Atomic Parity Violation as a Probe of New Physics

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Effects of physics beyond the standard model on electroweak observables are studied using the Peskin-Takeuchi isospin-conserving, S, and -breaking, T, parametrization of "new" quantum loop corrections. Experimental constraints on S and T are presented. Atomic parity-violating experiments are shown to be particularly sensitive to S with existing data giving $S=-2.7\pm2.0\pm1.1$. That constraint has important implications for generic technicolor models which predict $S\simeq 0.1N_TN_D$ (N_T is the number of technicolors, N_D is the number of technidoublets).

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Precision electroweak measurements have started to reach a sensitivity at which they are testing the standard $SU(3)_C\times SU(2)_L\times U(1)_Y$ model at the level of its electroweak radiative corrections and probing for small "new-physics" effects.[1,2] Already, one can infer a top-quark mass of $\sim 140\pm40$ GeV from loop corrections to m_W, m_Z, Γ_Z, and deep-inelastic $\nu_\mu N$ scattering. A deviation from standard-model expectations could be our first hint of additional tree-level interactions,[3] or a signal of further loop corrections.

In this Letter, we examine the effect of new high-mass-scale phenomena on electroweak observables via quantum loop corrections. We have in mind theories such as supersymmetry at high mass scales[4] or technicolor models[5] in which there is a wealth of heavy-particle spectroscopy, which primarily influences present-day electroweak observables through contributions to gauge-boson self-energies. Such studies were pioneered by Veltman[6] and recently extended to technicolor models.[7,8] Peskin and Takeuchi[8] have introduced a nice general formalism for parametrizing "new" loop contributions in terms of isospin-conserving, S, and -breaking, T, effects. We follow their approach and examine the sensitivity of various experiments to S and T. As we shall see, cesium atomic parity violation[9] is particularly sensitive to S.[10] This finding provides strong motivation for further improving cesium parity-violating experiments as well as the underlying atomic theory[11] which will soon contribute the dominant uncertainty in S.

We begin by assuming that the standard model is basically correct and take $\alpha=1/137.036$, $G_F=1.16637\times10^{-5}\ \mathrm{GeV}^{-2}$, $m_Z=91.17\pm0.03$ GeV, and the known fermion masses as input. We further assume $m_t=140$ GeV and $m_H=100$ GeV and later comment on deviations from those values. From that input, all electroweak observables are predicted, modulo the effect of additional new physics beyond the standard model and theoretical uncertainties. For example, the weak mixing angle defined by modified minimal subtraction[12,13] ($\overline{\mathrm{MS}}$) at mass scale $\mu=m_Z$ is given by (including radiative corrections[13-15] $\Delta\hat{r}$)

$$\sin^2 2\theta_W(m_Z)_{\overline{\mathrm{MS}}}=\frac{4\pi\alpha}{\sqrt{2}G_F m_Z^2(1-\Delta\hat{r})}\,, \tag{1}$$

with $\Delta\hat{r}=0.0624\pm0.0013$ in the standard model. The error in $\Delta\hat{r}$ comes from hadronic contributions to low-energy vacuum-polarization loops and possible two-loop effects. It can be reduced somewhat by better measurements of $e^+e^-\to$ hadrons.[16] One, therefore, expects

$$\sin^2\theta_W(m_Z)_{\overline{\mathrm{MS}}}=0.2323\pm0.0002\pm0.0005\,, \tag{2}$$

where the first error comes from m_Z and the second from $\Delta\hat{r}$.

A deviation in any measurement of $\sin^2\theta_W(m_Z)_{\overline{\mathrm{MS}}}\equiv\bar{x}$ from the value $\bar{x}^0=0.2323$ in (2) would imply $m_t\neq140$ GeV, $m_H\neq100$ GeV, or the appearance of new physics. [From here on, we adopt the shorthand notation $\bar{x}$ to denote $\sin^2\theta_W(m_Z)_{\overline{\mathrm{MS}}}$ and $\bar{x}^0=0.2323$.] Peskin and Takeuchi[8] have introduced a general prescription for parametrizing effects of certain types of new physics, those which primarily show up in the $W^\pm$ and Z boson self-energies $\Pi_{WW}(q^2)$ and $\Pi_{ZZ}(q^2)$ via the propagators

$$\frac{1}{q^2-m_W^{02}-\Pi_{WW}(q^2)}\,,\quad \frac{1}{q^2-m_Z^{02}-\Pi_{ZZ}(q^2)}\,. \tag{3}$$

