Atomic parity violation in cesium and implications for new physics

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Abstract

Recent high-precision measurements of atomic parity-nonconserving transitions between the 6S and 7S states of cesium allow for a determination of the weak nuclear charge with a precision of 1.3%, providing an improved test of the standard model at low energy. Implications for new physics are examined in terms of low energy effects on the weak charge, in particular contact interactions and scalar leptoquark limits. Prospects for further improvements are described.
I. INTRODUCTION

Nuclei and electrons are bound by electromagnetic interactions that do not violate parity. However the exchange of a Z gauge boson between the nucleus and the atomic electrons is parity violating. The dominant contribution arises from the vector coupling to the nucleus with the axial-vector coupling to the electrons, which allows normally forbidden transitions. The nuclear vector current is conserved and the nucleus acts as a source of the weak charge $Q_W$, which is a linear combination of the Z vector coupling to up and down quarks:

$$Q_W = -2[C_{1u}(2Z + N) + C_{1d}(Z + 2N)]$$  \hspace{1cm} (1)

where $N$ is the number of neutrons, $Z$ the number of protons and

$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2\theta_W, \quad C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W,$$ \hspace{1cm} (2)

at tree-level. The tree-level formula for the weak charge is modified by radiative corrections \cite{1} and by physics beyond the standard model, thus a precise determination of $Q_W$ provides a test of these corrections and bounds on new physics, complementing the results of high energy colliders. Theoretically the structure of cesium is the most accurately known (1\%) \cite{2} among heavy atoms, as it is an alkali-metal atom and it can be described as a valence electron and a closed-shell tightly bound core which is relatively unpolarizable.

Recently a factor of 7 improvement in the measurement of parity-nonconserving transitions between the $6S$ and $7S$ states of $^{133}Cs$ was reported \cite{3} with the use of a spin polarized atomic beam. The nucleus has spin $I = 7/2$ and the total angular momentum of the atomic $S$ states is then 3 or 4. The experiment measures both $6S(F = 3) \rightarrow 7S(F = 4)$ and $6S(F = 4) \rightarrow 7S(F = 3)$ transitions. The two measured transitions differ because of nuclear spin-dependent effects. A linear combination of the two values eliminates nuclear spin-dependent contributions, allowing a precise determination of the weak charge. The result of \cite{3} is:

$$Q_W = -72.11 \pm 0.27 \pm 0.89$$ \hspace{1cm} (3)
where the first error is experimental and the second one is the consequence of atomic theory uncertainty. Contrary to previous data [1], the theoretical uncertainty dominates the error.

The other linear combination allows a determination of the spin-dependent effects, mainly due to the anapole moment [3]. However it involves strong interaction uncertainties and I will not discuss it in the following.

Assuming the validity of the standard model one can extract the Weinberg angle from $Q_W$, in order to have an idea of the constraints implied by the new cesium data. Using the formulae of [1,3] and the updated analysis of [7] concerning the hadronic vacuum polarization corrections to $\gamma Z$ mixing, in the $\overline{MS}$ scheme at the scale $m_Z$, and with a Higgs mass of 300 GeV, I find $\sin^2 \theta_W(m_Z)_{\overline{MS}} = 0.2267 \pm 0.0040$. In order to compare this result with LEP data one should calculate instead $\sin^2 \theta_{\text{eff}}$, which is the usually quoted value, but the difference is tiny [3], and one can safely neglect it in the following considerations. From the previous determination one can see that in $\sin^2 \theta_W(m_Z)_{\overline{MS}}$ the error is reduced by a factor of two with respect to previous determinations from cesium [10]. Now the error is dominated by the atomic physics theoretical accuracy [2,8], which may improve in the near future to few parts in $10^3$. The present error in the $\sin^2 \theta_W$ determination is an order of magnitude larger than the one quoted by LEP, $\sin^2 \theta_{\text{eff}} = 0.23200(27)$ [11], but cesium is likely to play a more significant role in tests of the standard model in the future. For example assuming the atomic theory error to go down to 0.2% and the experimental error to stay the same, the induced error in the determination of $\sin^2 \theta_W$ would be 0.0013.

