible up to near the kinematic limit[23] [i.e., $M(\mathrm{LQ})<300$ GeV] and indirect searches via virtual effects can be probed somewhat beyond, perhaps using asymmetries. Higher center-of-mass energies are always possible in cosmic-ray interactions (witness the fact that the pp total cross section has been measured at $\sqrt{s}=20$ TeV in this way[36]), albeit with reduced fluxes. To compete energetically with HERA requires incident neutrino energies of $E_\nu \approx 314^2/2$ GeV$=50$ TeV$=5\times10^{13}$ eV. (ii) While charged leptons couple to LQ's in both the λ_1 and λ_2 terms in Eq. (3), neutrinos couple to LQ's only via λ_1 and so probe a different combination of Yukawa couplings than ep collisions. Neutrino interactions, then, will produce only $\tilde{D}_R$. (iii) While there is a measurable flux of atmospheric electron neutrinos, at a given energy the flux is predominantly muon neutrinos [$\Phi(\nu_e)\approx10^{-2}\Phi(\nu_\mu)$, Ref. 33] because of the neutrino production processes at these energies (mostly π and K decay). This means that the process $\nu_\mu s\to\tilde{D}_2$, although suppressed by the strange-quark distribution in the nucleon, can produce second-generation LQ's as well as first-generation leptoquark bosons via $\nu_e d\to\tilde{D}_1$. HERA will only probe the first generation via $eu\to\tilde{D}_1$. Last, because the limits on $\tilde{D}_2$ couplings are much weaker than those for $\tilde{D}_1$, the prospects for discovery or much improved limits may be better using ν_μ interactions. Because there are no final design specifications for any of the proposed underwater detectors (size especially, but also e vs μ efficiency, etc.), we will not attempt to calculate detailed event rates but rather limit ourselves to the calculation of representative cross sections and draw some general conclusions about the relative merits of the two processes.

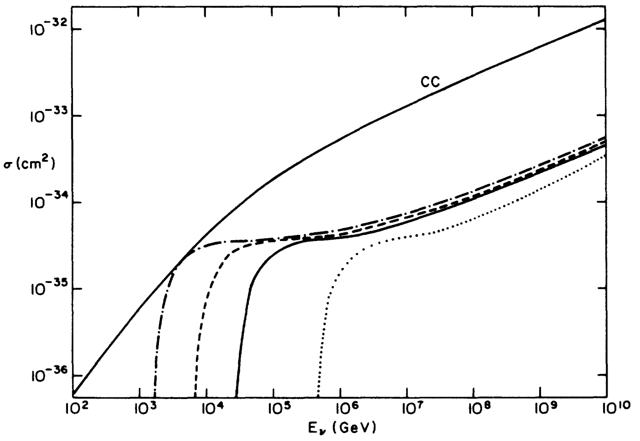

FIG. 1. The cross section for the reaction $\nu_e N\to e^-X$ for an isoscalar nucleon vs incident neutrino energy. The four lower curves represent contributions from the first-generation leptoquark-boson-mediated process for $M=50$ GeV, $\lambda=0.025$ (dash-dotted line), $M=100$ GeV, $\lambda=0.05$ (dashed line), $M=200$ GeV, $\lambda=0.1$ (solid line), and $M=800$ GeV, $\lambda=0.4$ (dotted line). The upper curve labeled CC is the standard W-mediated charged-current reaction as calculated in Ref. 38 for comparison.

Considering only $\tilde{D}_R$ and its decays into massless lq and νq pairs, we find the decay width $\Gamma(\tilde{D}_R)=\lambda^2M/8\pi$ (where $\lambda\equiv\lambda_1$) and using the narrow-width approximation for this s-channel process we find the partonic cross sections $\sigma(\hat{s}=xs)=\pi\lambda^2x\delta(x-M^2/s)/4M^2$ for $\nu q\to\nu q, lq'$ which gives the result for $\nu N\to\nu X, l^-X$,

$$\sigma(s)=\pi\lambda^2Q(x=M^2/s,Q^2=M^2)/4M^2\ , \tag{4}$$

where $Q(x,Q^2)=xq(x,Q^2)$ is the momentum-transfer-dependent probability of finding the desired quarks with momentum fraction x inside the nucleon. (We will always assume an isoscalar target.) Interference terms between LQ- and W,Z-mediated processes are negligible.