Assuming that all standard-model loop corrections have been properly accounted for, one need only consider[15] the new-physics contributions $\Pi_{WW}^{\rm new}(q^2)$ and $\Pi_{ZZ}^{\rm new}(q^2)$. If the new physics involves very high mass scales, then only the following quantities (and combinations of them) affect electroweak observables at present-day energies:

$$\begin{aligned}
&\rho(0)^{\rm new}\equiv1+\frac{\Pi_{WW}^{\rm new}(0)}{m_W^2}-\frac{\Pi_{ZZ}^{\rm new}(0)}{m_Z^2}=1+\alpha(m_Z)T\,,\\
&\left(\frac{\Pi_{WW}^{\rm new}(m_W^2)-\Pi_{WW}^{\rm new}(0)}{m_W^2}\right)_{\overline{\mathrm{MS}}}=\frac{\alpha(m_Z)}{4\bar{x}^0}S_W\simeq Z_W^{\rm new}-1\,,\\
&\left(\frac{\Pi_{ZZ}^{\rm new}(m_Z^2)-\Pi_{ZZ}^{\rm new}(0)}{m_Z^2}\right)_{\overline{\mathrm{MS}}}=\frac{\alpha(m_Z)}{4\bar{x}^0(1-\bar{x}^0)}S_Z\\
&\qquad\simeq Z_Z^{\rm new}-1\,,
\end{aligned} \tag{4}$$

where $\alpha(m_Z) \simeq 1/127.8$ (defined by $\overline{\rm MS}$) and the subscript $\overline{\rm MS}$ denotes that modified minimal subtraction is to be applied to the new quantum loops.[15] We next assume, as in Ref. 8, $S_W \simeq S_Z \simeq S$. In that way, only the isospin-conserving contribution S to the wave-function renormalizations $Z_W^{\rm new}$ and $Z_Z^{\rm new}$ is retained. In models such as technicolor, an underlying symmetry suppresses $S_W - S_Z$.

For S and T nonzero, the $\Delta\hat{r}$ in (1) gets an additional contribution[13,14]

$$\Delta\hat{r}^{\rm new} = \left[\frac{\Pi_{ZZ}^{\rm new}(m_Z^2)}{m_Z^2} - \frac{\Pi_{WW}^{\rm new}(0)}{m_W^2}\right]_{\overline{\rm MS}} = \frac{\alpha(m_Z)S}{4\bar{x}^0(1-\bar{x}^0)} - \alpha(m_Z)T\,, \tag{5}$$

or solving for $\bar{x}$ perturbatively

$$\bar{x} = 0.2323 + \alpha(m_Z)\left[\frac{1}{4(1-2\bar{x}^0)}S - \frac{\bar{x}^0(1-\bar{x}^0)}{1-2\bar{x}^0}T\right] = 0.2323 + 0.00365S - 0.00261T\,. \tag{6}$$

A direct measurement of $\bar{x}$, with standard-model radiative corrections applied, such as by $\mathcal{A}_{FB}$ or $\mathcal{A}_{LR}$ asymmetry measurements at the Z pole or via $\sigma(\nu_\mu e)/\sigma(\bar{\nu}_\mu e)$ should actually measure $\bar{x}$ in (6) rather than $\bar{x}^0 = 0.2323$ if S or T are nonzero. Having $m_t \neq 140$ GeV or $m_H \neq 100$ GeV can also be roughly expressed as T and S contributions,

$$T \simeq \frac{3}{16\pi\bar{x}^0}\left[\frac{m_t^2 - (140\ {\rm GeV})^2}{m_W^2}\right] - \frac{3}{16\pi(1-\bar{x}^0)}\ln\left[\frac{m_H}{100\ {\rm GeV}}\right]^2,$$
$$S \simeq \frac{1}{6\pi}\ln\left[\frac{m_H}{100\ {\rm GeV}}\right]. \tag{7}$$

The m_H sensitivity is relatively small while the shift to $T \simeq 0.82$ for $m_t \simeq 200$ GeV is big enough to already be accessible to experiment. Of course, for top-quark and Higgs-boson studies, complete one-loop calculations should be used to constrain their masses, rather than the approximations in (7).[14]

To determine the effect of S and T on electroweak observables, one need merely replace $\bar{x}$ by $0.2323 + 0.00365S - 0.00261T$ and multiply weak-neutral-current amplitudes or Z decay widths normalized in terms of G_F by $\rho(0)^{\rm new} = 1 + 0.00782T$.