II. CONTACT INTERACTIONS

Recently much interest was devoted to contact interactions and scalar leptoquarks as they might account for the excess of high $Q^2$ events at HERA [12] in $e^+p$ collisions. Atomic parity violation puts severe bounds on quark-lepton four-fermion contact interactions [13,14]. The relevant lagrangian is written in the form [15]:

$$3$$
\[ \mathcal{L}_{4f} = \sum_{i,j=L,R; q=u,d} \frac{4\pi \epsilon_{ij}^q}{(\Lambda_{qij}^q)^2} \bar{e}_i \gamma_\mu e_i \bar{q}_j \gamma^\mu q_j \]  

where \( \epsilon_{ij} = \pm 1 \). The contact interaction produces a shift of the weak charge:

\[
\delta Q_W = -(143 \text{TeV}^2) \left( \frac{\epsilon_{RL}^u}{\Lambda_{RL}^u} - \frac{\epsilon_{LL}^u}{\Lambda_{LL}^u} - \frac{\epsilon_{LR}^u}{\Lambda_{LR}^u} + \frac{\epsilon_{RR}^u}{\Lambda_{RR}^u} \right) 
\]

\[
- (160 \text{TeV}^2) \left( \frac{\epsilon_{RL}^d}{\Lambda_{RL}^d} - \frac{\epsilon_{LL}^d}{\Lambda_{LL}^d} - \frac{\epsilon_{LR}^d}{\Lambda_{LR}^d} + \frac{\epsilon_{RR}^d}{\Lambda_{RR}^d} \right) \]  

and using the experimental result for the weak charge \[8\] and the theoretical standard model value \(-72.88 \pm 0.06\) of \[10\], eq. (3) gives the limits of table I, which are larger than those coming from high-energy colliders (see for example \[16\] and recent bounds by CDF \[17\] and LEP 2 \[18\]). One should be careful, when comparing table I with the bounds reported in the literature, that the definition of \( \Lambda_{qij}^q \) may differ by a factor of \( \sqrt{4\pi} \). The limit coming from eq. (4) can however be eluded if the contact interactions are parity conserving or cancellations occur (see the discussion in \[19\]).

### III. SCALAR LEPTOQUARKS

Let us now consider the low energy effects of scalar leptoquarks that couple chirally and diagonally to the first generation. “Chiral” means that the leptoquark is coupled either to left-handed or to right-handed quarks but not to both, in order to avoid unacceptable deviations from lepton universality, for example in \( \pi \to e\nu \), while “diagonal” means that the leptoquark couples only to a single leptonic and quark generation (at least approximately as the CKM matrix induces mixing for left-coupled leptoquarks, and as a consequence flavour changing neutral currents).

I follow here the notation of \[20\], where previous cesium data was used to set bounds on the leptoquarks. From the general effective lagrangian satisfying baryon and lepton number conservation, with the most general dimensionless and \( SU(3)_c \times SU(2)_L \times U(1)_Y \) invariant couplings \[21\] one has scalar leptoquarks with the following quantum numbers with respect to \( SU(3)_c \times SU(2)_L \times U(1)_Y \): \( S(3^*, 1, 1/3), \bar{S}(3^*, 1, 4/3), T(3^*, 3, 1/3), D(3, 2, 7/6), \)
$\tilde{D}(3, 2, 1/6)$. $\tilde{S}$ and $\tilde{D}$ couple only to right-handed quarks, $T$ only to left-handed quarks, while $S$ and $D$ can couple to both.

In a class of supersymmetric theories it is natural to have $S_L$, $S_R$ of type $S$ and $D_L$, $D_R$ of type $D$ [22], where the subscripts $R$ and $L$ refer to the helicity of the quark coupled to the leptoquark. The requirement of having chiral couplings in the sense indicated before may therefore be fulfilled, if mixing between the left- and right-coupled leptoquarks is small.

