Atomic parity violation and precision electroweak physics — An updated analysis

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A new analysis of parity violation in atomic cesium has led to an improved value of the weak charge, $Q_W(\mathrm{Cs}) = -72.06 \pm 0.46$. The implications of this result for constraining the Peskin-Takeuchi parameters S and T and for guiding searches for new Z bosons are discussed.

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One prediction of the unified theory of weak and electromagnetic interactions [1] is the existence of parity-violating effects in atoms. In the latest contribution [2] to this subject through the study of such effects in atomic cesium [3,4], the JILA-Boulder group has performed measurements that reduce uncertainties in previous theoretical calculations of atomic physics corrections [5]. While there is no substitute for carrying out such calculations to the requisite higher order in many-body perturbation theory, it is worth examining the implications of the resulting weak charge, $Q_W(\mathrm{Cs}) = -72.06 \pm 0.28_{\mathrm{expt}} \pm 0.34_{\mathrm{theor}} = -72.06 \pm 0.46$, which represents a considerable improvement with respect to previous values in this and other [6–9] atoms. The present paper updates previous analyses [10–14], with special emphasis on the role of the new measurement. We indicate the effect of fits to precision electroweak observables in which the new measurement is included or omitted, and discuss the possibility [10,15] that a small discrepancy of $Q_W(\mathrm{Cs})$ with respect to electroweak predictions is due to the exchange of a new neutral vector gauge boson Z'. The weak charges Q_W provide unique information in such fits [10,16,17].

Data and theoretical expectations are presented in Table I. The notation and formalism are the same as in Refs. [12] and [13]. As mentioned previously, we use a subset of the data in which the effects of correlations are minimized, but which have the dominant statistical weight. For fits to the complete data set, see, e.g., [27] or [28]. Some new features with respect to our previous fits include the following:

(1) We use a new, more precise value $\alpha^{-1}(M_Z) = 128.933 \pm 0.021$ [29].

(2) The nominal top quark mass is now taken to be 173.9 GeV/c^2; the nominal Higgs boson mass continues to be 300 GeV/c^2. This permits us to use the calculations of Ref. [14] for several quantities, including M_W, $\Gamma_{ll}(Z)$, and $\sin^2\theta_{\mathrm{eff}}$.

(3) The fits are performed both with and without the new Cs data [2], in order to estimate their impact.

(4) The precision of the world average value of M_W [20] has improved considerably as a result of new measurements from LEP II and the Fermilab Tevatron.

(5) We take account of a new measurement of the neutral-current to charged-current ratio in deep inelastic neutrino scattering [23]. We present the result of this measurement, as well as that of a previous one [22], in terms of an effective W mass corrected for our nominal values of m_t and m_H. This correction amounts to -0.02 GeV/c^2 for [23] and $+0.01$ GeV/c^2 for [22]. The S and T coefficients differ from those in M_W since NuTeV measures the Paschos-Wolfenstein [30] ratio $R_- \equiv [\sigma_{NC}(\nu N) - \sigma_{NC}(\bar{\nu} N)]/[\sigma_{CC}(\nu N) - \sigma_{CC}(\bar{\nu} N)]$, while CCFR measures essentially $R_\nu \equiv \sigma_{NC}(\nu N)/\sigma_{CC}(\nu N)$.

(6) The precision of the LEP I values for $\Gamma_{ll}(Z)$ and $\sin^2\theta_{\mathrm{eff}}$ [24], the SLD value of $\sin^2\theta_{\mathrm{eff}}$ [25], and the top quark mass measurement [26] continues to improve. In our analysis we have combined the values of $\sin^2\theta_{\mathrm{eff}}$ from LEP I and SLD, with a scale factor [31] of $\sqrt{\chi^2} = 2.77$, and added in quadrature an error in the predicted value of ± 0.00009 due to the error in $\alpha(M_Z)$, to obtain a value $\sin^2\theta_{\mathrm{eff}} = 0.23153 \pm 0.00048$ used as a single input to the fit. We include values of $\sin^2\theta_{\mathrm{eff}}$ obtained at LEP both with purely leptonic asymmetries and with the help of quark asymmetries such as A_{FB}^b, assuming them to be governed by the predictions of the standard model. The degree to which this fails to be true [25], for example as a result of non-standard b quark couplings to the Z, is an interesting possibility not considered here. The LEP values of $\sin^2\theta_{\mathrm{eff}}$ obtained from purely leptonic asymmetries do appear to be more consistent with the SLD value.

