Atomic Parity Violation, Leptoquarks, and Contact Interactions

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Abstract

The recent measurement of atomic parity violation in cesium atoms shows a 2.3\textsigma deviation from the standard model prediction. We show that such an effect can be explained by four-fermion contact interactions with specific chiralities or by scalar leptoquarks which couple to the left-handed quarks. For a coupling of electromagnetic strength, the leptoquark mass is inferred to be 1.1 to 1.3 TeV. We also show that these solutions are consistent with all other low-energy and high-energy neutral-current data.

1.

Parity violation in the standard model (SM) results from exchanges of weak gauge bosons. In electron-hadron neutral-current processes parity violation is due to the vector axial-vector interaction terms in the Lagrangian. These interactions have been tested to a high accuracy in atomic parity violation (APV) measurements. A very recent measurement in cesium (Cs) atoms has been reported \cite{1} by measuring a parity-odd transition between the \(6S\) and \(7S\) energy levels of the Cs atoms. The measurement is stated in terms of the weak charge \(Q_W\), which parameterizes the parity violating Hamiltonian.

The new measurement of the atomic parity violation in cesium atoms is \cite{1}

\begin{equation}
Q_W^{133\text{Cs}} = -72.06 \pm 0.28(\text{expt}) \pm 0.34(\text{theo}) .
\end{equation}

This result represents a substantial improvement over the previously reported value \cite{2}, because of a more precise calculation of the atomic wavefunctions \cite{3}. Compared to the standard model prediction \(Q_W^{\text{SM}} = -73.09 \pm 0.03\) \cite{4}, the deviation \(\Delta Q_W\) is

\begin{equation}
\Delta Q_W \equiv Q_W(\text{Cs}) - Q_W^{\text{SM}}(\text{Cs}) = 1.03 \pm 0.44 ,
\end{equation}

which is 2.3\textsigma away from the SM prediction.

In this Letter, we propose leptoquark solutions to this APV measurement and also solutions with four-fermion contact interactions. We find that the weak-isospin-doublet leptoquark \(S^R_{1/2}\), which couples to the right-handed electron and left-handed \(u\) and \(d\) quarks, and the weak-isospin-triplet leptoquark \(S^L_1\), which
couples to left-handed electron and left-handed u, d quarks, can explain the measurement with the coupling-to-mass ratio $\lambda/M \sim 0.29$ and 0.24 TeV$^{-1}$, respectively, where $\lambda$ is the coupling and $M$ is the leptoquark mass. For a coupling of electromagnetic strength the leptoquark masses are 1.1 to 1.3 TeV. We verify that these leptoquark explanations are comfortably consistent with all existing experimental constraints. We also find that contact interactions with $\eta_{RL}^{uu} = \eta_{RL}^{dd} = -0.043$ TeV$^{-2}$ and others can alternatively explain the APV measurement and are consistent with a global fit to data on $\ell\ell q\bar{q}$ interactions.

Another possible explanation for the APV measurement is extra $Z$ bosons [5], which can come from a number of grand-unified theories. Previous work on constraining new physics using the atomic parity violation measurements can be found in Ref. [6].

2.

The parity-violating part of the Lagrangian describing electron-nucleon scattering is given by

$$\mathcal{L}^{eq} = \frac{G_F}{\sqrt{2}} \sum_{q=u,d} \left\{ C_{1q}(\bar{e}\gamma^\mu\gamma^5 e)(\bar{q}\gamma_\mu q) + C_{2q}(\bar{e}\gamma_\mu e)(\bar{q}\gamma^\mu\gamma^5 q) \right\}$$

(3)

where in the SM the coefficients $C_{1q}$ and $C_{2q}$ at tree level are given by

$$C_{1q}^{SM} = -T_3^q + 2Q_q \sin^2 \theta_w,$$

$$C_{2q}^{SM} = -T_3^q (1 - 4 \sin^2 \theta_w).$$

Here $T_3^q$ is the third component of the isospin of the quark $q$ and $\theta_w$ is the weak mixing angle. In terms of the $C_{1q}$, the weak charge $Q_W$ for Cs is

$$Q_W^{Cs} = -\frac{376}{C_{1u}} - \frac{422}{C_{1d}}.$$  

(4)

A convenient form [7] for four-fermion $eeqq$ contact interactions is [8]

$$\mathcal{L}_\Lambda = \sum_{q=u,d} \left\{ \eta_{LL}^{eq} e L^\gamma_\mu e L^\gamma_\mu q L + \eta_{LR}^{eq} e L^\gamma_\mu e R^\gamma_\mu q R + \eta_{RL}^{eq} e R^\gamma_\mu e L^\gamma_\mu q L + \eta_{RR}^{eq} e R^\gamma_\mu e R^\gamma_\mu q R \right\},$$