In the following I shall be mainly interested in $D_L$, $D_R$ and $\tilde{D}$ leptoquarks, which are relevant in the discussion of the excess of high $Q^2$ events at HERA in $e^+p$ collisions. Their Yukawa interactions are given by

$$L = g_R(\bar{e}u_R D^{(-5/3)}_R + \bar{\nu}u_R D^{(-2/3)}_R) + g_D(\bar{e}d_R \tilde{D}^{(-2/3)} + \bar{\nu}d_R \tilde{D}^{(1/3)})$$

$$+ g_L(\bar{e}u_L D^{(-5/3)}_L + \bar{d}d_L D^{(-2/3)}_L) + c.c.$$ (6)

where for the $D_L$ I neglected second and third generation couplings, as the leptoquark is assumed to be diagonal to a good approximation. The superscript in parentheses in the previous formula refers to the leptoquark electromagnetic charge.

One can easily derive the effective low energy 4-fermion interaction due to leptoquark exchange and obtain the corresponding shift in the weak charge. In order to have a compact notation, it is useful to introduce the parameter $\eta_I$ which has the value 1 when the leptoquark $I$ is present and otherwise is zero. The contribution to $Q_W$ is:

$$\delta Q^{\eta_I}_W = -\frac{1}{2\sqrt{2}G_F} \left( \frac{g}{M} \right)^2 \left[ (-\eta_{S_L} + \eta_{S_R} - \eta_{D_L} + \eta_{D_R} - \eta_T)(2Z + N) + (\eta_{\tilde{S}} - \eta_{D_L} + \eta_{\tilde{D}} - 2\eta_T)(Z + 2N) \right]$$ (7)

where $G_F$ is the Fermi constant. Using the experimental result for the weak charge [3] and the theoretical standard model value $-72.88 \pm 0.06$ of [10], one obtains the limits of table II, in terms of the ratio leptoquark mass $M$ over coupling $g$.

Limits from other experimental data can further constrain the leptoquarks, depending on the nature of the leptoquark, for example flavour changing neutral current limits or universality in leptonic $\pi$ decay. Moreover note that the limits coming from eq.(7) are
valid when one assumes that there is only one leptoquark multiplet and that there is no mass splitting within the multiplet (for a detailed discussion see appendix B of [20]). The presence of more than one leptoquark multiplet can both improve or reduce the bound, as different leptoquarks may contribute to the weak charge with the same or opposite sign.

I will not analyse the implications of leptoquarks for the high-$Q^2$ HERA data in detail, as this is the subject of dedicated papers [23]. Note however that $D_{L,R}$ and $\bar{D}$ leptoquarks are produced in $e^+p$ collisions in the s-channel, whereas they contribute to $e^-p$ non-resonantly. If a mass of 200 GeV is assumed for the leptoquarks, a bound on the couplings can be derived,

$$g_{L,R} < 0.09 \quad g_{\bar{D}} < 0.08$$

at 95 % C.L. while the coupling required to explain the HERA anomaly is lower, of the order of 0.02 for a scalar leptoquark coupled to $u$ quarks (like $D_R$), and 0.04 if coupled to $d$ quarks (like $\bar{D}$) and thus within the permitted region.

Limits from cesium can be combined with direct leptoquark searches to perform a two parameter fit in the mass and coupling of the leptoquarks. In the following $\chi^2$ analyses a small number of events has to be compared with theory. I use them the method of least squares with a $\chi^2$ function for Poisson-distributed data, which asymptotically behaves like a classical $\chi^2$ [24]. The goodness-of-fit (confidence level) is evaluated approximatively as if data were Gaussian-distributed.

Leptoquark production at Tevatron is insensitive to the $g$ coupling (the only requirement is $g > 10^{-12}$ due to the event reconstruction algorithms used in the experimental analysis), but detection of the leptoquark decay products depends on the leptoquark branching fraction to $\ell q$ and $\nu q$. A recent analysis from the D0 collaboration was used in the fit [25]. The leading order parton production cross-section [26] was convoluted with parton distribution functions [27], at a scale $\mu = M$ (this choice of the scale at leading order is supported by the next-to-leading result of [28]), in order to produce the theoretical cross section at Tevatron. The result of the fit is shown in Fig.1, as a 95% C.L. bound on the mass and coupling of the $\bar{D}$
scalar leptoquark (limits for $D_L$ and $D_R$ are similar and are not shown). It is assumed that $\tilde{D}$ has 100% branching fraction to $eq$. Fig. 2 shows the same limits assuming 50% branching to $eq$ and 50% to $\nu_e q$.