In Fig. 1 we plot this cross section for the charged-current-like reaction $\nu_eN\to e^-X$ for various M and λ consistent with our bound on first-generation LQ's [$\lambda<M/(2$ TeV$)$] where the distribution functions of Duke and Owens[37] (set I) are used and both valence and sea d-quark distributions contribute. Also plotted for comparison is the recently improved calculation of the standard neutrino charged-current process of Quigg, Reno, and Walker,[38] who use the distribution functions of Eichten, Hinchliffe, Lane, and Quigg[39] (EHLQ) for $x>10^{-4}$ and Gribov, Levin, and Ryskin[40] (GLR) for $x<10^{-4}$ (i.e., for $E_\nu>10^8$ GeV). Figure 2 shows the resonant nature of the $\tilde{D}_1$ production more clearly where the cross section increases dramatically from threshold to a (very wide) resonance peak and then levels off to an almost constant fraction of the standard cross section. For $\tilde{D}_1$ production in the mass range $M=50$–800 GeV, the resonance structure comes from neutrino fusion with valence d quarks with $x\approx0.2$ (instead of the naive $x=\frac{1}{3}$) and at larger energies (lower x) both mechanisms are dominated by the sea contribution and have a similar energy dependence. The distributions of Duke and Owens are known to be good representa-

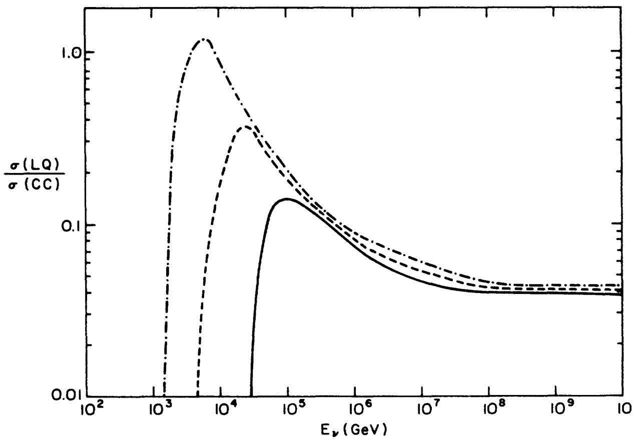

FIG. 2. The ratio of cross sections for the leptoquark-boson-mediated process to the standard charged-current reaction vs neutrino energy for the parameter choices in Fig. 1.

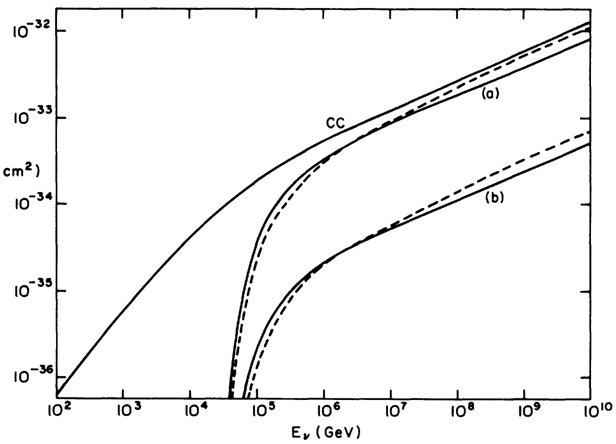

FIG. 3. The $\nu_\mu N \rightarrow \mu^- X$ cross section for second-generation LQ-mediated processes for (a) $M=200$ GeV, $\lambda=0.4$, (b) $M=200$ GeV, $\lambda=0.1$. In both cases the solid lines assume the Duke-Owens distribution functions (Ref. 37) while the dashed lines assume those of EHLQ/GLR (Refs. 39 and 40).

tions for $x > 10^{-3}$ and $Q^2 < (1\ \mathrm{TeV})^2$ and so are quite satisfactory for the resonance region of interest [$x \approx 0.2$ and $Q^2 = M^2 < (800\ \mathrm{GeV})^2$]. In Fig. 3 we plot the cross section for $\nu_\mu N \rightarrow \mu^- X$ induced by a second-generation $\tilde{D}_2$ via $\nu_\mu s \rightarrow \tilde{D}_2 \rightarrow \mu^- c$ and, in this case, the lack of any valence-quark distribution implies no resonance structure but the weaker limits on λ for this case mean that large changes in this process are still possible. The solid lines are those of the functions of Duke and Owens while the dashed lines are my calculations using EHLQ distribution functions supplemented by the double-logarithmic approximation of Ref. 40 for small x. As noted in Ref. 38, these improved distribution functions result in an increase in the predicted cross sections but not dramatically so in our application.

