# Impact of atomic parity violation measurements on precision electroweak physics

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The impact of atomic parity violation experiments on the determination of the weak mixing parameter $\sin^2\theta$ and the Peskin-Takeuchi parameters $S$ and $T$ is reassessed in the light of recent electroweak measurements at CERN LEP, SLAC, and Fermilab. Since the weak charge $Q_W$ provides unique information on $S$, its determination with a factor of 4 better accuracy than present levels can have a noticeable effect on global fits. However, the measurement of $\Delta Q_W/Q_W$ for two different isotopes provides primarily information on $\sin^2\theta$. To specify this quantity to an accuracy of $\pm 0.0004$, comparable to that now provided by other electroweak experiments, one would have to determine $\Delta Q_W/Q_W$ in cesium to about 0.1% of its value, with comparable demands for other nuclei. The relative merits of absolute measurements of $Q_W$ and isotope ratios for discovering effects of new gauge bosons are noted briefly.

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About five years ago it was recognized [1,2] that the precise knowledge of the $Z$ boson mass then becoming available would lead to a nearly unique prediction for atomic parity-violating effects in a wide range of nuclei, independently of standard model parameters such as the top quark mass $m_t$, the Higgs boson mass $M_H$, or the weak mixing angle $\sin^2\theta$. Thus any deviations of the weak charge $Q_W$ measured in such experiments from theoretical expectations would have to be ascribed to physics beyond the standard model.

A description of effects of new physics on electroweak gauge boson propagators (the so-called "oblique" corrections) was introduced by Peskin and Takeuchi [3] in terms of parameters called $S$, $T$, and $U$. The parameter $S$ describes wave-function renormalization effects, $T$ describes violations of a "custodial SU(2)" symmetry such as arise from the large $t-b$ mass difference, and $U$ describes differences between wave-function renormalizations of the $W$ and $Z$ propagators. (The only electroweak observable sensitive to $U$ is the $W$ mass.)

In terms of these parameters, the measurement [4] of atomic parity violation (APV) in cesium to an experimental accuracy of 2.2% (for which the theoretical interpretation [5], standing at a 1.2% level, is more precise) was found to constrain $S$ almost exclusively, with the $T$ dependence nearly cancelling. The $S$ dependence of the cesium measurement provided a useful constraint on global fits of electroweak parameters in terms of the Peskin-Takeuchi variables.

Since the original analysis [1], precise electroweak data have been obtained in many experiments at the CERN $e^+e^-$ collider LEP [6], in the measurement of the asymmetry for polarized-electron positron annihilation at the $Z$ at SLAC [7], and in the discovery of the top quark [8], the more precise measurement of the $W$ mass [9], and in the analysis of neutral-current deep inelastic neutrino scattering [10] at Fermilab. These results, when combined in a global fit, provide very strong constraints on $\sin^2\theta$ and on the Peskin-Takeuchi parameters. Concurrently, precise measurements of atomic parity-violation effects have appeared in a number of nuclei, including a 2% measurement in bismuth [11], a 1% measurement in lead [12], and 1% and 3% measurements in thallium [13,14]. The theoretical calculations for these effects are at levels of about 11% for bismuth [15,16], 8% for lead [16], and 3% in the most optimistic estimate [17] for thallium (though more recent calculations [18] quote larger errors, of the order of 10%).

It is the purpose of this paper to indicate the precision to which APV experiments (and the accompanying theoretical calculations) have to specify $Q_W$ in order to have a significant impact on present global fits to electroweak data. Previous analyses (see, e.g., Ref. [19]) have considered the impact of such measurements in the context of a smaller body of electroweak data.

We begin with a brief review of notation and formalism [20]. We then specify the data germane to our fit and perform an analysis including APV data at their present level of precision and with hypothetical errors reduced by an appropriate factor. We then discuss the effects of measurements of isotope ratios, and conclude with remarks on the relative merits of absolute measurements of $Q_W$ and isotope ratios for discovering effects of new gauge bosons. Previous analyses of the implications of electroweak data for limits on new gauge bosons include those of Refs. [1,19,21,22].