(5)

where $\eta_{\alpha\beta} = 4\pi\epsilon/(\Lambda_{\alpha\beta}^{eq})^2$ and $\epsilon = \pm 1$. The contact interaction contributions to the $\Delta C_{1q}$’s are

$$\Delta C_{1q} = \frac{1}{2\sqrt{2}G_F} \left[ -\eta_{LL}^{eq} + \eta_{RR}^{eq} - \eta_{LR}^{eq} + \eta_{RL}^{eq} \right],$$

(6)

and the corresponding contributions to $\Delta Q_W$ are

$$\Delta Q_W = (-11.4 \text{ TeV}^2) \left[ -\eta_{LL}^{eq} + \eta_{RR}^{eq} - \eta_{LR}^{eq} + \eta_{RL}^{eq} \right] + (-12.8 \text{ TeV}^2) \left[ -\eta_{LL}^{ed} + \eta_{RR}^{ed} - \eta_{LR}^{ed} + \eta_{RL}^{ed} \right].$$

(7)

In order to explain the data in Eq. (2) using contact interactions, we can apply Eq. (7) with nonzero $\eta$’s. However, from Eq. (7) we see that there could be cancellations among the $\eta$-terms. When we assume one nonzero $\eta$ at a time, the values required to fit the APV data are tabulated in Table I. The value of $\Lambda$
Table 1: The values of $\eta_{\alpha\beta}^{eu,ed}$ required to fit the $\Delta Q_W$ data of Eq. (2). We assume one nonzero $\eta$ at a time.

| $\eta_{\alpha\beta}$ | fitted value (TeV$^{-2}$) | $\eta_{\alpha\beta}$ | fitted value (TeV$^{-2}$) |
|----------------------|---------------------------|----------------------|---------------------------|
| $\eta_{uL}^{eu}$     | 0.090                     | $\eta_{uL}^{ed}$     | 0.081                     |
| $\eta_{dR}^{ed}$     | $-0.090$                  | $\eta_{dR}^{ed}$     | $-0.081$                  |
| $\eta_{dR}^{ed}$     | 0.090                     | $\eta_{dL}^{ed}$     | 0.081                     |
| $\eta_{dL}^{ed}$     | $-0.090$                  | $\eta_{dR}^{ed}$     | $-0.081$                  |

corresponding to $\eta = 0.090(0.081)$ TeV$^{-2}$ is 11.8(12.5) TeV. If we further assume a SU(2)$_L$ symmetry, then $\eta_{uL}^{eu}$ equals $\eta_{dL}^{ed}$ and the value to fit the APV data is

$$\eta_{uL}^{eu} = \eta_{uL}^{ed} = -0.043 \text{ TeV}^{-2},$$

which corresponds to a $\Lambda \sim 17$ TeV. Equation (8) is relevant to one of the leptoquark solutions that we present in the next section.

The next question to ask is whether the above solutions are in conflict with other existing data. To answer this, we performed an analysis [7] of the neutral-current lepton-quark contact interactions using a global set of $\ell\ell qq$ data, which includes (i) the neutral-current (NC) deep-inelastic scattering at HERA, (ii) Drell-Yan production at the Tevatron, (iii) the hadronic production cross sections at LEPII, (iv) the parity violation measurements in $e$-(D, Be, C) scattering at SLAC, Mainz, and Bates, (v) the $\nu$-nucleon scattering measurements by CCFR and NuTeV, and (vi) the lepton-hadron universality of weak charged-currents. This is an update of the analysis in Ref. [7] with new data from LEPII, finalized and published data from H1 and ZEUS [3], and including DØ data on Drell-Yan production [10]. The 95% C.L. one-sided limits on $\eta$’s and the corresponding limits on $\Lambda$ are given in Table 2. In obtaining these limits, we do not include the data on atomic parity violation, which is the new physics data that we want to describe in this paper.