A few comments can now be made. (i) Because of the strong limits on $\tilde{D}_1$ couplings, only first-generation LQ's with masses up to ≈ 200 GeV will likely have observable effects in ν_e-induced reactions, a region which will be well explored by HERA. If such light leptoquark bosons are seen they will appear as a real, if broad, resonance in $\nu_e N \rightarrow e^- X$ at $E_\nu = 10^4 - 10^5$ GeV. (ii) As mentioned above, the weaker limits on $\tilde{D}_2$ couplings may well allow for interesting limits to be set on second-generation LQ masses and couplings using the ν_μ flux. In this case, there will be no resonance structure but a rapid rise above threshold to a value of the charged-current cross section consistently higher than expected. (There is a similar phenomenon in the case of neutrino interactions with a spectrum of excited W bosons or other new thresholds.[41]) (iii) In addition to contributing to the charged-current reaction $\nu_l N \rightarrow l^- X$, there will be an identical contribution to the neutral-current interactions, $\nu_l N \rightarrow \nu_l X$, which might also be used as a probe. The standard NC cross section is roughly $\frac{1}{3}$ smaller than the CC cross section (at low energies) so bigger *relative* effects are possible. (iv) More information on these reactions than just the total cross section may be available. The average value of y may be measured and will be changed by the s-channel nature of the νq fusion process. (v) Resonance reactions of muons via $\mu^- c \rightarrow \tilde{D}_2$ will not be a significant muon interaction mechanism because of the smallness of the nucleon charm-quark content. Other types of models[5,6] have $Q = \pm\frac{2}{3}$ leptoquark bosons which could couple to μs but these reactions would still have no resonant structure and would be swamped by the muons electromagnetic interactions. In such models, the process $\nu_e u \rightarrow$ first-generation LQ would be possible and would have the same cross section for $\nu_e N \rightarrow e^- X$ as plotted in Figs. 1 and 2, at least for the isoscalar nucleon targets we consider. The reaction $\nu_\mu c \rightarrow$ second-generation LQ would then be negligible. (vi) If the produced leptoquark bosons decay predominantly into $D\tilde{\gamma}$ with $D \rightarrow lq\tilde{\gamma}$, one would still have an observable signal of leptons (e,μ) and hadronic energy, but with a very different kinematic structure. (vii) A comment on Yukawa couplings might be made here. From the current experimental lower bound on the top-quark mass, we can infer that its Yukawa coupling to the standard Higgs bosons must be larger than ≈ 0.13 while constraints from radiative corrections to neutral-current phenomena imply that its mass must be less than 180 GeV (Ref. 42) which implies a Yukawa coupling less than ≈ 1.0. So, while the LQ couplings may be much smaller than we have considered, the values discussed here are consistent with current data and perhaps not unreasonable in this light.

We have argued that UHE cosmic-ray neutrino interactions can indeed be complimentary to planned accelerator ep experiments, perhaps most importantly because of the possibility of setting improved limits on leptoquark bosons which couple chiefly to the second generation, whether or not in the context of superstring models. While violations of flavor universality are certainly testable using rare processes at low energies and in the decays of new particles produced via their gauge couplings[43] (in a flavor-independent way), we argue that interactions of UHE neutrinos with the strange-quark content of the nucleon provide a unique laboratory, the only direct collisions of second-generation particles at large center-of-mass energies where possible new interactions are not masked by strong or electromagnetic effects. Such collisions allow one to test for violations of flavor universality in the production process, as well as in decays. In this context, neutrino interactions at multi-TeV energies may prove to be the best laboratory for investigating other new types of physics, e.g., compositeness,[44] as well as for doing neutrino astronomy and astrophysics[45] and should be thoroughly explored.

Note added in proof. The UA1 Collaboration has recently presented limits on leptoquark-boson masses for the second-generation LQ which decays into μ+quark. They find $M(\mathrm{LQ}) > 33$ GeV (at 90% C.L.). See S. Geer, Proceedings of the International Europhysics Conference on High Energy Physics, Uppsala, Sweden, 1987 (unpublished). See also Report No. CERN-EP/87-163 (unpublished).