The low-energy limits of $W$ and $Z$ exchange are described by

$$\frac{G_F}{\sqrt{2}}=\frac{g^2}{8M_W^2}, \quad \frac{G_F}{\sqrt{2}}\rho=\frac{g^2+g'^2}{8M_Z^2}, \tag{1}$$

where $G_F$ is the Fermi constant, $g=e/\sin\theta$ and $g'=e/\cos\theta$ are SU(2) and U(1) coupling constants, $e$ is the proton charge, and $\theta$ is the weak mixing angle. The parameter $\rho$, which receives contributions from quark loops to $W$ and $Z$ self-energies, is dominated by the top quark [23]:

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$$\rho \simeq 1 + \frac{3 G_F m_t^2}{8 \pi^2 \sqrt{2}}. \tag{2}$$

Consequently, if we define $\theta$ by means of the precise measurement at LEP of $M_Z$,

$$M_Z^2 = \frac{\pi \alpha}{\sqrt{2} G_F \rho \sin^2\theta \cos^2\theta}, \tag{3}$$

then $\theta$ will depend on $m_t$, and so will

$$M_W^2 = \frac{\pi \alpha}{\sqrt{2} G_F \sin^2\theta}. \tag{4}$$

Here one must use the value of $\alpha$ appropriate to the electroweak scale; we take $\alpha^{-1}(M_Z) = 128.9 = \pm 0.1$ [24].

The Higgs boson also affects the parameter $\rho$ through loop diagrams. It is convenient to express contributions to $\rho$ in terms of deviations of the top quark and Higgs boson masses from nominal values. For $m_t = 175$ GeV, $M_H = 300$ GeV, the measured value of $M_Z$ leads to a nominal expected value of $\sin^2\theta_{\rm eff} = 0.2315$. In what follows we shall interpret the effective value of $\sin^2\theta$ as that measured via leptonic vector and axial-vector couplings: $\sin^2\theta_{\rm eff} \equiv \frac{1}{4}(1 - [g_V^l/g_A^l])$. We have corrected the nominal value of $\sin^2\theta_{\overline{\rm MS}} \equiv \hat{s}^2$, where $\overline{\rm MS}$ denotes the modified minimal subtraction scheme, as quoted by DeGrassi, Kniehl, and Sirlin [25] for the difference [26] $\sin^2\theta_{\rm eff} - \hat{s}^2 = 0.0003$ and for the recent change in the evaluation of $\alpha(M_Z)$ [24].

Defining the parameter $T$ by $\Delta\rho \equiv \alpha T$, we find

$$T \simeq \frac{3}{16\pi \sin^2\theta}\left[\frac{m_t^2 - (175 \text{ GeV})^2}{M_W^2}\right] - \frac{3}{8\pi \cos^2\theta} \ln \frac{M_H}{300 \text{ GeV}}. \tag{5}$$

The weak mixing angle $\theta$, the $W$ mass, and other electroweak observables depend on $m_t$ and $M_H$.

The weak charge-changing and neutral-current interactions are probed under a number of different conditions, corresponding to different values of momentum transfer. For example, muon decay occurs at momentum transfers small with respect to $M_W$, while the decay of a $Z$ into fermion-antifermion pairs imparts a momentum of nearly $M_Z/2$ to each member of the pair. Small "oblique" corrections [3], logarithmic in $m_t$ and $M_H$, arise from contributions of new particles to the photon, $W$, and $Z$ propagators. Other (smaller) "direct" radiative corrections are important in calculating actual values of observables.