Assuming that the excess of events seen at high-$Q^2$ in $e^+p$ collisions at HERA \cite{12} is due to the production of a scalar leptoquark, I calculated bounds in the plane $(M,g)$ using cesium data \cite{3} and the leading order parton cross-section for scalar leptoquark production \cite{21} with parton densities \cite{27}, taking into account initial state photon radiation from the positron. The combined integrated luminosity of 34.3 pb$^{-1}$ from H1 and ZEUS collaborations at $\sqrt{s} = 300$ GeV in the $e^+p \rightarrow eX$ mode was used, taking into account that the two experiments have seen 24 events with $Q^2 > 15000$ GeV$^2$, while the standard model expectation is $13.4 \pm 1$ events. Fig.3 refers to a $\tilde{D}$ leptoquark, while Fig.4 to a $D_R$ leptoquark. The limits for a $D_L$ leptoquark assuming that the members of the doublet are degenerate in mass, are similar to those of Fig.4 and are not shown. No information was given to the fit on the invariant mass distribution of the anomalous HERA events, in order to see if the preferred $(M,g)$ values were consistent with those required by the leptoquark interpretation of HERA anomalous events. They turn out to be consistent, however $\chi^2$ is small in a narrow band over a wide range of masses. Note that if the contour plot is performed using a too coarse-grained grid of points, this can be missed. One can at most say that for the $\tilde{D}$ leptoquark the preferred region is for $M \lesssim 220$ GeV, $g \lesssim 0.06$ (for a mass of 200 GeV the preferred value of $g$ is 0.034) and for the $D_R$ leptoquark $M \lesssim 250$ GeV, $g \lesssim 0.07$ (for a mass of 200 GeV the preferred value of $g$ is 0.017). The preferred region for the fit is obtained demanding $\chi^2 < 2$, note however that for low $\chi^2$ the Gaussian confidence-level estimate is not appropriate.

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REFERENCES

[1] W.Marciano and A.Sirlin, Phys. Rev. D29 (1984) 75; D31 (1985) 213 (Erratum).

[2] S.Blundell, J.Sapirstein and W.Johnson, Phys. Rev. D45 (1992) 1602.

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

[4] M.A.Bouchiat et al., J. Phys. (Paris) 47 (1986) 1709; M.Noecker, B.Masterson and C.Wieman, Phys. Rev. Lett. 61 (1988) 310.

[5] Ya.Zel’dovich, Sov. Phys. JETP 6 (1958) 1184 [Zh. Eksp. Teor. Fiz. 33 (1957) 1531].

[6] P.Langacker, in Precision Tests of the Standard Electroweak Model, P.Langacker ed., World Scientific (1995).

[7] F.Jegerlehner, in Testing the Standard Model, M.Cvetic and P.Langacker eds., World Scientific (1991).

[8] S.A.Blundell, J.Sapirstein and W.R.Johnson in [1], p.577.

[9] P.Gambino and A.Sirlin, Phys. Rev. D49 (1994) 1160; P.Gambino, Acta Phys. Polon. B27 (1996) 3671.

[10] Particle Data Group, Phys. Rev. D54 (1996) 1.

[11] G.Altaorelli, hep-ph/9611239, Lectures at the 3rd International Symposium on Radiative Corrections, Cracow, Poland, August 1996.

[12] C. Adloff et al., H1 collaboration, Z. Phys. C74 (1997) 191 [hep-ex/9702012]; J. Breitweg et al., ZEUS collaboration, Z. Phys. C74 (1997) 207 [hep-ex/9702013].

[13] P.Langacker, Phys. Lett. B256 (1991) 277.

[14] N.G.Deshpande, B.Dutta and Xiao-Gang He, hep-ph/9705230; N.Di Bartolomeo and M.Fabbrichesi, hep-ph/9703373.
[15] E.Eichten, K.Lane and M.Peskin, Phys. Rev. Lett. 50 (1983) 811; R.Rückl, Phys. Lett. B129 (1983) 363 and Nucl. Phys. B234 (1984) 91.

