

Relaxing Atomic Parity Violation Constraints on New Physics

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Abstract

The weak charge Q_W measured in atomic parity violation experiments can receive compensating contributions from more than one new physics source. We show explicitly that the ΔQ_W contribution from the exchange of an extra Z -boson can cancel that from the s -channel scalar top or scalar charm exchange in R -parity violating SUSY models proposed to explain the HERA high- Q^2 anomaly.

Parity violation in the Standard Model results from exchanges of weak gauge bosons. In electron-hadron neutral current (NC) processes parity violation is due to vector axial-vector (VA) and axial-vector vector (AV) interaction terms in the Lagrangian. These interactions are tested at the percent level at low momentum transfers ($Q^2 \approx 0$) by the latest atomic parity violation (APV) measurements [1] and at high momentum transfers ($Q^2 \gtrsim 2,500 \text{ GeV}^2$) by deep inelastic NC scattering at HERA. The recently published NC data from the H1 experiment [2] raise the possibility of a scalar resonance in $e^+q \rightarrow e^+q$ scattering with mass $M_{\bar{q}} \approx 200 \text{ GeV}$ [3].

Given the high precision of the APV measurements, parity violating new physics interpretations of the HERA high- Q^2 “anomaly” are fairly tightly constrained. A recent survey of the situation [4] concludes that in R -parity violating SUSY models an s -channel resonance interpretation of the H1 events is only marginally consistent with APV measurements. In this brief note we examine this issue and point out that richer models of new physics, which contain new particles beyond an eq resonance, can quite naturally relax the constraints from APV measurements. The two extra contributions that we consider are the exchange of an extra Z boson and the exchange of squarks in the crossed channel.

In low-momentum transfer NC processes, the Z boson exchange is well approximated by effective four-fermion contact terms. The parity violating part of the NC interaction Lagrangian is conventionally parametrized by constants C_{1q} and C_{2q} as

$$\mathcal{L}^{e\text{Hadron}} = \frac{G_F}{\sqrt{2}} \sum_q \left[C_{1q} (\bar{e}\gamma^\mu\gamma^5 e) (\bar{q}\gamma_\mu q) + C_{2q} (\bar{e}\gamma^\mu e) (\bar{q}\gamma_\mu\gamma^5 q) \right]. \quad (1)$$

APV experiments are mostly sensitive to C_{1q} , for which the radiatively corrected SM values are given by [5]

$$C_{1q}^{\text{SM}} = \rho'_{eq} \left[-T_{3q} + 2Q_q(\kappa'_{eq} \sin^2 \theta_w) \right], \quad (2)$$

where $\sin^2 \theta_w = 0.2236$, $\rho'_{eq} = 0.9884$, and $\kappa'_{eq} = 1.036$.

Atomic parity violation has been measured by several methods [6]. The most recent and precise experiment measures a parity-odd atomic transition in Cesium atoms [1]. The advantage of using the heavy Cs atom, with only a single valence electron, is the smallness of the theoretical uncertainty due to atomic wave-function effects.

APV experiments probe the weak charge Q_W that parametrizes the parity violating Hamiltonian [7]

$$\mathcal{H}_{\text{APV}} = \frac{G_F}{2\sqrt{2}} Q_W \rho_{\text{nucleus}}(\mathbf{r})\gamma_5. \quad (3)$$

In terms of the parameters C_{1u} and C_{1d} of the NC Lagrangian (1), the weak charge is given by [6]

$$Q_W = -2 \left[C_{1u}(2Z + N) + C_{1d}(Z + 2N) \right], \quad (4)$$

where Z and N are the number of protons and neutrons in the nucleus of the atom, respectively. For $^{133}_{55}\text{Cs}$, the relation of Q_W to the C_{1q} is

$$Q_W = -376C_{1u} - 422C_{1d} . \quad (5)$$

With the radiatively corrected C_{1q} of (2), the SM value of Q_W for Cs is [8]

$$Q_W^{\text{SM}} = -73.11 \pm 0.05 . \quad (6)$$

The recent precise measurement on Cesium atoms [1] finds

$$Q_W^{\text{exp}} = -72.11 \pm 0.27 \pm 0.89 , \quad (7)$$

where the first error is statistical and the second one is theoretical. This result is a substantial improvement from the value in the 1996 Particle Data Book [5] and shows better agreement with the SM than previously. The Q_W measurement places strong constraints on possible new physics contributions [9,10], ΔC_{1u} and ΔC_{1d} , that give

$$\Delta Q_W \equiv Q_W - Q_W^{\text{SM}} = -2 \left[\Delta C_{1u}(2Z + N) + \Delta C_{1d}(Z + 2N) \right] . \quad (8)$$