The results are shown in Figs. 1 and 2. In Fig. 1 we have

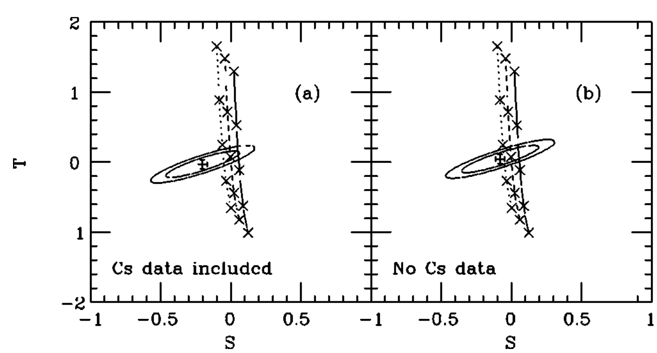

FIG. 1. Allowed ranges of S and T at 68% (inner ellipses) and 90% (outer ellipses) confidence levels, corresponding to $\chi^2 = 2.3$ and 4.6 above the minima (crosses at the center of ellipses). Dotted, dashed, and solid lines correspond to standard model predictions for $M_H = 100$, 300, and 1000 GeV/c^2. Symbols $\times$, from bottom to top, denote predictions for $m_t = 100$, 140, 180, 220, and 260 GeV/c^2. (a) Fit including APV experiments with present errors; (b) fit excluding new Cs measurement.

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TABLE I. Electroweak observables described in the fit.

Quantity	Experimental value	Theoretical value
Q_W (Cs)	-72.06 ± 0.46 [a]	-73.19 [b] $-0.80S-0.007T$
Q_W (Tl)	-115.0 ± 4.5 [c]	-116.8 [d] $-1.17S-0.06T$
$M_W(\mathrm{GeV}/c^2)$	80.394 ± 0.042 [e]	80.315 [f] $-0.29S+0.45T$
''M_W'' (GeV/c^2)	80.36 ± 0.21 [g]	80.315 [f] $-0.29S+0.52T$ [h]
''M_W'' (GeV/c^2)	80.24 ± 0.11 [i]	80.315 [f] $-0.54S+0.70T$ [h]
$\Gamma_{ll}(Z)$ (MeV)	83.958 ± 0.089 [j]	83.92 [f] $-0.18S+0.78T$
$\sin^2\theta_{\mathrm{eff}}$	0.23195 ± 0.00023 [j]	0.23200 [f] $+0.0036S-0.0026T$
$\sin^2\theta_{\mathrm{eff}}$	0.23099 ± 0.00026 [k]	0.23200 [f] $+0.0036S-0.0026T$
$m_t(\mathrm{GeV}/c^2)$	174.3 ± 5.1 [l]	$173.9+241S+82T$

[a]Weak charge in cesium [2] incorporating recalculated atomic physics corrections.
[b]Calculation [10] incorporating electroweak corrections, updated in [14].
[c]Weak charge in thallium [8,9] incorporating atomic physics corrections [18].
[d]Calculation incorporating electroweak corrections [19].
[e]Average of direct hadron collider and CERN e^+e^- collider LEP II measurements [20].
[f]Calculation by [14] based on results of the program ZFITTER 4.9 [21].
[g]CCFR value from deep inelastic neutrino scattering [22] for $m_t=173.9$ GeV/c^2 and $M_H=300$ GeV/c^2.
[h]Approximate dependence including residual corrections.
[i]NuTeV value from deep inelastic neutrino scattering [23] for $m_t=173.9$ GeV/c^2 and $M_H=300$ GeV/c^2.
[j]LEP average as of July 1999 [24,25].
[k]From left-right asymmetry and forward-backward left-right asymmetry at the SLC Large Detector (SLD) [25].
[l]See Ref. [26].

not imposed the constraint of the top quark mass, while in Fig. 2 this constraint has been included.

