Atomic parity violation and the HERA anomaly

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Abstract

We show that the two scenarios able to explain the HERA anomaly — a new leptoquark coupling or a new contact interaction — predict new contributions to atomic parity violation. These corrections are sufficiently large and different that a feasible reduction in the dominant atomic theory uncertainty could give some hint in favour of one of the two scenarios.

1 The excess of events at large $Q^2$ observed at HERA could be due to new physics. In this case two different mechanisms can account for the HERA anomaly without contradicting present experimental bounds:

- an effective four-fermion interaction, related to a new physics scale or produced by an exchange of a particle in the $t$-channel;
- the resonant $s$-channel exchange of a particle with ‘leptoquark’ couplings, that would give a characteristic peaked distribution for the invariant mass of the final states.

The aim of this work is to show that the new physics would give a non negligible predictable extra contribution to atomic parity violation (APV) in both cases. This happens as follows.

In the first scenario, the new contact interaction does not contribute resonantly to the HERA process, and affects significantly other physical observables. In particular, the correction to APV is the most interesting one: if a single new operator should explain the HERA anomaly, the correction to APV would be $(10 \div 20)$ times larger than the present error on its determination. It is thus necessary to assume the existence of different contact operators which individually give a too large contribution to APV, but related in such a way that the total contribution cancels. Such cancellation, at tree-level, can be justified invoking appropriate global symmetries. As discussed in section 2, however, radiative corrections from the standard gauge interactions upset the cancellation giving a predictable correction to APV.
In the second scenario the leptoquark exchange gives a resonantly enhanced contribution to the HERA process and a contribution to APV \[Q_W\] that is not completely negligible, as discussed in section 3.

Before discussing these points in more detail, let us summarize the present determination of APV. The ‘weak charge’ \[Q_W\] that parametrizes the parity-violating effective Hamiltonian

\[
\mathcal{H}_{\text{APV}} = \frac{G_F}{2\sqrt{2}} Q_W \rho_{\text{nucleus}}(r) \gamma_5
\]

that dominates APV in cesium, is predicted by the SM (constrained by the LEP data) to be \[Q_{W|\text{SM}} = -73.17 \pm 0.13,\]

and has recently been measured to be \[Q_{W|\text{exp}} = -72.11 \pm (0.27)_{\text{exp}} \pm (0.89)_{\text{th}}.\]

The dominant theoretical error is due to uncertainty in the atomic wave function: even in the most favourable case of cesium this error is about 1%. A lengthy computation based on an expansion in the number of excited electrons can however reduce significantly this theoretical error, maybe down to the few per mille level \[\%.\] Furthermore, the accuracy of this computation can be tested comparing its results with some accurately measured properties of cesium, like the hyperfine constants and the energy levels \[\%.\]

The main result of this work, summarized in the conclusion, is that a reduction of the uncertainty on \[Q_W\] could reasonably give interesting indications about the nature of the (eventual) new physics suggested by the HERA data.

2 In this section we consider the case where the HERA anomaly is produced by contact interactions, present in combinations that, at tree level, do not contribute to APV. Even in this case, a contribution to APV arises because weak radiative corrections do not respect the cancellation between different contributions (or the symmetry at the basis of the cancellation). Since the contribution of each individual term is quite large, \[\Delta Q_W \sim (10^{-20})\] \[\%\], the radiatively generated effect\[\%\] that only depends on the operator structure

\[
\mathcal{L}^{\alpha A}\mathcal{L}^{\alpha B} = \frac{4\pi}{\Lambda_{\text{HERA}}^2} (e_R r_R u) \left\{ (\bar{q} \gamma^\mu q) + (\bar{u} \gamma^\mu u_R) - (\bar{d} \gamma^\mu d_R) \right\}
\]

in case “A”, and

\[
\mathcal{L}^{\beta A}\mathcal{L}^{\beta B} = \frac{4\pi}{\Lambda_{\text{HERA}}^2} \left\{ (\bar{e} r_R)^\mu (\bar{\nu} \gamma^\mu) (\bar{Q} \gamma^\mu) + (\bar{u} r_R)^\mu (\bar{\nu} \gamma^\mu) (\bar{u} R) \right\}
\]

in case “B”. Here \(Q, u_R, d_R, L, e_L\) are the standard notations for the SM matter fermions. The relative sign between the various operators is fixed to cancel the contributions to APV; the overall sign is fixed by the necessity of having a positive interference with the SM contribution to the HERA process \[\%\].