This work was supported, in part, by the National Science Foundation under Grant No. PHY-8620118.

[1] J. Pati and A. Salam, Phys. Rev. D **10**, 275 (1974).

[2] O. Shankar, Nucl. Phys. **B206**, 253 (1982); R. W. Robinett, Phys. Lett. **116B**, 144 (1982).

[3] For a review, see E. Farhi and L. Susskind, Phys. Rep. **74**, 277 (1981). For a recent phenomenological analysis, see E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, Phys. Rev. D **34**, 1547 (1986).

[4] Technicolor ideas have undergone something of a modest revival due, in part, to T. Appelquist, D. Karabali, and L. Wijewardhana, Phys. Rev. Lett. **57**, 957 (1986).

[5] See B. Schrempp and F. Schrempp, Phys. Lett. **153B**, 101 (1985), and references therein.

[6] R. Mohapatra, G. Segrè, and L. Wolfenstein, Phys. Lett. **145B**, 433 (1984).

[7] M. Claudson, E. Farhi, and R. L. Jaffe, Phys. Rev. D **34**, 873 (1986); R. L. Jaffe and S. Devyanin, *ibid.* **33**, 2615 (1986).

[8] M. Green, J. Schwarz, and E. Witten, *Superstring Theory* (Cambridge University Press, Cambridge, England, 1987).

[9] J. Ellis, K. Enqvist, D. Nanopoulos, and F. Zwirner, Mod. Phys. Lett. **A1**, 57 (1986); Nucl. Phys. **B276**, 14 (1986); D. London and J. L. Rosner, Phys. Rev. D **34**, 1530 (1986).

[10] See Ref. 9 and L. Ibañez and J. Mas, Nucl. Phys. **B286**, 107 (1987).

[11] J. L. Rosner, Comments Nucl. Part. Phys. **15**, 195 (1986); V. Barger, N. Deshpande, R. J. N. Phillips, and K. Whisnant, Phys. Rev. D **33**, 1908 (1986); R. W. Robinett, *ibid.* **33**, 1912 (1986).

[12] G. Kane and M. Peskin, Nucl. Phys. **B195**, 29 (1982).

[13] V. Angelopoulos, J. Ellis, H. Kowalski, D. Nanopoulos, N. Tracas, and F. Zwirner, Nucl. Phys. **B292**, 59 (1987).

[14] E. Witten, Nucl. Phys. **B258**, 75 (1985).

[15] See, e.g., A. Masiero, D. Nanopoulos, and A. Sanda, Phys. Rev. Lett. **58**, 1048 (1987); G. Branco and C. Qeng, *ibid.* **58**, 969 (1987); M. Drees and X. Tata, *ibid.* **59**, 528 (1987).

[16] See Ref. 13 and V. Barger, N. Deshpande, and J. Gunion, in *Proceedings of the 1986 Summer Study on the Design and Utilization of the SSC,* Snowmass, Colorado, 1986, edited by R. Donaldson and J. Marx (Division of Particles and Fields of the APS, New York, 1987).

[17] W. Buchmüller and D. Wyler, Phys. Lett. B **177**, 377 (1986).

[18] B. Campbell, J. Ellis, M. Gaillard, and D. Nanopoulos, Int. J. Mod. Phys. **A2**, 831 (1987).

[19] High-precision neutrino scattering data cannot be used to bound the first-generation LQ's because such data involve muon neutrinos almost exclusively. Data on ν_e-e scattering exist but are not very restrictive. Most theoretical analyses of neutral-current interactions, such as Ref. 42, assume universal neutrino couplings and care must be taken to extract limits on new interactions with flavor-violating couplings.

[20] CELLO Collaboration, H. Behrend *et al.*, Phys. Lett. B **178**, 452 (1986). The search described here is actually for leptoquark bosons with $Q=\frac{2}{3}$ (but with similar couplings) so that the bounds on $Q=-\frac{1}{3}$ LQ's would be somewhat, but not dramatically, weaker. See also JADE Collaboration, W. Bartel *et al.*, Z. Phys. C **36**, 15 (1987).

[21] R. W. Robinett, Phys. Rev. D **36**, 719 (1987).