In Table 2, the most tightly constrained are $\eta_{uL}^{eu}$ and $\eta_{uL}^{ed}$, mainly due to the constraint of lepton-hadron universality of weak charged currents. In general, the constraints on $eu$ parameters are stronger than those on $ed$ parameters, because of Drell-Yan production, in which the $u\bar{u}$-initial-state channel is considerably more important than the $d\bar{d}$-initial-state channel. From Table 2 the 95% C.L. one-sided limits on $\eta_{RL}$ are 0.30 TeV$^{-2}$ and $-0.64$ TeV$^{-2}$ for $\epsilon = +$ and $\epsilon = -$, respectively. Thus, the fit to the APV data in Eq. (8) lies comfortably within the limits and so are the solutions with $\eta_{LR}$ and $\eta_{RR}$. On the other hand, the solution using $\eta_{LL}^{eu}$ is ruled out while the solution using $\eta_{LL}^{ed}$ is marginal.
The SU(2)\textsubscript{L} handedness of the lepton that the leptoquark couples to. The components of the isospin singlets with hypercharges $Y$, where the electric charge of the component fields is given in the parentheses, and the corresponding hyper-charges are $Y(S_{1/2}^L) = Y(S_{1/2}^R) = -7/3$ and $Y(S_{1/2}^L) = -1/3$. The $F = -2$ leptoquarks $S_L^0, S_R^0, S_0^R$ are isospin singlets with hypercharges $2/3, 2/3, 8/3$, respectively, while $S_1^L$ is a triplet with hypercharge $2/3$:

$$S_1^L = \begin{pmatrix} S_1^{L,(4/3)} \\ S_1^{L,(1/3)} \\ S_1^{L,(-2/3)} \end{pmatrix}.$$  

The SU(2)\textsubscript{L} × U(1)\textsubscript{Y} symmetry is assumed in the Lagrangians of Eqs. (9) and (10).

We have verified that the contributions of leptoquarks $S_{1/2}^L, S_{1/2}^L, S_0^R, S_0^R$, and $S_0^R$, that couple to the right-handed quarks, only give a negative $\Delta Q_W$, which cannot explain the measurement in Eq. (11). The only viable
choices are the leptoquarks $S_{1/2}^R$, $S_0^L$, and $\vec{S}_1^L$ that couple to the left-handed quarks. Let us first examine the contribution from the $F = 0$ leptoquark $S_{1/2}^R$. The effective interaction of electron-quark scattering via this leptoquark is

$$\mathcal{L} = -\frac{\lambda_{SR}^2}{M_{S_{1/2}^R}^2} (\bar{d}_L e_R e_R d_L + \bar{u}_L e_R e_R u_L) , \quad (13)$$

where we have assumed $M_{S_{1/2}^R}^2 \gg s, |t|, |u|$ and the overall negative sign is due to the ordering of the fermion fields relative to the $\gamma, Z$ diagrams. After a Fierz transformation, the above amplitude can be transformed to

$$\mathcal{L} = -\frac{\lambda_{SR}^2}{2M_{S_{1/2}^R}^2} \left( \bar{e}_R \gamma^\mu e_R d_L \gamma^\mu d_L + \bar{e}_R \gamma^\mu e_R u_L \gamma^\mu u_L \right) . \quad (14)$$

Comparing with the contact interaction terms, we can relate the above equation to $\eta_{RL}$ as

$$\eta_{RL}^{eu} = -\frac{\lambda_{SR}^2}{2M_{S_{1/2}^R}^2} . \quad (15)$$

Using the result on contact terms in Eq. (8) and the above equation, we obtain the value for $\lambda_{SR}/M_{S_{1/2}^R}$ to be

$$\frac{\lambda_{SR}}{M_{S_{1/2}^R}} = 0.29 \text{ TeV}^{-1} . \quad (16)$$

This result cannot specifically indicate the value for the mass or the coupling of the leptoquark, because the APV is a low-energy atomic process that only probes the $\lambda_{SR}/M_{S_{1/2}^R}$ ratio.

Similarly, the effective interaction of electron-quark scattering involving $S_0^L$ is

$$\mathcal{L} = \frac{g_3^2}{2M_{S_0^L}^2} \bar{e}_L \gamma^\mu e_L u_L \gamma^\mu u_L . \quad (17)$$

Therefore, the contribution from $S_0^L$, in terms of contact interaction, is

$$\eta_{LL}^{eu} = \frac{g_3^2}{2M_{S_0^L}^2} . \quad (18)$$

Matching with the results in Table 2, the coupling-to-mass ratio of the leptoquark is given by

$$\frac{g_3}{M_{S_0^L}} = 0.43 \text{ TeV}^{-1} . \quad (19)$$

However, this leptoquark $S_0^L$ contributes $\eta_{LL}^{eu} = 0.09 \text{ TeV}^{-2}$ and that is ruled out by the limit in Table 3.