For m_W predictions, one uses

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F\bar{x}[1-\Delta r(m_Z)_{\overline{\rm MS}}]}\,,$$
$$\Delta r(m_Z)_{\overline{\rm MS}} = 0.0698 + \left[\frac{\Pi_{WW}^{\rm new}(m_W^2) - \Pi_{WW}^{\rm new}(0)}{m_W^2}\right]_{\overline{\rm MS}} = 0.0698 + \frac{\alpha(m_Z)}{4\bar{x}^0}S\,, \tag{8}$$

where 0.0698 is the standard-model prediction.[14] Combining (8) and (6) gives

$$m_W = 80.20 - 0.29S + 0.45T\ {\rm GeV}\,. \tag{9}$$

Using the above modifications, we have obtained the S and T dependences for various electroweak observables listed in Table I. Some measurements such as m_W, Γ_Z, and R_ν are already sensitive to $T \sim 1$. They have, therefore, been used to indirectly infer m_t or bound new isospin-breaking loop effects such as mass differences[6] within any heavy $SU(2)_L$ doublet. Neglecting S, we see that a future ± 70 MeV determination of m_W or a $\pm 0.5\%$ measurement of R_ν would give T to about ± 0.2 and pinpoint m_t to $\pm$(15–20) GeV (modulo Higgs-boson mass uncertainties). Measurements of Z-boson decay asymmetries $\mathcal{A}_{FB}$ and $\mathcal{A}_{LR}$ also offer the possibility of similar future T precision, but with somewhat larger Higgs-boson mass uncertainties.

S, the isospin-conserving new radiative correction, has not been as carefully scrutinized as T. Table I illustrates that, in general, a given experiment constrains a linear combination of S and T. We have presented in Fig. 1 the allowed S and T domain obtained from the present constraints in Table I. Existing data do not indicate significant deviations in S or T from 0. Those bounds are to be compared with the generic one-generation technicolor prediction[7,8] $S \sim +2$, which, unlike T,[26] is supposed to be fairly model independent.[8] [For theories with N_T technicolors and N_D $SU(2)_L$ technidoublets, one roughly expects[7,8] $S \sim 0.1 N_T N_D$. In addition, m_H is effectively ~ 1 TeV in such models; so S is further increased by about 0.12 and T reduced by -0.36 via Eq. (7).] The bounds also have interesting implications for any model with many new heavy-fermion doublets in which each contributes $+1/6\pi$ to S.[6,10]

Table I indicates that cesium atomic parity violation is particularly sensitive to S and insensitive to T. (Figure 1 illustrates the important role atomic parity violation plays in globally constraining S.) Ongoing cesium experiments,[27] therefore, offer the possibility of improving the bound on S (or seeing an effect). We now elaborate on this point.

Including one-loop electroweak radiative corrections,[28] the so-called weak charge of cesium (for an isotope with N neutrons) is given by

$$Q_W(^{55+N}_{55}{\rm Cs}) = (0.9857 \pm 0.0004)\rho(0)^{\rm new} \times \{-N + 55[1 - (4.012 \pm 0.010)\bar{x}]\}\,, \tag{10}$$

where we have included an estimate of the hadronic-loop uncertainties.[29] The S and T dependence is found using $\rho(0)^{\rm new} = 1 + 0.00782T$ and $\bar{x} = 0.2323 + 0.00365S - 0.00261T$:

$$Q_W(^{55+N}_{55}{\rm Cs}) = -73.20 \pm 0.13 - 0.8S - 0.005T + 0.986(78-N)(1+0.008T)\,. \tag{11}$$

For $N = 78$, the stable isotope used at present, the T dependence is completely negligible as a result of a re-

TABLE I. Comparison of electroweak predictions for arbitrary S and T with existing and possible future experimental constraints. Predictions are normalized by standard-model values for $S=T=0$, $m_t=140$ GeV, $m_H=100$ GeV, and $\bar{x}^0=0.2323$, which are denoted by superscript zero. In some cases, we assume $\bar{x}_{\rm expt}$ is extracted from data after standard-model radiative corrections with $S=T=0$ have been applied.