We may then replace (1) by

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8 M_W^2}\left(1 + \frac{\alpha S_W}{4 \sin^2\theta}\right),$$
$$\frac{G_F \rho}{\sqrt{2}} = \frac{g^2 + g'^2}{8 M_Z^2}\left(1 + \frac{\alpha S_Z}{4 \sin^2\theta \cos^2\theta}\right), \tag{6}$$

where $S_W$ and $S_Z$ are coefficients representing variation with momentum transfer. Together with $T$, they express a wide variety of electroweak observables in terms of quantities sensitive to new physics. The Peskin-Takeuchi variable $U$ is equal to $S_W - S_Z$, while $S \equiv S_Z$.

Expressing the "new physics" effects in terms of deviations from nominal values of top quark and Higgs boson masses, we have the expression for $T$ written above, while contributions of Higgs bosons and of possible new fermions $U$ and $D$ with electromagnetic charges $Q_U$ and $Q_D$ to $S_W$ and $S_Z$, in a leading-logarithm approximation, are [27]

$$S_Z = \frac{1}{6\pi}\left[\ln \frac{M_H}{300 \text{ GeV}} + \sum N_C \left(1 - 4\bar{Q} \ln \frac{m_U}{m_D}\right)\right], \tag{7}$$

$$S_W = \frac{1}{6\pi}\left[\ln \frac{M_H}{300 \text{ GeV}} + \sum N_C \left(1 - 4 Q_D \ln \frac{m_U}{m_D}\right)\right]. \tag{8}$$

The expressions for $S_W$ and $S_Z$ are written for doublets of fermions with $N_C$ colors and $m_U \geqslant m_D \geqslant m_Z$, while $\bar{Q} \equiv (Q_U + Q_D)/2$. The sums are taken over all doublets of new fermions. In the limit $m_U = m_D$, one has equal contributions to $S_W$ and $S_Z$. For a single Higgs boson and a single heavy top quark, Eqs. (7) and (8) become

$$S_Z = \frac{1}{6\pi}\left[\ln \frac{M_H}{300 \text{ GeV}} - 2 \ln \frac{m_t}{175 \text{ GeV}}\right],$$
$$S_W = \frac{1}{6\pi}\left[\ln \frac{M_H}{300 \text{ GeV}} + 4 \ln \frac{m_t}{175 \text{ GeV}}\right], \tag{9}$$

where the leading-logarithm expressions are of limited validity for $M_H$ and $m_t$ far from their nominal values.

We now list the electroweak observables used in our fit. Recent direct $W$ mass measurements, in GeV, include 79.92 $\pm 0.39$ [28], $80.35 \pm 0.37$ [29], and $80.41 \pm 0.18$ [9], with average $80.33 \pm 0.15$. Data [10,30,31] on the ratio $R_\nu \equiv \sigma(\nu N \to \nu + \cdots)/\sigma(\nu N \to \mu^- + \cdots)$ lead to information on $\rho^2$ times a function of $\sin^2\theta$ roughly equivalent to the constraint $M_W = 80.27 \pm 0.26$ GeV.

Measured $Z$ parameters [6] include $M_Z = 91.1887$ $\pm 0.0022$ GeV, $\Gamma_Z = 2.4971 \pm 0.0033$ GeV, $\sigma_h^0 = 41.492$ $\pm 0.081$ nb (the hadron production cross section), and $R_l \equiv \Gamma_{\rm hadrons}/\Gamma_{\rm leptons} = 20.800 \pm 0.035$, which may be combined to obtain the $Z$ leptonic width $\Gamma_{ll}(Z) = 83.94 \pm 0.13$ MeV. Leptonic asymmetries include the forward-backward asymmetry parameter $A_{\rm FB}^l$ leading to a value of $\sin^2\theta_{\rm eff} = 0.23096 \pm 0.00073$, and independent determinations from the parameters $A_\tau \to \sin^2\theta_{\rm eff} = 0.2324 \pm 0.0010$ and $A_e \to \sin^2\theta_{\rm eff} = 0.2328 \pm 0.0011$. The last three values may be combined to yield $\sin^2\theta_{\rm eff} = 0.23176 \pm 0.00052$. [We do not use asymmetries as measured in decays of $Z$ to $b\bar{b}$ (which may reflect additional new-physics effects [32]), to $c\bar{c}$ (which are of limited weight because of large errors), or to light quarks (for which interpretations are more model dependent).] This last result is to be compared with that based on the left-right asymmetry parameter $A_{\rm LR}$ measured with polarized electrons at the SLAC Linear Collider (SLC) [7]: $\sin^2\theta_{\rm eff} = 0.2305 \pm 0.0005$.

