Contact Terms, Compositeness, and Atomic Parity Violation

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The most severe constraints on quark-lepton four-fermion contact interactions come from the agreement of atomic parity violation measurements with the standard model. In this Letter, I note that, for contact interactions which arise in theories of composite quarks and leptons, approximate global symmetries other than parity can eliminate the contribution of contact terms to atomic parity violation. The most stringent tests of compositeness therefore come from the high energy collider experiments at LEP II, HERA, and the Fermilab Tevatron. [S0031-9007(97)03304-8]

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Four-fermion contact terms between quarks and leptons may appear in a low energy effective theory from integrating out heavy bosons or from quark and lepton substructure. Such terms are constrained both by high precision, low energy experiments, such as measurements of atomic parity violation, as well as by results from high energy colliders. The two sources of constraints tend to be complementary since the high precision measurements tend to give much stronger constraints on the size of four-fermion interactions but are sensitive only to certain linear combinations of operators, typically only to combinations which violate symmetries of the relevant interactions. In contrast, high energy collider experiments can constrain arbitrary terms, whether or not they preserve any symmetries.

Recently, there has been great interest in four-fermion contact interactions between quarks and leptons, as such terms might account for the reported excess of high Q^2 events in the HERA experiments [1–7]. The eight terms which could produce such an excess are usually written in the form

$$\Delta\mathcal{L} = \sum_{i,j=L,R;q=u,d} \frac{4\pi\eta_{ij}^q}{(\Lambda_{ij}^q)^2}\,\bar{e}_i\gamma_\mu e_i\bar{q}_j\gamma^\mu q_j\,, \qquad (1)$$

where $\eta_{ij}^q = \pm 1$.

It is just possible to find such terms which can account for the HERA excess while still satisfying the constraints deduced from studies of $e^+e^- \to$ hadrons [8] and $p\bar{p} \to e^+e^-X$ [9], for $\Lambda \sim 3$ TeV [3–5].

Stronger limits on such contact terms arise from atomic parity violation (APV) measurements [10–12]. A contact interaction apparently shifts the nuclear weak charge Q_W by an amount

$$\Delta Q_W = -2[\Delta C_{1u}(2Z+N) + \Delta C_{1d}(2N+Z)], \qquad (2)$$

where

$$\Delta C_{1q} = \frac{\sqrt{2}\,\pi}{G_F}\left(\frac{\eta_{RL}^q}{(\Lambda_{RL}^q)^2} - \frac{\eta_{LR}^q}{(\Lambda_{LR}^q)^2} + \frac{\eta_{RR}^q}{(\Lambda_{RR}^q)^2} - \frac{\eta_{LL}^q}{(\Lambda_{LL}^q)^2}\right). \qquad (3)$$

If no cancellations in Eq. (3) occur among the various terms, measurements of the weak charge of cesium [13] imply $\Lambda \gtrsim 10$ TeV. Thus the bounds from atomic parity violation on quark-lepton contact terms appear to be much stronger than those from any collider experiments. Several authors [4,5] have invoked a new parity conserving contact interaction in order to explain the HERA data while avoiding the APV constraint. They therefore assume that

$$\frac{\eta_{RL}^q}{(\Lambda_{RL}^q)^2} = \frac{\eta_{LR}^q}{(\Lambda_{LR}^q)^2}\,, \qquad \frac{\eta_{RR}^q}{(\Lambda_{RR}^q)^2} = \frac{\eta_{LL}^q}{(\Lambda_{LL}^q)^2}\,. \qquad (4)$$

The theoretical motivation for imposing the restrictions of Eq. (4) is unclear. An awkward feature of Eq. (4) is that $SU(2)_W$ gauge symmetry makes it necessary to introduce a right handed neutrino in order to have parity invariant and gauge invariant contact terms involving leptons.

One interesting class of models which will lead to contact terms at low energies are theories of composite quarks and leptons. In such theories there are new strong confining dynamics at a scale Λ. Unbroken approximate chiral global symmetries of the strong dynamics explain why the quark and lepton bound states are much lighter than Λ [14]. Any contact terms produced by the strong dynamics will respect its global symmetries. These chiral symmetries may be explicitly broken by small effects, e.g., by weak gauge interactions; however, small symmetry breaking terms do not affect the conclusions of this Letter.

It is an easy matter to find plausible approximate global symmetries, other than parity, which will ensure cancellations in Eq. (3) [15]. For instance, consider an approximate global SU(12) acting on all left handed first generation quark states. The left chiral fields,

$$(u_L, d_L, u_L^c, d_L^c)\,, \qquad (5)$$

transform as a 12-plet ψ_L. Note that approximate global $SU(N)$ symmetries are typical of strongly coupled gauge theories, arising whenever N matter fields carry the same strong gauge charges.

Assuming that the new strong dynamics respects such a symmetry, it could generate only an SU(12) singlet combination of the operators in Eq. (1), which can be written in the form

$$\begin{aligned}&\sum_{i=L,R} \frac{4\pi\eta_i}{(\Lambda_i)^2}\,\bar{e}_i\gamma_\mu e_i\bar{\psi}_L\gamma^\mu\psi_L \\ &= \sum_{i=L,R;q=u,d} \frac{4\pi\eta_i}{(\Lambda_i)^2}\,\bar{e}_i\gamma_\mu e_i(\bar{q}_L\gamma^\mu q_L - \bar{q}_R\gamma^\mu q_R)\,. \quad (6)\end{aligned}$$

Thus the SU(12) symmetry guarantees that

$$\frac{\eta_{iL}^q}{(\Lambda_{iL}^q)^2} = -\frac{\eta_{iR}^q}{(\Lambda_{iR}^q)^2}\,, \tag{7}$$

and so there is a cancellation in the contribution to Q_W.

The SU(12) symmetry still allows for a nonzero contribution to the parity violating weak coefficient C_{2q} [16]; however, the experimental constraints on this term are less severe. In any case, an SU(3) symmetry acting on all the left handed first generation leptons,

$$(\nu_L^e, e_L, e_L^c)\,, \tag{8}$$

would eliminate this contribution as well.

Much stronger constraints on contact terms can be obtained by considering flavor changing neutral current decays and muon number violation. However, such constraints can be satisfied by contact terms which respect a horizontal flavor symmetry, such as an $SU(2) \times SU(2)$, where one SU(2) acts on the first two quark generations and the other acts on the first two lepton generations. If the contact terms respect an $SU(12) \times SU(2) \times SU(2)$ symmetry, then contact terms between ν_μ and first generation quarks are required. Deep inelastic scattering experiments with ν_μ beams will then place slightly stronger constraints on Λ; $\Lambda \gtrsim 4$ TeV [3,17].

In summary, I have shown that composite models of quarks and leptons could naturally contain approximate global symmetries, other than parity, which would prevent four fermion contact terms from contributing to atomic parity violation. It would be interesting to reanalyze the effects of contact terms on physics at the various colliders, assuming the relations of Eq. (7) are satisfied. With SU(2) gauge invariance,

$$\frac{\eta_{iL}^u}{(\Lambda_{iL}^u)^2} = \frac{\eta_{iL}^d}{(\Lambda_{iL}^d)^2} \tag{9}$$

(neglecting quark CKM mixing) and so only two independent contact terms need to be considered.

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