The central values S_0 and T_0 implied by each of the fits are summarized in Table II. We do not fit separately for the Peskin-Takeuchi parameter U, but set it equal to zero. A fit to similar data without the addition of the new Cs results finds [14] $S=-0.30\pm0.13$, $T=-0.14\pm0.15$, $U=0.15\pm0.21$.

In the absence of the m_t constraint (Fig. 1), the new Cs analysis leads to a small shift of the overall fit away from predictions of the standard electroweak theory for the minimum acceptable Higgs boson mass (roughly 95 GeV/c^2 [32]). The change in the central value of the parameter S is -0.12. In the presence of the m_t constraint (Fig. 2), the fit is affected only very slightly by the Cs result. The observed value of Q_W then differs from the predicted value by 2.4 standard deviations. Strictly speaking, we should have omitted the Tl results from the fits when omitting Cs. However, their impact is much smaller than that of Cs.

We now explore the implications of the small discrepancy between the observed and predicted values of Q_W(Cs) in terms of an extra Z, as suggested in Refs. [10] and [12]. Our results differ slightly from those of Ref. [15] as a consequence of a different standard-model prediction for Q_W.

We consider a Z' which is a linear combination of the Z_χ and Z_ψ [33], two neutral bosons which arise in E_6 theories: $Z'=Z_\psi\cos\phi+Z_\chi\sin\phi$. Here ϕ is the angle called θ in Ref. [34]. The Z_ψ is the gauge boson associated with the symmetry $\mathrm{U}(1)_\psi$ when E_6 breaks down to $\mathrm{SO}(10)\times\mathrm{U}(1)_\psi$; the Z_χ is the gauge boson associated with the symmetry $\mathrm{U}(1)_\chi$ when SO(10) breaks down to $\mathrm{SU}(5)\times\mathrm{U}(1)_\chi$. The change in Q_W at the tree level due to an unmixed Z' is then [12]

$$\Delta Q_{W\ \mathrm{tree}}^{\mathrm{new}}\simeq0.4(2N+Z)(M_W/M_{Z'})^2f(\phi),$$

TABLE II. Central values of S and T implied by fits to electroweak data, omitting new Cs data, m_t value, or both.

Data omitted	S_0	T_0	Predicted Q_W(Cs)
m_t	-0.20	-0.03	-73.03
m_t and Cs	-0.08	0.04	-73.13
None	-0.029	0.083	-73.17
Cs	-0.026	0.080	-73.17

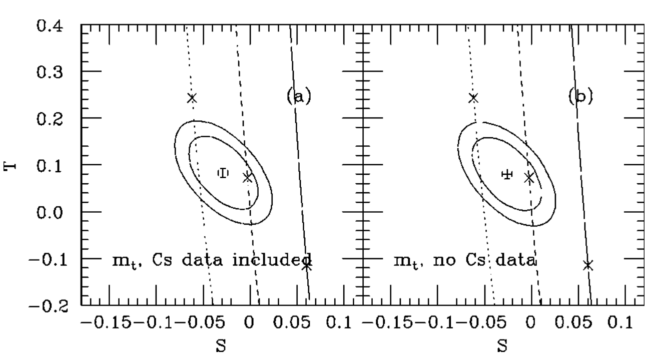

FIG. 2. Magnified view of Fig. 1. Dotted, dashed, and solid lines correspond to standard model predictions for $M_H=100$, 300, and 1000 GeV/c^2. Symbols $\times$ denote predictions for $m_t=180$ GeV/c^2 on each curve. The constraint $m_t=173.8\pm5$ GeV/c^2 has been imposed. (a) New Cs value [2] included; (b) new Cs value omitted.