Parity violation in atoms, stemming from the interference of $Z$ and photon exchanges between the electrons and the nucleus, provides further information on electroweak couplings. The most precise constraint at present arises from the

TABLE I. Electroweak observables described in fit.

| Quantity | Experimental value | Theoretical value |
|---|---|---|
| $Q_W$ (Cs) | $-71.0\pm1.8$[a] | $-73.2$[b]$-0.80S-0.005T$ |
| $Q_W$ (Tl) | $-115.0\pm4.5$[c] | $-116.8$[d]$-1.17S-0.06T$ |
| $M_W$ (GeV) | $80.31\pm0.14$[e] | $80.35$[f]$-0.29S+0.45T$ |
| $\Gamma_{ll}(Z)$ (MeV) | $83.94\pm0.13$[g] | $83.90-0.18S+0.78T$ |
| $\sin^2\theta_{\rm eff}$ | $0.23176\pm0.00052$[h] | $0.2315$[i]$+0.0036S-0.0026T$ |
| $\sin^2\theta_{\rm eff}$ | $0.2305\pm0.0005$[j] | $0.2315$[i]$+0.0036S-0.0026T$ |

[a]Weak charge in cesium [4].
[b]Calculation [1] incorporating atomic physics corrections [5].
[c]Weak charge in thallium [13,14] (see text).
[d]Calculation [33] incorporating atomic physics corrections [17].
[e]Average of direct measurements and indirect information from neutral/charged current ratio in deep inelastic neutrino scattering [10,30,31].
[f]Including perturbative QCD corrections [25].
[g]LEP average as of May, 1995 [6].
[h]From asymmetries at LEP [6].
[i]As calculated [25] with correction for relation between $\sin^2\theta_{\rm eff}$ and $\hat{s}^2$ [26].
[j]From left-right asymmetry in annihilations at SLC [7].

measurement of the *weak charge* (the coherent vector coupling of the $Z$ to the nucleus), $Q_W=\rho(Z-N-4Z\sin^2\theta)$, in atomic cesium [4], with the result $Q_W(\mathrm{Cs})=-71.04\pm1.58\pm0.88$. The first error is experimental, while the second is theoretical [5]. The prediction [1] $Q_W(\mathrm{Cs})=-73.20\pm0.13$ is insensitive to standard-model parameters [1,2]; discrepancies are good indications of new physics (such as exchange of an extra $Z$ boson). Recently the weak charge has also been measured in atomic thallium. The Seattle group [13] obtains $Q_W(\mathrm{Tl})=-114.2\pm1.3\pm3.4$, to be compared with the theoretical estimate [17,33] $Q_W=-116.8$. From information presented by the Oxford group [14] we deduce their value of $Q_W(\mathrm{Tl})$ to be $-120.5\pm3.5\pm4.0$. Here the first errors refer to the total experimental error, while the second refer to the error associated with the atomic physics calculations. The Oxford group has taken account of uncertainties uncovered in more recent theoretical calculations [18] in quoting a slightly larger theoretical error. Averaging the two experimental values, multiplying the experimental error by a scale factor of $(\chi^2)^{1/2}$, and allowing for the larger of the two theoretical uncertainties as a common error, we find $Q_W(\mathrm{Tl})=-115.0\pm2.1\pm4.0=-115.0\pm4.5$.