The structure of the operators, seemingly very artificial, can receive some partial theoretical justification. For example, the quark current in \[\%\] can be forced to be axial (so that the contribution to \[Q_W\] vanishes) imposing an SU(12) symmetry acting on the quark fields \[\%\]. Such a symmetry could naturally arise in composite models. However, considerations of this kind do not explain the suppression of other, possible but unwanted, contact interactions, for example involving leptons only.

The computation of the renormalization corrections to the various contact operators is lengthy but straightforward. The leading logarithmic correction to APV produced by SM gauge interactions in the two interesting cases “A” and “B” are:

\[
\Delta Q_W = \frac{4\pi}{\sqrt{2} G_F \Lambda_{\text{HERA}}} \left\{ C_{\text{e.m.}} \frac{\alpha_{\text{e.m.}}}{4\pi} \ln \frac{M_Z^2}{\Lambda_{\text{QCD}}^2} + C_V \frac{\alpha_Y}{4\pi} \ln \frac{\Lambda_{\text{HERA}}^2}{M_Z^2} \right\}
\]

(2)

where we have used standard notations for the various quantities, in particular \(\Lambda_{\text{QCD}} \approx 300\) GeV is the
Table 1: Correction to parity violation in atoms in the two scenarios “A” and “B” of contact interactions. The coefficients $C_i$ are defined by eq. (2). $Z$ is the atomic number and $N$ is the number of neutrons.

| correction to | contact operators “A” | contact operators “B” |
|---------------|------------------------|------------------------|
| $C_{e.m.}$    | $12Z$                  | $0$                    |
| $C_Y$         | $9Z + 3N$              | $\frac{1}{3}(2Z + 11N)$|
| $\Delta Q_W$ | $+0.72$                | $+0.15$                |

In low-energy soft mass term of light quarks, and the numerical coefficients $C_i$ are given in table 1. Their computation is simplified noticing that many diagrams give no contribution. Strong interactions cannot upset the cancellation. In our approximation, SU(2)$_L$ gauge interactions do not contribute due to gauge invariance and to the absence of operators involving both lepton and quark doublets. ‘Penguin’ diagrams can give a contribution only when mediated by the hypercharge gauge boson, and vanish in case “A” because the quark current is axial.

Assuming that $\Lambda_{\text{HERA}} = 3$ TeV $\text{[2,3]}$ so that the new interactions can account for HERA anomaly, the correction to the weak charge in cesium ($Z = 55$ and $N = 58$) is

$$\Delta Q_W|_{\text{“A”}} = +0.72, \quad \Delta Q_W|_{\text{“B”}} = +0.15. \quad (3)$$

In both cases “A” and “B” the contribution to the smaller spin-dependent APV effects remains below the uncertainty due to QCD effects.

The result (3) is not much different in supersymmetric models for the contact interactions. In these cases it is natural to assume that contact interactions arise as supersymmetric $D$-term operators, like the supergauge-invariant extension of $\int d\theta \bar{e}^i \tilde{e} \tilde{q}^i \tilde{q}$, where $\theta$ is the superspace parameter and $\bar{e}$ and $\tilde{q}$ are lepton and quark superfields. The computation of the full supersymmetric ‘supergauge’ corrections, i.e. the inclusion of gaugino-sfermion loops, can be conveniently done via superfield techniques (of course, the fact that now we employ the supersymmetric Feynman gauge does not affect the gauge-invariant correction to atomic parity violation). Assuming that the various squarks of first generation have a common mass $m_\tilde{q}$, the contribution to $Q_W$ in eq. (4) from operators “A” at energies between $\Lambda_{\text{HERA}}$ and $\Lambda_{\text{SUSY}} = \max(m_{\tilde{q}}, m_\tilde{e}, M_\tilde{B})$ has a modified coefficient $C_Y^{\text{SUSY}} = 6Z + 2N$, giving a slightly reduced contribution to $Q_W$. We have indicated with $m_\tilde{e}$ a generic selectron mass and with $M_\tilde{B}$ the bino mass. In case “B” there are contributions from supersymmetric penguins, so that two distinct supersymmetric masses, one for quarks and one for leptons, should be introduced. Assuming, for simplicity, that the two masses are equal, we find a value $C_Y^{\text{SUSY}} = 3N + Z$ almost numerically identical to the non supersymmetric case.