From (6) and (7) one obtains

$$\Delta Q_W = 1.00 \pm 0.93 , \quad (9)$$

where the stated uncertainty combines the statistical and theoretical errors in quadrature. The central value of ΔQ_W is about 1σ above zero.

SQUARKS WITH R -PARITY VIOLATING COUPLINGS

The H1 and ZEUS [2] experiments at HERA observed an excess of events above SM expectations at high momentum transfer squared ($Q^2 > 15,000 \text{ GeV}^2$). Although the excess is only at a 2σ statistical level, this potential anomaly has stimulated a large number of new physics interpretations that have focused mainly on an s -channel exchange of a squark in supersymmetry with R -parity violating couplings [3] and on contact interactions representing particle exchanges of mass-squared much larger than Q^2 [11]. A recent comprehensive fit [9] of all low and high energy data relevant to $eeqq$ contact interactions found that contact terms can improve the description of the HERA data. However, once the most recent Drell-Yan data [12] from the Tevatron are considered as well, contact terms do not improve the overall quality of the fit compared to the SM [9]. Thus, s -channel squark exchange remains the most attractive interpretation of the HERA events if the anomaly exists. The s -channel production of a squark of mass $M_{\tilde{q}} \approx 200 \text{ GeV}$ could account for the excess events in the $187.5 < M < 212.5 \text{ GeV}$ mass region seen by H1 (8 events observed, 1.5 events expected), but not by ZEUS (3 events observed, 3 events expected) [2].

The squark interpretation faces severe constraints from direct searches for first generation leptoquarks at the Tevatron [13,14] and from the APV measurement [1]. The CDF and D0 experiments rule out squarks of mass up to 213 and 225 GeV, respectively, at 95% CL, that decay with branching fraction $B = 100\%$ into eq . In order for a squark with $M_{\tilde{q}} \approx 200 \text{ GeV}$ to be consistent with the Tevatron limits, the branching fraction is bounded from above by [13,14]

$$B \lesssim 0.6 . \quad (10)$$

The APV measurement, on the other hand, puts a lower limit on B , which we will consider shortly.

The relevant term in the superpotential for the R -parity violating squark explanation of the HERA anomaly is $\lambda'_{ijk} L_i Q_j \overline{D}_k$. The corresponding terms in the Lagrangian are

$$\begin{aligned} \mathcal{L}_{L_i Q_j \overline{D}_k} = \lambda'_{ijk} \left[\tilde{e}_{iL} \overline{d_{kR}} u_{jL} + \tilde{u}_{jL} \overline{d_{kR}} e_{iL} + \tilde{d}_{kR}^* \overline{(e_{iL})^c} u_{jL} \right. \\ \left. - \tilde{\nu}_{iL} \overline{d_{kR}} d_{jL} - \tilde{d}_{jL} \overline{d_{kR}} \nu_{iL} - \tilde{d}_{kR}^* \overline{(\nu_{iL})^c} d_{jL} \right] + h.c. \end{aligned} \quad (11)$$

where i, j, k are the family indices, and c denotes the charge conjugate. The effective Lagrangians for the ed and eu scattering in the low-energy limit are

$$\mathcal{L}_{ed} = \frac{\lambda'_{ijk}{}^2}{M_{\tilde{u}_{jL}}^2} (\overline{e_{iL}} d_{kR}) (\overline{d_{kR}} e_{iL}) \quad (12)$$

$$\mathcal{L}_{eu} = \frac{\lambda'_{ijk}{}^2}{M_{\tilde{d}_{kR}}^2} (\overline{(e_{iL})^c} u_{jL}) (\overline{u_{jL}} (e_{iL})^c) . \quad (13)$$