We have performed a fit to the electroweak observables listed in Table I. The "nominal" values (including [25] $\sin^2\theta_{\rm eff}=0.2315$) are calculated for $m_t=175$ GeV and $M_H=300$ GeV. We use $\Gamma_{ll}(Z)$, even though it is a derived quantity, because it has little correlation with other variables in our fit. It is mainly sensitive to the axial-vector coupling $g_A^l$, while asymmetries are mainly sensitive to $g_V^l$. We also omit the total width $\Gamma_{\rm tot}(Z)$ from the fit, since it is highly correlated with $\Gamma_{ll}(Z)$ and mainly provides information on the value of the strong fine-structure constant $\alpha_s$. With $\alpha_s=0.12\pm0.01$, the observed total $Z$ width is consistent with predictions. The partial width $\Gamma(Z\to b\bar{b})$ is the subject of several discussions of new physics [32] which we do not address here.

Each observable in Table I specifies a band in the $S$-$T$ plane with different slope, as seen from the ratios of coefficients of $S$ and $T$. Parity violation in atomic cesium and thallium is sensitive almost entirely to $S$ [1,2]. The impact of $\sin^2\theta_{\rm eff}$ determinations on $S$ is considerable. The leptonic width of the $Z$ is sensitive primarily to $T$. The $W$ mass specifies a band of intermediate slope in the $S$-$T$ plane; here we assume $S_W=S_Z$. Strictly speaking, the ratio $R_\nu$ specifies a band with slightly more $T$ and less $S$ dependence than $M_W$ [1,3]; we have ignored this difference here.

The resulting constraints on $S$ and $T$ are shown in Fig. 1(a). A top quark mass of $180\pm12$ GeV [the Collider Detector at Fermilab (CDF) and D0 average] is compatible with all Higgs boson masses between 100 and 1000 GeV, as seen by the curved lines intersecting the error ellipses. Independently of the standard model predictions, values of $S$ between $-0.5$ and 0.3 are permitted at the 90% confidence level. This

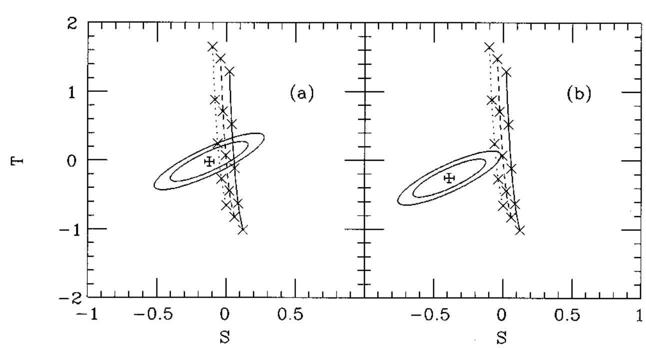


FIG. 1. Allowed ranges of $S$ and $T$ at 68% (inner ellipses) and 90% (outer ellipses) confidence levels, corresponding to $\chi^2=2.3$ and 4.6 above the minimum (crosses at center of ellipses). Dotted, dashed, and solid lines correspond to standard model predictions for $M_H=100$, 300, and 1000 GeV. Symbols $\times$, from bottom to top, denote predictions for $m_t=100$, 140, 180, 220, and 260 GeV. (a) Fit including APV experiments with present errors; (b) errors on APV experiments reduced by a factor of 4, with present central values of $Q_W$ retained.

is to be compared with the determinations $S=-2.7\pm2.3$ [4] based on cesium and $S=-1.5\pm3.8$ based on the average mentioned above of two recent thallium experiments [13,14]. Averaging, we find $S=-2.4\pm2.0$. It is clear that the value of $S$ is now known much more precisely than specified by the APV experiments. Omission of the APV data (the first two lines) in Table I in the fit shifts the ellipses by $\Delta S=0.020$, $\Delta T=0.018$ without affecting their sizes noticeably.

What improvement in accuracy of the APV experiments would begin to have an impact on the fits? Since the 90% confidence level limits on $S$ are of order $\pm0.4$, one should ask for a factor of about 4 improvement in the combined error on $Q_W$ from cesium and thallium. The effect of reducing the total errors in each experiment by a factor of 4 while keeping the same central values is shown in Fig. 1(b). The standard model predictions now graze the edge of the 90% C.L. ellipse.