[16] P.Chiappetta and J.M.Virey, Phys. Lett. B389 (1996) 89.

[17] A.Bodek, CDF collaboration, FERMILAB-Conf-96/381-E.

[18] G.Alexander et al., OPAL collaboration, CERN-PPE/96-156.

[19] A.E.Nelson, Phys. Rev. Lett. 78 (1997) 4159 hep-ph/9703379; W.Buchmüller and D.Wyler, hep-ph/9704317.

[20] M.Leurer, Phys Rev. D49 (1994) 333.

[21] W.Buchmüller, R.Rückl and D.Wyler, Phys. Lett. B191 (1987) 442.

[22] W.Buchmüller and D.Wyler, Phys. Lett. B177 (1986) 377.

[23] See for example: K.S.Babu, C.Kolda, J.March-Russel and F.Wilczek, hep-ph/9703299; G.Altarelli et al., hep-ph/9703276; J.Kalinowski, R.Rückl, H.Spiesberger, and P.M.Zerwas, Z. Phys. C74 (1997) 595 hep-ph/9703288; V.Barger, K.Cheung, K.Hagivara and D.Zeppenfeld, hep-ph/9703311.

[24] S.Baker and R.Cousins, Nucl. Instr. and Meth. 221 (1984) 437.

[25] J.Hobbs for the D0 Collaboration, in XXXII Rencontres de Moriond, March 15-22, 1997. Previous limits on first generation leptoquarks at Tevatron can be found in: S.Abachi et al., Phys Rev. Lett. 72 (1994) 965; F.Abe et al., Phys. Rev. D48 (1993) 3939.

[26] J.Blümlein, E.Boos and A.Kryukov, hep-ph/9610408.

[27] A.D.Martin, R.G.Roberts and W.J.Stirling, Phys. Lett. B354 (1995) 155.

[28] M.Krämer, T.Plehn, M.Spira and P.M.Zerwas, hep-ph/9704322.

[29] S.Wolfram, The Mathematica Book, Wolfram Media and Cambridge University Press (1996).
TABLES

|       | $\epsilon^u = 1$ | $\epsilon^u = -1$ | $\epsilon^d = 1$ | $\epsilon^d = -1$ |
|-------|------------------|------------------|------------------|------------------|
| LL, LR | 7.4              | 11.7             | 7.9              | 12.3             |
| RR, RL | 11.7             | 7.4              | 12.3             | 7.9              |

TABLE I. 95% C.L. lower bounds from contact interactions on $\Lambda_{ij}^q$ in TeV units assuming only one of the $\epsilon_{ij}^q$ terms is responsible for the shift in the weak charge.

|       | $S_L$ | $S_R$ | $D_L$ | $D_R$ | $T$  | $\tilde{S}$ | $\tilde{D}$ |
|-------|-------|-------|-------|-------|------|-------------|-------------|
| $M/g$ | 1500  | 2300  | 2200  | 2300  | 2700 | 2500        | 2500        |

TABLE II. 95% C.L. lower bounds on scalar leptoquarks in GeV units for the ratio $M/g$. 
Fig. 1 - 95% C.L. limit in the mass $M$ (GeV) and coupling $g$ of a $\tilde{D}$ leptoquark from atomic parity violation in cesium [3] and the direct search at TEVATRON (data from the D0 collaboration [25]), assuming a branching ratio of the leptoquark to $ed$ equal to 100%. The allowed region in the parameter space is the grey area. Darker regions correspond to lower $\chi^2$ values.

Fig. 2 - 95% C.L. limit in the mass $M$ (GeV) and coupling $g$ of a $\tilde{D}$ leptoquark assuming a branching ratio of the leptoquark to $ed$ of 50% and to $\nu_ed$ of 50%.
Fig. 3 - 95% C.L. limit in the mass $M$ (GeV) and coupling $g$ of a $\tilde{D}$ leptoquark from the combination of cesium data and the cross-section excess at HERA.

Fig. 4 - 95% C.L. limit in the mass $M$ (GeV) and coupling $g$ of a $D_R$ leptoquark from the combination of cesium data and the cross-section excess at HERA.