Observable	Prediction	Present constraint	Future sensitivity
Cesium parity violation [a]	$Q_W(^{133}_{55}\mathrm{Cs})=-73.20-0.8S-0.005T$	$-71.04\pm1.58\pm0.88$	±0.4
$W^\pm$ mass [b]	$m_W=80.20-0.29S+0.45T$ GeV	80.14 ± 0.31 GeV	±0.07 GeV
$\Gamma(Z\to\nu\bar{\nu})$ [c]	$\Gamma_\nu/\Gamma_\nu^0=1+0.0078T$	0.992 ± 0.036	±0.018
$\Gamma(Z\to e^+e^-)$ [c]	$\Gamma_e/\Gamma_e^0=1-0.0021S+0.0093T$	1.004 ± 0.011	±0.005
$\Gamma(Z\to \text{all})$ [c]	$\Gamma_Z/\Gamma_Z^0=1-0.0038S+0.0105T$	1.002 ± 0.008	±0.004
Z asymmetries [d]	$\bar{x}_{\rm expt}/\bar{x}^0=1+0.016S-0.011T$	0.978 ± 0.056	±0.0017
eD asymmetry [e]	$\bar{x}_{\rm expt}/\bar{x}^0=1+0.016S-0.017T$	0.965 ± 0.086	$\cdots$
eC asymmetry [f]	$\bar{x}_{\rm expt}/\bar{x}^0=1+0.016S-0.003T$	0.86 ± 0.22	±0.01
$R_\nu\equiv\sigma(\nu_\mu N)_{\rm NC}/\sigma(\nu_\mu N)_{\rm CC}$ [g]	$R_\nu/R_\nu^0=1-0.0078S+0.0212T$	$0.990\pm0.007\pm0.011$	±0.005
$R_{\bar{\nu}}\equiv\sigma(\bar{\nu}_\mu N)_{\rm NC}/\sigma(\bar{\nu}_\mu N)_{\rm CC}$ [h]	$R_{\bar{\nu}}/R_{\bar{\nu}}^0=1+0.0003S+0.0154T$	1.02 ± 0.02	±0.01
$R\equiv\sigma(\nu_\mu e)/\sigma(\bar{\nu}_\mu e)$ [i]	$R/R^0=1-0.029S+0.021T$	0.997 ± 0.11	±0.04
$R'\equiv\sigma(\nu_\mu e)/[\sigma(\bar{\nu}_\mu e)+\sigma(\nu_e e)]$ [j]	$R'/R'^0=1-0.027S+0.037T$	Proposed	±0.02

[a]References 9 and 11.
[b]Reference 17.
[c]Reference 18.
[d]Reference 19.
[e]Reference 20.
[f]Reference 21.
[g]Reference 22.
[h]Reference 23.
[i]Reference 24.
[j]Reference 25.

markable cancellation; so, we drop it. One therefore expects

$$Q_W(^{133}_{55}\mathrm{Cs})=-73.20-0.8S\pm0.13\,, \tag{12}$$

which is to be compared with[9,11]

$$Q_W(^{133}_{55}\mathrm{Cs})^{\rm expt}=-71.04\pm1.58\pm0.88\,, \tag{13}$$

where the first error is experimental[9] (mainly statistical) and the second comes from atomic theory.[11] Comparing (12) and (13) gives

$$S=-2.7\pm2.0\pm1.1\pm0.16\,. \tag{14}$$

Future experimental effort is expected[27] to lower the ±2.0 experimental uncertainty to a negligible level. It then becomes a challenge for atomic theorists to reduce the present ±1.1 theory uncertainty as much as possible. A benchmark is provided by the estimated hadronic-loop uncertainty ±0.16 in (14) which might also be improved by new $e^+e^-\to$ hadrons data. An effort to reduce the total S uncertainty to ±0.2 is extremely important. At that level it is even sensitive to the minimal one-doublet technicolor model which predicts[8] $S\simeq+0.4$ (for four technicolors) or heavy new generations of ordinary fermions, each of which contributes[10] $4/6\pi\simeq0.21$ to S.