The interaction of the $F = -2$ leptoquark $\vec{S}_1^L$ is given by

$$\mathcal{L} = g_{3L} \left\{ - \frac{u_L^{(c)}}{\bar{d}_L^{(c)}} e_L + \bar{u}_L^{(c)} \nu_L \right\} S_1^{L(1/3)} - \sqrt{2} \frac{u_L^{(c)}}{\bar{d}_L^{(c)}} e_L S_1^{L(2/3)} + \sqrt{2} \frac{u_L^{(c)}}{\bar{d}_L^{(c)}} \nu_L S_1^{L(-2/3)} + h.c. \right\} . \quad (20)$$

The effective interaction of electron-quark scattering involving $\vec{S}_1^L$ is

$$\mathcal{L} = \frac{g_{3L}^2}{2M_{S_1^L}^2} \bar{e}_L \gamma^\mu e_L u_L \gamma^\mu u_L + \frac{g_{3L}^2}{M_{S_1^L}^2} \bar{e}_L \gamma^\mu e_L \bar{d}_L \gamma^\mu d_L . \quad (21)$$

Therefore, the contributions from $\vec{S}_1^L$, in terms of contact interaction, are

$$\eta_{LL}^{eu} = \frac{\eta_{LL}^{ed}}{2} = \frac{g_{3L}^2}{2M_{S_1^L}^2} . \quad (22)$$
Fitting to $\Delta Q_W$ using Eq. (7), we obtain the coupling-to-mass ratio of $S_1^L$ to be

$$\frac{g_{3L}}{M_{S_1^L}} = 0.24 \text{ TeV}^{-1},$$

(23)

which gives $\eta_{eL}^u = 0.028 \text{ TeV}^{-2}$ and $\eta_{eL}^{cd} = 0.056 \text{ TeV}^{-2}$. We recalculate the limit from the global set of neutral-current $\ell\ell qq$ data for the case of nonzero $\eta_{eL}^u$ and $\eta_{eL}^{cd}$ with $\eta_{eL}^u = \eta_{eL}^{cd}/2$. We obtain the 95% C.L. one-sided limits on $\eta_{eL}^u = \eta_{eL}^{cd}/2$ as $0.11 \text{ TeV}^{-2}$ and $-0.04 \text{ TeV}^{-2}$ for $\epsilon = +$ and $\epsilon = -$, respectively (this result is listed in the last row of Table 2). Therefore, this leptoquark $S_1^L$ solution is also consistent with all other data.

As discussed above, there are two leptoquark solutions that are consistent with the limits in Table 2. The one with the $F = 0$ leptoquark $S_1^R/2$ requires the coupling-to-mass ratio equal $0.29 \text{ TeV}^{-1}$. With a coupling strength about the same as $e = 0.31$, the inferred leptoquark mass is about $1.1 \text{ TeV}$ for $S_1^R/2$. Similarly, the coupling-to-mass ratio for the $F = -2$ leptoquark $\bar{S}_1^L$ is required to be $0.24 \text{ TeV}^{-1}$, which corresponds to a mass of $1.3 \text{ TeV}$.

4.

In the following we discuss the above leptoquarks that describe the APV measurement in the context of the limits from various collider experiments.

The model-independent search for the first generation scalar leptoquark at the Tevatron by CDF and DØ puts a lower bound of $242 \text{ GeV}$ on the mass of the leptoquark [13]. The direct search for the first generation scalar leptoquark at HERA, on the other hand, depends on the coupling constants and the type of the leptoquark. ZEUS [14] excluded the first generation scalar leptoquark (fermion number $F = 0$) with electromagnetic coupling strength up to a mass of $280 \text{ GeV}$ while H1 [15] excluded a mass up to $275 \text{ GeV}$ in $e^+p$ collisions. In the most recent searches in $e^-p$ collisions, ZEUS excluded $F = -2$ scalar leptoquarks up to about $290 \text{ GeV}$ mass [14]. In general, $e^\pm p$ colliders can search for leptoquarks up to mass almost equal to the center-of-mass energy of the machine.