3 In the leptoquark scenario the correction to atomic parity violation is somewhat smaller than its present accuracy. Since this point has already been discussed in $\text{[3,4]}$, we will concentrate on a specific and motivated realization of this scenario, in which the APV effect turns out to be interesting. Supersymmetric theories furnish a theoretically more motivated realization of the leptoquark scenario that automatically offers ‘invisible’ channels for the leptoquark ($LQ$) decay, $B \equiv \text{B.R.}(LQ \to eq) < 1$ (as suggested by TeVATRON bounds $\text{[3]}$). More precisely, in the context of supersymmetry, introducing ‘$R$-parity violating’ supersymmetric interactions $\text{[13]}$, a squark $\tilde{Q}_3$ can have the ‘leptoquark’ interaction

$$\lambda_{131}^L \tilde{L}_1 \tilde{Q}_3 d_{R1} + \text{h.c.}$$

able of producing the HERA anomaly if a stop state is sufficiently light (here 131 are generation indices $\text{[3]}$). In supersymmetry a (mainly right-handed) stop state can naturally be lighter than the gluino and the other squarks. In this scenario the contribution to the APV parameter $Q_W$ is

$$\Delta Q_W = -\frac{|\lambda_{131}|^2(2N + Z)}{2\sqrt{2}G_F} \left[ \frac{\sin^2 \theta_l}{m_t^2} + \frac{\cos^2 \theta_l}{m_F^2} \right].$$

Here $\theta_l$ is the $\text{Left}/\text{Right}$ stop mixing angle ($\theta_l = 0$ for a purely right-handed lighter stop), $m_\tilde{t}$ is the mass of the lighter stop $\tilde{t}$ that gives rise to the HERA anomaly $\text{[3]}$.

Another possible operator “C” $\text{[2,3]}$ $(4\pi / A_{\text{HERA}}^2) (L\gamma^\mu L) \times (\bar{u}_R\gamma^\mu u_R - d_R\gamma^\mu d_R)$ is accompanied by a much larger effect $\Delta Q_W \approx -3$ (given by a tree level term, proportional to $N - Z$, plus a radiatively generated contribution).

A leptoquark of second generation, $\tilde{Q}_2$, or an interaction with a ‘sea’ quark, $s_R$, are less interesting, but not excluded, alternative possibilities $\text{[3]}$. 
Acknowledgments

and $m_{\tilde{T}}$ is the mass of the heavier stop $\tilde{T}$. Inserting the values suggested by the HERA data \[1\],

$$m_t \approx 200 \text{ GeV}, \quad |\lambda'_{131} \sin \theta_t| \approx \frac{0.04}{\sqrt{B}}$$ \[3\], \[4\],

the correction to the weak charge in Cesium is

$$\Delta Q_W = -\frac{0.26}{B} \left( 1 + \frac{1}{\tan^2 \theta_t} m_{\tilde{T}}^2 \right). \quad (4)$$

Naturalness considerations suggest that $|\theta_t| \lesssim 0.3$ (a light left-handed stop would also give a too large electroweak correction to $M_Z/M_W$) and $m_{\tilde{T}} \lesssim 500$ GeV \[4\], so that, including the contribution from the heavier stop, one finds a result $2 \div 3$ times larger than the ‘naive’ one.