[22] See, e.g., R. M. Barnett, H. Haber, and G. Kane, Nucl. Phys. **B267**, 625 (1986).

[23] J. Wudka, Phys. Lett. **167B**, 337 (1986); W. Buchmüller, R. Rückl, and D. Wyler, Phys. Lett. B **191**, 442 (1987); A. Dobudo, M. J. Nerrero, and C. Muñoz, *ibid.* **191**, 449 (1987); J. F. Gunion and E. Ma, *ibid.* **195**, 257 (1987).

[24] J. Bagger and M. Peskin, Phys. Rev. D **31**, 2211 (1985); **32**, 1260(E) (1985); R. J. Cashmore *et al.*, Phys. Rep. **122**, 275 (1985).

[25] See *DUMAND 80,* proceedings of the 1980 DUMAND Symposium, Honolulu, Hawaii, 1980, edited by V. J. Stenger (Hawaii DUMAND Center, Honolulu, Hawaii, 1981).

[26] M. Koshiba, 11th International Workshop on Weak Interactions, Santa Fe, New Mexico, 1987 (unpublished).

[27] S. Glashow, Phys. Rev. **118**, 316 (1960); J. Bahcall and S. Frautschi, *ibid.* **135**, 788B (1964); V. Berezinsky, D. Cline, and D. Schramm, Phys. Lett. **78B**, 635 (1978).

[28] F. Wilczek, Phys. Rev. Lett. **55**, 1252 (1985).

[29] R. W. Robinett, Phys. Rev. Lett. **55**, 469 (1985); Phys. Rev. D **33**, 1239 (1986); S. Midorikawa and S. Yoshimoto, Phys. Lett. B **171**, 226 (1986).

[30] R. Mohapatra, S. Nussinov, and J. Valle, Phys. Lett. **165B**, 417 (1985); A. Zee, *ibid.* **161B**, 141 (1985).

[31] R. Pascual, Z. Phys. C **32**, 401 (1986).

[32] V. J. Stenger, Nature (London) **317**, 411 (1985); G. Auriemma, L. Maiani, and S. Petrarca, Phys. Lett. **164B**, 179 (1985); V. S. Berezinsky, E. V. Bugaev, and E. Zaslavskya, Yad. Fiz. **43**, 938 (1986) [Sov. J. Nucl. Phys. **43**, 600 (1986)]; F. Halzen, K. Hikasa, and T. Stanev, Phys. Rev. D **34**, 2061 (1986).

[33] V. J. Stenger, in *DUMAND 80* (Ref. 25), p. 190; L. Volkova, Yad. Fiz. **31**, 1510 (1980) [Sov. J. Nucl. Phys. **31**, 784 (1980)].

[34] See, e.g., Ref. 22.

[35] V. S. Berezinskii, Yad. Fiz. **41**, 393 (1985) [Sov. J. Nucl. Phys. **41**, 251 (1985)].

[36] T. Hara *et al.*, Phys. Rev. Lett. **50**, 2058 (1983); R. M. Baltrosaitis *et al.*, *ibid.* **52**, 1380 (1984).

[37] D. Duke and J. Owens, Phys. Rev. D **30**, 49 (1984).

[38] C. Quigg, M. Reno, and T. Walker, Phys. Rev. Lett. **57**, 774 (1986). See also, D. McKay and J. Ralston, Phys. Lett. B **178**, 103 (1986).

[39] E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, Rev. Mod. Phys. **56**, 579 (1984).

[40] L. Gribov, E. Levin, and M. Ryskin, Phys. Rep. **100**, 1 (1983).

[41] R. W. Brown and F. Stecker, Phys. Rev. D **26**, 373 (1982).

[42] For a recent and comprehensive analysis pertaining to the weak neutral current, see U. Amaldi *et al.*, Phys. Rev. D **36**, 1385 (1987).

[43] V. Barger, N. Deshpande, and K. Hagiwara, Phys. Rev. D **36**, 3541 (1987).

[44] G. Domokos and S. Nussinov, Phys. Lett. B **187**, 372 (1987).

[45] T. K. Gaisser and T. Stanev, Phys. Rev. Lett. **54**, 2265 (1985); E. Kolb, M. Turner, and T. Walker, Phys. Rev. D **32**, 1145 (1985).