The comparison of $Q_W$ for more than one isotope can provide electroweak information in which atomic physics corrections play a much less significant role [34]. One can measure the ratio of the difference for two isotopes, $\Delta Q_W\equiv Q_W(N_1)-Q_W(N_2)$, with respect to an average value $\bar{Q}_W\equiv[Q_W(N_1)+Q_W(N_2)]/2$ for the two. Since $\bar{Q}_W=\rho(Z-\bar{N}-4Z\bar{x})$, $r\equiv\Delta Q_W/\bar{Q}_W$ is a function of $\bar{x}\equiv\sin^2\theta_{\rm eff}$ alone; the $\rho$ dependence cancels. The errors in $\bar{x}$ and $r$ are related to one another by

$$\frac{\delta r}{r}\approx\frac{4Z}{Z-\bar{N}-4Z\bar{x}}\delta\bar{x},\tag{10}$$

where $\bar{N}\equiv(N_1+N_2)/2$. For $^{133}_{55}\mathrm{Cs}$, the coefficient is $4Z/(Z-\bar{N}-4Z\bar{x})\approx-3$, so that in order to obtain a measurement of $\bar{x}$ to $\pm0.0004$ (competitive with the average of the LEP and SLC determinations mentioned in Table I), one must measure $r$ to 0.1% of its value. [This is considerably more demanding then requiring the isotope *ratio* $Q_W(N_1)/Q_W(N_2)=1+\Delta Q_W/Q_W(N_2)$ to be measured to 0.1%.] At this level it is likely that isotope-dependent effects and uncertainties in electroweak radiative corrections become significant. Some statistical power can be added to the determination of $\Delta Q_W$ if more than two isotopes are used.

In fact, the range of variation of models for the neutron charge radius in lead [35] is equivalent to about a 1% uncertainty in $\sin^2\theta$, comparable to that envisioned for several future experiments involving parity violation in the scattering of medium-energy polarized electrons [36] on nucleons and nuclei. A calculation of the uncertainty due to the neutron charge radius in cesium [37] is more optimistic, corresponding to an error of 0.5% in $\sin^2\theta$ for a measurement with $N_1=70$, $N_2=84$.

The theoretical error in $r$ for cesium [1] is itself about 0.2%, and is dominated by the error in the coefficient of $\sin^2\theta$ in $Q_W$; most of the error cancels in $\Delta Q_W$. Other determinations of $\sin^2\theta$ at low momentum transfers $|q^2|\ll M_Z^2$ include the most recent CHARM II result [38], $\sin^2\theta=0.2324\pm0.0083$, a measurement to 3.6% accuracy, and the ratio $R_\nu$ mentioned above, which is roughly equivalent to a measurement of the on-shell parameter $\sin^2\theta_W\equiv1-M_W^2/M_Z^2=0.225\pm0.005$. An error $\delta\sin^2\theta_W$ is equivalent by virtue of (3) and (4) [39] to an error $\delta\hat{s}^2=(\hat{s}^2/\hat{c}^2)\,\delta\sin^2\theta_W\approx0.3\delta\sin^2\theta_W$, where $\hat{c}^2\equiv1-\hat{s}^2$. Thus deep inelastic neutrino scattering is now providing a measurement of $\sin^2\theta$ at $|q^2|\ll M_Z^2$ to slightly better than a percent, but with residual dependence on top quark and Higgs boson masses.