The LEP collaborations performed both direct searches for leptoquarks and indirect searches for virtual effects of leptoquarks in fermion-pair production. OPAL [16] searched for real leptoquarks in pair production and excluded scalar leptoquarks up to about $88 \text{ GeV}$; DELPHI [17] searched for leptoquarks in single production and excluded scalar leptoquarks up to about $161 \text{ GeV}$. Various LEP Collaborations [18] analyzed fermion-pair production and were able to rule out some leptoquark coupling and mass ranges, which depend sensitively on the leptoquark type and couplings. The best mass limit is around $300 \text{ GeV}$ for electromagnetic coupling strength. The virtual effects in fermion-pair production have already been included in our global analysis presented in Sec. 2. If we take $\lambda_R$ and $g_{3L}$ of electromagnetic strength, the leptoquark masses are inferred to be $1.1$ and $1.3 \text{ TeV}$, respectively, as already noted above. Therefore, the solutions in Eqs. (16) and (23) lie comfortably with both the direct search limits and the virtual effects in neutral-current $\ell\ell qq$
An important low-energy constraint to leptoquarks or contact interactions is lepton-hadron universality of weak charged-currents (CC), which we have already included in the global analysis in Sec. 2. Since it is particularly important to leptoquark interactions, we would like to explain it briefly. Because of the SU(2)\textsubscript{L} symmetry, the $\eta_{LL}^d$ and $\eta_{LL}^u$ are related to the CC contact interaction $\eta_{CC}^{-}\bar{\nu}_L\gamma_\mu e_L\bar{d}_L\gamma_\mu u_L$ by $\eta_{LL}^d - \eta_{LL}^u = \eta_{CC}$. Thus, the NC contact interactions and leptoquarks are subject to the constraint on $\eta_{CC}$. The leptoquarks that are constrained by this $\eta_{CC}$ are $S_0^L$ and $S_0^L$, which couple to the left-handed leptons and quarks. The CC contact interaction $\eta_{CC}^{-}\bar{\nu}_L\gamma_\mu e_L\bar{d}_L\gamma_\mu u_L$ could upset two important experimental constraints: (i) lepton-hadron universality in weak CC, and (ii) $e-\mu$ universality in pion decay, of which the former gives a stronger constraint. Using the values for the CKM matrix elements the constraint on $\eta_{CC}$ is $2\eta_{CC} = (0.102 \pm 0.073) \text{ TeV}^{-2}$ [7]. It is mainly because of this constraint that the leptoquark $S_0^L$ is ruled out while $S_1^L$ remains consistent in our global analysis.

Studies of a future scalar leptoquark search at the LHC [19] show that with a luminosity of 100 fb\(^{-1}\) the LHC can probe leptoquark mass up to 1.5 TeV in the pair production channel (which does not depend on the Yukawa coupling) and up to about 3 TeV (with the Yukawa coupling the same as $e$) in the single production channel. Thus, the leptoquarks in our solutions can be observed or ruled out at the LHC. On the other hand, Run II at the Tevatron can only probe leptoquarks up to a mass of 425 GeV [20].

Comments about the origin of these leptoquarks are in order.

(i) The $R$-parity violating (RPV) squarks, which arise from the supersymmetry framework without the $R$ parity, are special leptoquarks. The natural question to ask is whether the coexistence of $S_0^L$ and $\tilde{S}_{1/2}^L$ can help $S_0^L$ to evade the constraint of lepton-hadron universality of weak charged currents, and at the same time still gives a positive $\Delta Q_W$. In Sec. 3, we have shown that $S_0^L$ gives a positive $\Delta Q_W$ while $\tilde{S}_{1/2}^L$ gives a negative $\Delta Q_W$, so that their contributions to $\Delta Q_W$ cancel. In fitting to the $Q_W$ measurement, the coexistence of $S_0^L$ and $\tilde{S}_{1/2}^L$ would give a lower $S_0^L$ mass or a higher Yukawa coupling. However, $S_0^L$ induces $\eta_{CC}$ as it couples to both left-handed leptons and quarks, while $\tilde{S}_{1/2}^L$ does not because it couples to left-handed leptons and right-handed quarks. Therefore, the simultaneous existence of $S_0^L$ and $\tilde{S}_{1/2}^L$ would not help $S_0^L$ to evade the constraint from lepton-hadron universality of weak charged-currents.

(ii) The $F = -2$ leptoquark $S_0^L$ is one of the leptoquarks of $E_6$ [12]. The $F = 0$ leptoquark $S_{1/2}^L$ can be embedded [12] in the flipped SU(5) $\times U(1)_X$ model [31], in which the SM fermion content is extended by
right-handed neutrinos. The associated right-handed neutrinos could be used to generate the neutrino masses by the see-saw mechanism. The $S^R_{1/2}$ can be placed into $10 + \overline{10}$, which would also contain the $F = -2$ leptoquark $\tilde{S}^R_0$. The simultaneous existence of these two leptoquarks with similar masses and couplings would give cancelling contributions to $\Delta Q_W$. Thus, from the viewpoint of fitting to the $Q_W$ data, this is not favorable.

In summary, we have found leptoquark and contact interaction solutions to the atomic parity violation measurement, which stands at a 2.3σ deviation from the SM prediction. In addition, we have shown that these solutions are consistent with all other data.

Acknowledgments

This research was supported in part by the U.S. Department of Energy under Grants No. DE-FG03-91ER40674 and No. DE-FG02-95ER40896 and in part by the Davis Institute for High Energy Physics and the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.

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