By making a Fierz transformation these terms can be cast into a product of leptonic and hadronic vector- or axial-vector currents, as in (1). The resulting squark contributions to ΔC_{1q} are given by

$$\Delta C_{1d} = \frac{\sqrt{2}}{G_F} \left(\frac{\lambda'_{1j1}{}^2}{8M_{\tilde{u}_{jL}}^2} \right) , \quad \Delta C_{1u} = -\frac{\sqrt{2}}{G_F} \left(\frac{\lambda'_{11k}{}^2}{8M_{\tilde{d}_{kR}}^2} \right) . \quad (14)$$

which cause a shift in ΔQ_W of:*

$$\Delta Q_W = (2.4 \text{ TeV})^2 \left[\frac{\lambda'_{11k}{}^2}{M_{\tilde{d}_{kR}}^2} - 1.12 \frac{\lambda'_{1j1}{}^2}{M_{\tilde{u}_{jL}}^2} \right] . \quad (15)$$

In order to account for the observed rate of the anomalous HERA high- Q^2 events with $e^+d \rightarrow \tilde{t}_L/\tilde{c}_L$ production, the coupling must be [4]

$$\lambda'_{131} \text{ or } \lambda'_{121} \simeq \frac{0.03}{\sqrt{B}} \quad (16)$$

for which (15) gives

$$\Delta Q_W \approx -\frac{0.14}{B} . \quad (17)$$

*Note that ΔQ_W does not constrain $e^+s \rightarrow \tilde{t}_L$ production [4], which is another viable mechanism to explain the HERA anomaly.

At the 2σ level the APV measurement requires $\Delta Q_W > -0.87$ (implying λ'_{131} or $\lambda'_{121} < 0.074$ for $M_{\tilde{q}} \simeq 200$ GeV), bounding the eq branching fraction from below by

$$0.2 \lesssim B. \quad (18)$$

Combining the constraints in Eqs. (10) and (18), B is restricted to the range

$$0.2 \lesssim B \lesssim 0.6. \quad (19)$$

In Ref. [15] it was pointed out that most of the parameter space of the minimal supersymmetric standard model (MSSM), with universal masses at the unification scale, gives B of order 0.1. With $B \simeq 0.1$ the constraint from the APV measurement would be violated at the 3σ level. Since up- and down-type squarks contribute with opposite sign to ΔQ_W [see (15)], can the ΔQ_W conflict be resolved by a cancellation of the squark contributions?

The answer is yes, but marginally so. According to (11) a \tilde{d}_{kR} couples to both $e_L^- u_L$ and $\nu_L d_L$ and thus \tilde{d}_{kR} exchange contributes to CC observables. One finds that λ'_{111} is constrained to be less than 0.00035 from double-beta decay [16,17] (for a squark mass of 100 GeV) and thus is irrelevant to our considerations. The $\lambda'_{112,113}$ are constrained by charged-current universality to [17,18]

$$|\lambda'_{112,113}| < 0.02 \frac{M_{\tilde{d}_{kR}}}{100\text{GeV}}. \quad (20)$$

With (15) the maximal contribution of a \tilde{d}_{kR} to ΔQ_W is

$$\Delta Q_W \approx +0.23 \quad (21)$$

and may thus cancel the contribution from an up-type squark in (17), but only for large branching ratios B . Given the stringent constraint on the R -parity violating couplings in (20) it is unlikely that a \tilde{d}_{kR} would have been observed in direct production in e^-p collisions at HERA for which each of the HERA experiments has collected ~ 1 pb $^{-1}$ of data [19].

EXTRA Z MODELS

The Lagrangian describing the SM Z boson (Z_1^0) and an extra Z boson (Z_2^0) can be written as [20]

$$-\mathcal{L}_{Z_1^0 Z_2^0} = g_1 Z_{1\mu}^0 \sum_i \bar{\psi}_i \gamma^\mu (g_L^{i(1)} P_L + g_R^{i(1)} P_R) \psi_i + g_2 Z_{2\mu}^0 \sum_i \bar{\psi}_i \gamma^\mu (g_L^{i(2)} P_L + g_R^{i(2)} P_R) \psi_i, \quad (22)$$

where $P_{L/R} = (1 \mp \gamma_5)/2$, $g_1 = e/(\sin \theta_w \cos \theta_w)$, $g_L^{i(1)} = T_{3i} - \sin^2 \theta_w Q_i$ and $g_R^{i(1)} = -\sin^2 \theta_w Q_i$, $g_2/g_1 = \sqrt{5 \sin^2 \theta_w \lambda/3}$ and $\lambda \simeq 1$. In general, the SM Z boson and the extra Z boson will mix to form the physical mass eigenstates Z_1 and Z_2 ,

$$\begin{pmatrix} Z_1 \\ Z_2 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} Z_1^0 \\ Z_2^0 \end{pmatrix} \quad (23)$$