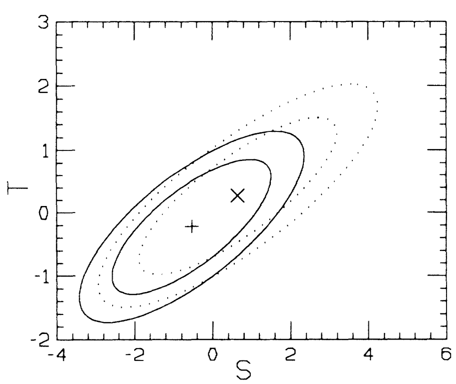

FIG. 1. Error ellipses in the parameters S and T for fits to the electroweak observables listed in Table I. The inner and outer ellipses correspond to 68%- and 90%-confidence-level limits. Dotted curves and point $\times$, no cesium data; solid curves and point $+$, present cesium data included.

An experimental approach comparing several different cesium isotopes has been suggested to circumvent atomic theory.[27] In the ratio of two different weak charges corresponding to N_1 and N_2 neutrons, respectively, most of the atomic theory [as well as the $\rho(0)^{\rm new}$] cancels. A 0.1% measurement of such a ratio would then determine $\Delta\bar{x}=\bar{x}-\bar{x}^0=0.0037S-0.0026T$ to

$$\Delta\bar{x}=\pm\frac{(N_1-3.74)(N_2-3.74)}{N_2-N_1}(4.5\times10^{-6})\,. \tag{15}$$

By measuring several isotope ratios with high precision and large N_2-N_1, one may be able to determine $\bar{x}$ to ±0.001 or better. Atomic parity violation would then be competitive with Z-asymmetry determinations of $\bar{x}$ which are expected to reach ±0.001 and may ultimately go to ±0.0004.

An alternative way to determine S is to improve the parity-violating polarized e-carbon scattering asymmetry measurements.[21] From Table I, we see that a 1% asymmetry measurement (which appears possible[30]) would determine S to ±0.6.

A nice direct S probe, implicit in the work of Peskin and Takeuchi,[8] is a comparison of the W-mass measurement with $\bar{x}$ obtained directly via Z asymmetries $\mathcal{A}_{FB}$ or $\mathcal{A}_{LR}$ [or Q_W(Cs) isotope ratios previously mentioned]. From (8), one finds

$$S \simeq 118\left[2\left(\frac{m_W-80.2\ \mathrm{GeV}}{80.2\ \mathrm{GeV}}\right)+\frac{\bar{x}-0.2323}{0.2323}\right] \tag{16}$$

independent of m_Z. [The quantity in (16) is actually S_W, whereas S_Z enters (6).] If m_W is measured to ± 70 MeV and $\bar{x}$ to ± 0.0004 (requiring 10^6 Z's for $\mathcal{A}_{LR}$ or 3×10^7 Z's for $\mathcal{A}_{FB}$), the error on S will be $\pm 0.20 \pm 0.20 \simeq \pm 0.28$. If $\bar{x}$ can only be determined to ± 0.001, the combined error increases to ± 0.55.

What if $S<0$ [see (14)] persists in future cesium experiments, but is not confirmed in the m_W-Z-asymmetry comparison of (16)? It could indicate new physics at the tree level. For example, the extra Z_χ boson in SO(10) models[3] would not affect ordinary W and Z physics (assuming no Z_χ-Z mixing) but would modify the cesium weak charge by

$$\Delta Q_W({}^{55+N}_{55}\mathrm{Cs}) \simeq 0.4(2N+55)m_W^2/m_{Z_\chi}^2 . \tag{17}$$

The current $\Delta Q_W(\mathrm{Cs}) \simeq 2.16$ central value corresponds to $m_{Z_\chi} \simeq 500$ GeV. Such a heavy Z_χ would have so far escaped detection in other neutral-current experiments, but would eventually appear as higher precision is reached.

In conclusion, we have seen that both S and T provide windows to the high-energy domain of electroweak symmetry breaking. Together, they complement direct searches for new physics at the Superconducting Super Collider and can severely constrain or even rule out new theories. All experiments with good sensitivity to S or T should be pushed as far as possible, since many measurements will be needed to sort out non-null-values and unravel the puzzle nature has prepared for us.

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