We conclude with a comparison of absolute and relative measurements of $Q_W$ for discovering or placing limits on effects of new gauge bosons. In Ref. 1 the effect of a $Z_\chi$ [the extra $Z$ in SO(10) theories] was expressed as

$$\Delta Q_{W\ \rm tree}^{\rm new}\simeq0.4(2N+Z)(M_W/M_{Z_\chi})^2.\tag{11}$$

The central value of $\Delta Q_W=(-71.04\pm1.81)-(-73.20\pm0.13)=2.16\pm1.81$ in cesium, with $N=78$ and $Z=55$, could be accounted for with a $Z_\chi$ of mass 500 GeV, to be compared with the lower bound of 425 GeV set by a direct search at the Tevatron [40]. Thus, to place a bound $M_{Z_\chi}>1$ TeV at the $1\sigma$ level, one would have to reduce the discrepancy to $\Delta Q_W<0.54$, requiring about a factor of 4 greater accuracy than the present determination.

To obtain a bound $M_{Z_\chi}>1$ TeV by measuring an isotope ratio, one would have to measure $r$ in cesium to 0.2%. To see this, we express

$$r=\frac{\Delta N[-\rho+0.8(M_W/M_{Z_\chi})^2]}{\rho(Z-\bar{N}-4Z\sin^2\theta)+0.4(2\bar{N}+Z)(M_W/M_{Z_\chi})^2},\tag{12}$$

where $\Delta N\equiv N_1-N_2$. Expanding to first order in $\mathscr{R}\equiv(M_W/M_{Z_\chi})^2/\rho$, we find

$$r\approx r^0\left[1+\frac{0.4Z(8\sin^2\theta-3)}{Q_W^0}\mathscr{R}\right],\tag{13}$$

where quantities with the superscript zero refer to those in the absence of the $Z_\chi$ contribution. Note that the terms with $\bar{N}$ cancel. The coefficient of $\mathscr{R}$ is about 0.34 for cesium and 0.31 for lead. Thus, to set a limit $M_{Z_\chi}>1$ TeV, corresponding to $\mathscr{R}<0.64\%$ with $\rho\simeq1$, one has to measure $r$ to 0.2%.

The $Z_\chi$ is one of a family of possibilities arising in $E_6$ theories, which also contain a boson $Z_\psi$ which arises when $E_6$ breaks down to SO(10). Let us parametrize a general $Z_\phi\equiv Z_\psi\cos\phi+Z_\chi\sin\phi$. Here $\phi$ is the same as the angle $\theta$ employed in Ref. [21], and opposite to the angle $\theta_U$ defined in Ref. [41]. The boson sometimes called $Z_\eta$, which arises in superstring theories, corresponds to $\phi=\arctan(3/5)^{1/2}\simeq37.8°$ in our notation. We find that Eq. (11) is merely multiplied by a factor $f(\phi)\equiv\sin\phi[\sin\phi-(5/3)^{1/2}\cos\phi]$. This function vanishes at $\phi=0$ and $\phi=52.2°$ and is negative in between, attaining its most negative value of $-0.32$ at $\phi=26.1°$ and its maximum value of 1.32 at $\phi=116.1°$. The corresponding bounds on $Z_\phi$ masses can be rescaled accordingly.

To summarize, atomic parity violation experiments can still play a key role in providing information on fundamental parameters in particle physics, despite recent strides in precise electroweak measurements. Absolute determination of $Q_W$ for one or more atoms to an accuracy of half a percent is now the most important goal. This will help to constrain the

Peskin-Takeuchi parameter $S$ in a useful manner and can roughly double the present lower limits on extra gauge bosons. Measurements of ratios of isotopes are likely to provide information on $\sin^2\theta$ at low momentum transfers to an accuracy of at best a percent, given present theoretical uncertainties about nuclear effects in lead [35], or slightly better in cesium on the basis of the estimate of Ref. [37]. An error of a percent in $\sin^2\theta$ is comparable to that envisioned for other medium- and low-energy tests; indeed, deep inelastic neutrino scattering already is close to providing such a constraint. Measurement of the parameter $r \equiv \Delta Q_W / \bar{Q}_W$ to an accuracy of about 0.5% would constrain $\sin^2\theta$ to a percent, while an accuracy of 0.2% in $r$ would roughly double the present limit on new gauge boson masses.

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