$$f(\phi) \equiv \sin\phi[\sin\phi - (5/3)^{1/2}\cos\phi]. \qquad (1)$$

In order to fit the positive value of $\Delta Q_{W\ \mathrm{tree}}^{\mathrm{new}} = 1.10 \pm 0.46$, we need ϕ to lie between $\tan^{-1}(5/3)^{1/2} = 52.2°$ and 180°. The corresponding values of $M_{Z'}$ leading to such a contribution are shown for the central value and $\pm 1\sigma$ limits on Q_W by the curves in Fig. 3. Typical direct lower limits from the Collider Detector at Fermilab (CDF) Collaboration on masses of a Z' depend to some extent on ϕ, but lie around 600 GeV/c^2 [28,35]. At the 1σ level, one can thus account for the discrepancy between the observed and predicted values of Q_W(Cs) for values of ϕ between about 70° and 160°. This includes the values $\phi = 90°$ ($Z' = Z_\chi$) and $\phi = 127.8°$ [$Z' = Z_I$, where the subscript denotes an ''inert'' SU(2) subgroup of E_6 [33,36] in the decomposition $E_6 \to SU(6) \otimes SU(2)_I$].

To conclude, reanalysis of an atomic parity violation experiment in Cs [2] affects fits of electroweak parameters to a small but perceptible degree, when information on the top quark mass is not included. When this information is added, however, the fits are nearly independent of the Cs result, which differs from the standard model prediction by 2.4 standard deviations. This difference can be reproduced by the inclusion of a new Z', lying above present experimental limits of about 600 GeV/c^2 in mass, for a range of the parameter $70° \leqslant \phi \leqslant 160°$ characterizing the new boson. If it exists at a mass accessible to run II of the Fermilab Tevatron, this boson must be very weakly mixed with the standard Z in order to avoid a number of constraints associated with precision electroweak observables [28].

Despite the consistency of the new measurements in Cs with more precisely specified matrix elements [2], a calculation of atomic physics effects in Cs whose accuracy matches that of the experimental measurement is sorely needed. The last such calculations [5] need to be extended to higher order in many-body perturbation theory to confirm the optimism inherent in the small theoretical error quoted in Ref. [2]. An improved determination of the neutron charge radius in Cs also would be helpful, since the present uncertainty in this quantity may constitute an error at least as large as that ($\Delta Q_W \simeq 0.1$) associated with electroweak radiative corrections [37,38]. There is room for considerable improvement in the overall error in Q_W(Cs) if this program proves successful.

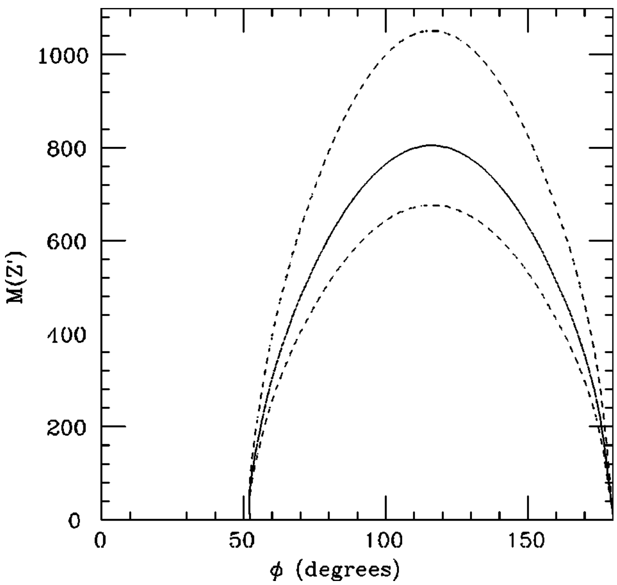

FIG. 3. Values of $M(Z')$ corresponding to central value (solid line) and $\pm 1\sigma$ errors (dashed lines) of Q_W(Cs) in a model where the discrepancy with respect to the standard electroweak prediction is due to the exchange of a new unmixed Z'.

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