Here θ is the mixing angle, $M_{Z_1} = 91.1863$ GeV is the mass of the Z boson observed at LEP and SLC. For simplicity we neglect the mixing since it is constrained to be small by the LEP and SLC data at the Z pole [20]. In the zero mixing angle limit the Lagrangian in Eq. (22) describes the interactions of physical Z_1 and Z_2 bosons. The contributions from the extra Z boson to the coefficients C_{1q} and C_{2q} are

$$\Delta C_{1q} = 2 \left(\frac{M_{Z_1}}{M_{Z_2}} \right)^2 \left(\frac{g_2}{g_1} \right)^2 g_a^{e(2)} g_v^{q(2)}, \quad \Delta C_{2q} = 2 \left(\frac{M_{Z_1}}{M_{Z_2}} \right)^2 \left(\frac{g_2}{g_1} \right)^2 g_v^{e(2)} g_a^{q(2)}, \quad (24)$$

where $g_v = g_L + g_R$ and $g_a = g_L - g_R$. From these expressions we can calculate ΔQ_W in terms of the mass M_{Z_2} and the couplings $g_{L,R}^{f(2)}$ of the extra Z boson. Weakly-coupled extended gauge models, like E_6 , give the coupling constant g_2 on the order of the weak coupling constant $g_1 = e/\sin\theta_w$. We shall take $\lambda = 1$ for which $g_2/g_1 \simeq 0.62$.

COMPENSATING CONTRIBUTIONS TO ΔQ_W

A low energy supersymmetry and an extra Z boson with mass of order 1 TeV are both natural consequences of string theory [21]. Then with R -parity violating interactions both squark and Z_2 exchanges would contribute to ΔQ_W . Their combined effect on ΔQ_W is

$$\Delta Q_W = (2.4 \text{ TeV})^2 \left[\frac{\lambda'_{11k}}{M_{d_{kR}}^2} - 1.12 \frac{\lambda'_{1j1}}{M_{u_{jL}}^2} - 0.42 \frac{g_a^{e(2)}}{M_{Z_2}^2} \left(g_v^{u(2)} + 1.12 g_v^{d(2)} \right) \right]. \quad (25)$$

We can see that the Z_2 contribution can make the overall ΔQ_W positive. For example, for a 1 TeV Z_2 with $g_a^{e(2)} = -1 = -g_v^{u(2)}$ and $g_v^{d(2)} = 0$, the Z_2 contribution to ΔQ_W is +2.4. Then with $B(\tilde{t}_L \rightarrow e^+d) = 0.1$ in (17) the combined ΔQ_W contribution from \tilde{t}_L and Z_2 is $\Delta Q_W = +1.0$, which is the central value of the experimental measurement (9).

SUMMARY

We briefly summarize our main points.

(i) The deviation ΔQ_W of the cesium APV measurement from the SM is positive, but the deviation is only 1σ .

(ii) The ΔQ_W contribution of the scalar top or scalar charm via R -parity violating $\tilde{t}_L e^+ d$ or $\tilde{c}_L e^+ d$ couplings are negative.

(iii) The ΔQ_W contributions of the scalar bottom or scalar strange are positive, but they are likely too small to cancel the contribution from the scalar top or scalar charm because of the tight constraints on their couplings and masses.

(iv) Extra Z boson contributions to ΔQ_W can naturally be positive and sufficiently large to compensate negative contributions of scalar top or scalar charm and make the overall ΔQ_W positive.

(v) In particular, a scalar top interpretation of the HERA anomaly with the MSSM branching fraction of $B(\tilde{t}_L \rightarrow e^+d) \approx 0.1$ is not excluded, since positive extra Z contributions to ΔQ_W may compensate the negative contributions from the scalar top.

(vi) Our discussion applies similarly to leptoquark models for the HERA anomaly [22].

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