In conclusion, the most appealing scenarios able of explaining the HERA anomaly predict the following non-SM contribution $\Delta Q_W$ to the weak charge $Q_W$ that gives the dominant parity-violating effect in Cesium:

contact operators

\begin{align*}
\text{“A” and “B” in (1)} & \quad \Delta Q_W |_{\text{“A”}} \approx + (0.6 \div 0.7) \\
\text{light stop with} & \quad \Delta Q_W |_{\text{“B”}} \approx +0.15 \\
\text{leptoquark couplings} & \quad \Delta Q_W |_{\text{stop}} \lesssim -0.6
\end{align*}

These results should be compared with

$$Q_W|_{\text{exp}} - Q_W|_{\text{SM}} = +1.06 \pm (0.30)_{\text{exp}} \pm (0.89)_{\text{th}}$$

As mentioned above, a lengthy but feasible and checkable atomic theory computation can reduce the dominant theoretical uncertainty below the experimental one \[3\]. In this case, depending on the new central value of $Q_W$ (for example if would remain unchanged), one could obtain some hint in favour of one of the possible scenarios.

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**References**

[1] C. Adloff et al., H1 collaboration, hep-ex/9702013

[2] V. Barger, K. Cheung, K. Hagiwara and D. Zeppenfeld, hep-ph/9703311; M.C. Gonzales and S.F. Novaes, hep-ph/9703416; N. di Bartolomeo and M. Fabbrichesi, hep-ph/9703375; N.G. Deshpande, B. Dutta and X.-G. He, hep-ph/9705257.

[3] G. Altarelli, J. Ellis, G.F. Giudice, S. Lola and M.L. Mangano, hep-ph/9703276; J. Kalinowski, R. Rückl, H. Spiesberger and P.M. Zerwas, hep-ph/9703288; T. Plehn, H. Spiesberger, M. Spira and P. M. Zerwas, hep-ph/9704333.

[4] D. Choudhury and S. Raychaudhuri, hep-ph/9703392; H. Dreiner and P. Morawitz, hep-ph/9703279; E. Perez, Y. Sirois and H. Dreiner, hep-ph/9703444; T. Kon and T. Kobayashi, hep-ph/9704224; R. Barbieri, Z. Berezhiani and A. Strumia, hep-ph/9704273; J. Ellis, S. Lola and K. Sridhar, hep-ph/9705410.

[5] J. Blümlein, hep-ph/9703287; K.S. Babu, C. Kolda, J. March-Russel and F. Wilczek, hep-ph/9703295; M. Dreess, hep-ph/9703332; J.L. Hewett and T.G. Rizzo, hep-ph/9703333; G.K. Leontaris and J.D. Vergados, hep-ph/9703338; Z. Kunst and W.J. Stirling, hep-ph/9704332; S.F. King and G.K. Leontaris, hep-ph/9704336; B. Dutta, R.N. Mohapatra and S. Nandi, hep-ph/9704428.

[6] A.E. Nelson, hep-ph/9703375; W. Buchmüller and D. Wyler, hep-ph/9704313.

[7] A. Deandrea, hep-ph/9705432.

[8] S. Blundell, J. Sapirstein and W. Johnson, Phys. Rev. D45 (1992) 1602; J. Sapirstein, in Atomic Physics 14, D. Wineland, C. Wieman and S. Smith ed.s (AIP Press, New York, 1995).

[9] Particle Data Group, Phys. Rev. D54 (1996) 1. The SM prediction of $Q_W$ reported here is slightly different from the PDG value and is based on an updated analysis by B. Marciano (B. Marciano, private communication).

[10] W.J. Marciano and J.L. Rosner, Phys. Rev. Lett. 65 (1990) 2963.

[11] C.S. Wood et al., Science 275 (1997) 1759.

[12] B. Marciano and A. Sanda, Phys. Rev. D17 (1978) 3055.

[13] G. Farrar and P. Fayet, Phys. Lett. B76 (1978) 575.

[14] A. Strumia, Phys. Lett. B397 (1997) 204.